UNIT- I
Basic Concepts & Necessity of HVDC systems

1. INTRODUCTION:

➢ HVDC stands for **High Voltage Direct Current** transmission system.
➢ It transmits electrical power using **direct current (DC)** instead of alternating current (AC).
➢ Electric power transmission was originally developed with direct current. The availability of transformers and the development and improvement of induction motors at the beginning of the 20th century, led to the use of AC transmission.
➢ DC Transmission now became practical when long distances were to be covered or where cables were required. Thyristors were applied to DC transmission and solid state valves became a reality.
➢ With the fast development of converters (rectifiers and inverters) at higher voltages and larger currents, DC transmission has become a major factor in the planning of the power transmission. In the beginning all HVDC schemes used mercury arc valves, invariably single phase in construction, in contrast to the low voltage polyphase units used for industrial application.
➢ The most significant contribution to HVDC came when the Gotland Scheme in Sweden was commissioned in 1954 to be the World's first commercial HVDC transmission system. This was capable of transmitting 20 MW of power at a voltage of -100 kV and consisted of a single 96 km cable with sea return.
➢ Today, the highest functional DC voltage for DC transmission is 600kV. D.C transmission is now an integral part of the delivery of electricity in many countries throughout the world.
➢ In India, the longest HVDC link is the Talcher-Kolar transmission link (1450km long) of 500kV,with a rated capacity of 2500MW.

Necessity/Advantages of HVDC systems:

❖ HVDC systems are more economical for long distances and have lower power losses compared to AC systems
  - ➢ In AC transmission, power losses occur due to: Reactive power, Skin effect, Charging currents. HVDC does not have these problems because it uses direct current (DC).Therefore, less energy is wasted during transmission.
  - ➢ AC lines carry both: Active power, Reactive power. Reactive power increases losses and reduces efficiency. HVDC transmits only active power, so efficiency is higher.
  - ➢ AC transmission generally requires **three conductors**. HVDC can operate with **two conductors**. This reduces: Conductor cost, Tower size, Insulation cost.

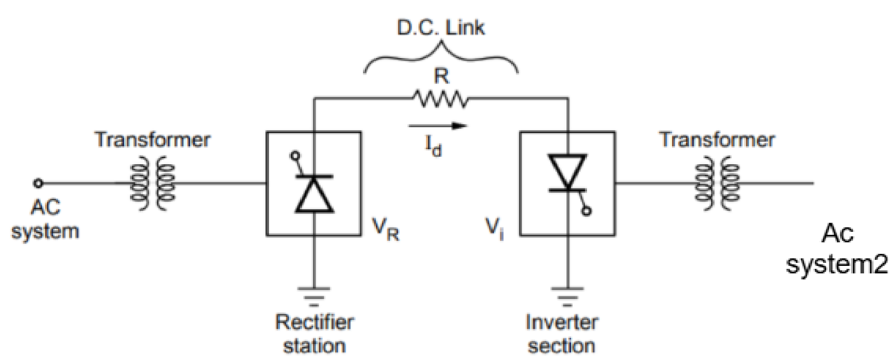
- ➢ HVDC converter stations are expensive. But for very long distances, the savings from: lower losses, cheaper transmission lines become greater than the converter cost. Hence HVDC becomes more economical than AC.

❖ HVDC systems avoid heavy charging and discharging currents caused by cable capacitance in AC systems. Therefore, HVDC is best suited for Submarine cables, Underground cables.

- ➢ AC voltage continuously changes its direction and magnitude. Because of this, the cable capacitance is continuously: charged and discharged in every cycle. This produces large **charging currents**. Which causes Increase in power losses, Heating of cables, Reduction in transmission efficiency
- ➢ In HVDC Systems, DC voltage is constant and does not change direction continuously. The cable capacitance is charged only once when the system is switched on. After that, almost no charging current flows. Therefore Lower power losses, Better efficiency, Longer transmission distance possible, Suitable for underwater and underground transmission

❖ HVDC can connect two AC systems that are not synchronized.

- ➢ Two AC power systems are said to be **synchronized** when they operate at the same: frequency, voltage, and phase angle. If these conditions are not the same, the systems are called **unsynchronized systems**. Two unsynchronized AC systems cannot be directly connected because: large circulating currents may flow, system instability may occur and equipment may get damaged. For example: One grid may operate at **50 Hz** Another grid may operate at **60 Hz** Direct AC connection between them is difficult.
- ➢ If the systems are connected through DC, synchronization is not required. Power can be exchanged between different grids safely. Systems operating at different frequencies can be connected. That improves: stability, reliability and power sharing between networks.



❖ Power flow in HVDC can be controlled independently. This improves System stability, Reliability of the network.

- ➢ In AC transmission systems, power flow mainly depends on: phase angle, line impedance and system conditions. So, controlling AC power flow is difficult.

- ➢ HVDC uses electronic converters such as: rectifiers and inverters. These converters control: the magnitude of DC voltage and DC current. Since power in DC is: P=V*I, by controlling **V** (voltage) or **I** (current), the transmitted power can be adjusted easily.
- ❖ HVDC can connect systems operating at different frequencies (50 Hz or 60 Hz). This helps in power exchange between incompatible grids.

2. Types of HVDC Links:

For connecting two networks or systems, various types of HVDC links are used. HVDC links are classified into three types. These links are explained below:

a) Monopolar link: It has a single conductor of negative polarity and uses earth or sea for the return path of current. Sometimes the metallic return is also used. In the Monopolar link, two converters are placed at the end of each pole. Earthling of poles is done by earth electrodes placed about 15 to 55 km away from the respective terminal stations. But this link has several disadvantages because it uses earth as a return path. The monopolar link is not much in use nowadays.

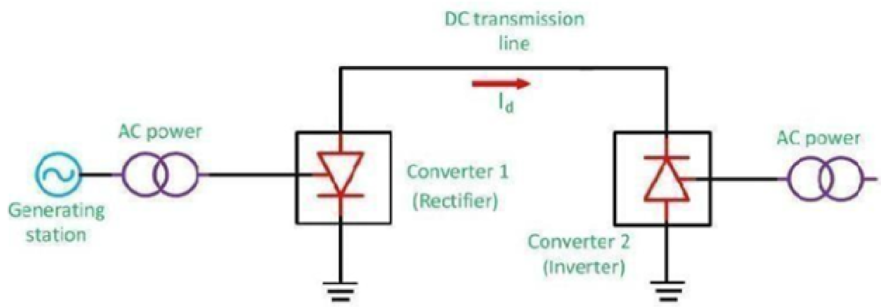


Fig 1: Monopolar DC link

b) Bipolar link: The Bipolar link has two conductors, one is positive, and the other one is negative to the earth. The link has a converter station at each end. The midpoints of the converter stations are earthed through electrodes. The voltage of the earthed electrodes is just half the voltage of the conductor used for transmission of the HVDC. The most significant advantage of the bipolar link is that if any of their links stop operating, the link is converted into Monopolar mode because of the ground return system. The half of the system continues to supply the power. Such types of links are commonly used in the HVDC systems.

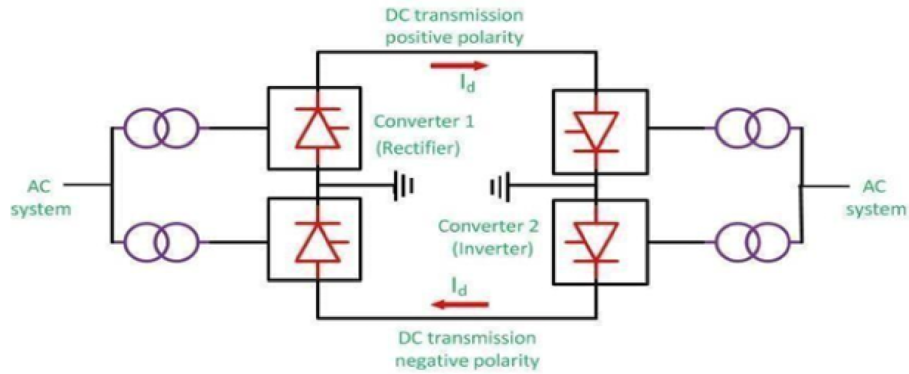


Fig 2: Bipolar DC link

c) Homopolar link: It has two conductors of the same polarity, usually negative polarity, and always operates with earth or metallic return. In the homopolar link, poles are operated in parallel, which reduces the insulation cost. The homopolar system is not used presently.

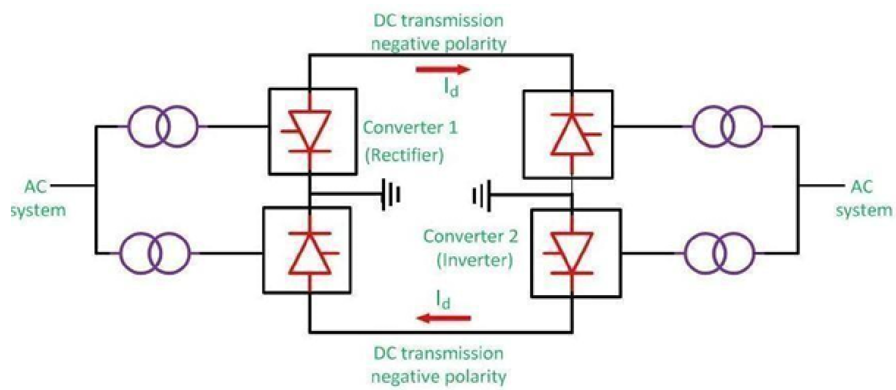


Fig 3 : Homopolar DC link

3. Apparatus required for HVDC Systems/ Terminal equipment of HVDC transmission systems:

The HVDC system has the following main components.

- ➢ Converter Stations/ unit
- ➢ Converter valves
- ➢ Converter Transformers
- ➢ Filters
  - ○ AC filter
  - ○ DC filter
  - ○ High-frequency filter
- ➢ Reactive Power compensation equipment

➢ Smoothing Reactor

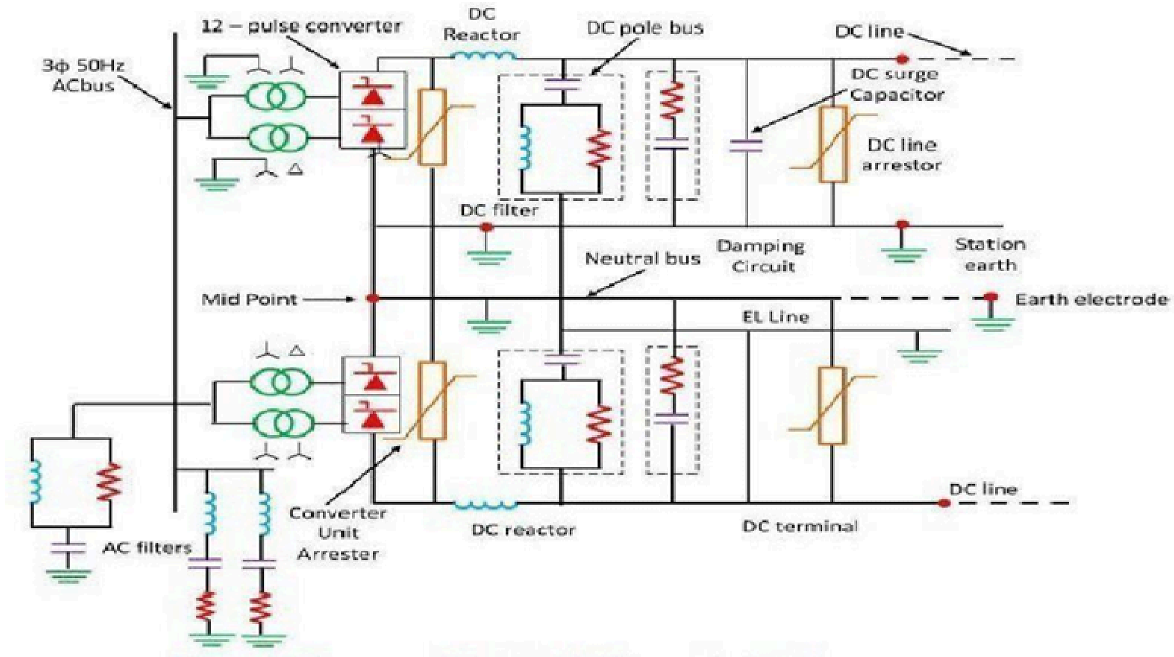


Fig : schematic diagram of typical HVDC converter station

3.1. Converter stations/unit : The conversion from AC to DC and vice versa is done in HVDC converter stations by using three-phase bridge converters. This bridge circuit is also called the Graetz circuit. In HVDC transmission a 12-pulse bridge converter is used. The converter is obtained by connecting two, 6-pulse bridges in series.

Converter Valves: Bridge converters consisting of power electronic devices like: Thyristors, IGBTs, these are also known as converter valves. The number of thyristor valves depends on the required voltage across the valve. The valves are installed in valve halls, and they are cooled by air, oil and water cooling systems.

Functions

- Switching and control of current
- Power conversion
- Regulation of DC output voltage

3.2.Transformer: There are two sets of three phase converter transformers. one side winding is connected to the AC bus bar, and the other side winding is connected to valve Bridge. The AC side windings of the two, three phase transformers are connected in stars with their neutrals grounded. One of the valve side transformer winding is connected in star and another in delta and designed to withstand alternating voltage stress and direct voltage stress from Valve Bridge. Phase-shifted connection(Y-△) of the Converter **transformer** helps in reducing harmonics in the system.

3.3 Filters: The AC and DC harmonics are generated in HVDC converters.

The harmonics have the following disadvantages.

- It causes interference in telephone lines.
- Due to the harmonics, the power losses in machines and capacitors are connected in the system.
- The harmonics produced resonance in an AC circuit resulting in over voltages.
- Instability of converter controls.

The harmonics are minimized by using the AC, DC and high-frequency filters. The types of filter are explained below in detail.

AC Filters: These are passive circuits used to provide how impedance, shunt paths for AC harmonic currents. Both tuned and damped filter arrangements are used.

DC Filters: These are similar to AC filters and are used for the filtering of DC harmonics.

High Frequency (RF/PLC) Filters: These are connected between the converter transformer and the station AC bus to suppress any high frequency currents. Sometimes such filters are provided on high-voltage DC bus connected between the DC filter and DC line and also on the neutral side.

3.4. Reactive power compensation equipment: Converter stations require reactive power supply that is dependent on the active power loading. But part of the reactive power requirement is provided by AC filters. In addition, shunt capacitors, synchronous condensers and static VAR systems are used depending on the speed of control desired.

3.5. Smoothing reactor: Smoothing reactor is an oil filled oil cooled reactor having a large inductance. It is connected in series with the converter before the DC filter. It can be located either on the line side or on the neutral side. Smoothing reactors serve the following purposes.

- ➢ They smooth the ripples in the direct current.
- ➢ They decrease the harmonic voltage and current in the DC lines.
- ➢ They limit the fault current in the DC line.
- ➢ Consequent commutation failures in inverters are prevented by smoothing reactors by reducing the rate of rising of the DC line in the bridge when the direct voltage of another series connected voltage collapses.
- ➢ Smoothing reactors reduce the steepness of voltage and current surges from the DC line. Thus, the stresses on the converter valves and valve surge diverters are reduced.

3. 6. Circuit Breakers: These are used to interrupt DC fault currents.

- Protect the HVDC system during faults
- Isolate faulty sections

Breaking DC current is difficult because DC has no natural current zero.

3. 7. **Surge Arresters:** These protect equipment from overvoltages caused by Lightning, Switching surges and also

- Divert surge energy safely to ground
- Protect converter valves and insulation

3. 8. **Ground Electrodes:** Used in monopolar and homopolar HVDC systems

- Provide return current path through earth
- Maintain system continuity

4. COMPARISON OF AC AND DC TRANSMISSION

The relative merits of the two modes of transmission (AC and DC) which need to be considered by a system planner are based on the following factors :

1) Economics of transmission
2) Technical performance
3) Reliability.

A major feature of power systems is the continuous expansion necessitated by increasing power demand. This implies that the establishment of a particular line must be considered as a part of an overall long term system planning.

4.1 Economics of transmission:

Fig.1 shows a typical cost comparison curve between AC and DC transmission

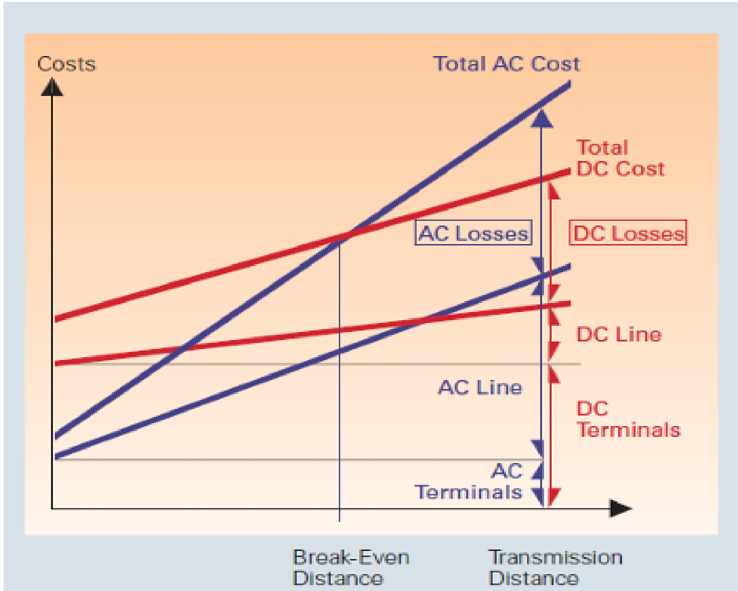


Fig : cost vs distance

- In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop.
- There is no leakage or charging current of the line under steady conditions.
- A DC line requires only 2 conductors whereas an AC line requires 3 conductors in 3-phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line.
- Break-even distance is one at which the cost of the two systems is the same. It is understood from the above figure that a DC line is economical for long distances which are greater than the break-even distance.
- The break-even distance is in the range of 500 to 800 km depending on a number of other factors, like country- specific cost elements, interest rates for project financing, loss evaluation, cost of right of way etc.

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

a) Stability :The power transfer in an AC line is dependent on the angle difference between the voltage phasors at the two line ends.

- For a given power transfer level, this angle increases with distance.

- The maximum power transfer is limited by the considerations of steady state and transient stability. The power carrying capability of an AC line is inversely proportional to transmission distance.

The power transmitted through an AC line is approximately given by:

$$P = \frac{V_1 V_2}{X} \sin \delta$$

Where:

- P = Power transferred
- V_1, V_2 = Sending and receiving end voltages
- X = Line reactance
- δ = Power angle

From the equation:

- As transmission distance increases,
- Reactance X increases,
- Therefore power transfer capability decreases.

DC transmission does not suffer from stability problems and is therefore more suitable for long-distance bulk power transmission.

b) Voltage Control: Voltage control in ac lines is complicated by line charging and voltage drops. The voltage profile in an AC line is relatively flat only for a fixed level of power transfer corresponding to its Surge Impedance Loading (SIL).

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

c) Line Compensation: Line compensation is necessary for long distance AC transmission to overcome the problems of line charging and stability limitations. The increase in power transfer and voltage control is possible through the use of shunt inductors, series capacitors, Static Var Compensators (SVCs) and, lately, the new generation Static Compensators (STATCOMs). In the case of DC lines, such compensation is not needed.

d) Problems of AC Interconnection:

- The interconnection of two power systems through ac ties requires the automatic generation controllers of both systems to be coordinated using tie line power and frequency signals.
- Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to:
  - The presence of large power oscillations which can lead to frequent tripping,
  - Increase in fault level, and
  - Transmission of disturbances from one system to the other.
- The fast controllability of power flow in DC lines eliminates all of the above problems.
- Furthermore, the asynchronous interconnection of two power systems can only be achieved with the use of DC links.

e) Ground Impedance:

- In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to the high magnitude of ground impedance which will not only affect efficient power transfer, but also result in telephonic interference.
- The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (monopolar operation).
- The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow.
- While operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents.
- Hence, single pole operation of dc transmission systems is possible for extended periods, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.

4. 3. Reliability: Reliability means the ability of the system to continuously supply power without failure.

AC Transmission
- Technology is simple and widely used.
- Protection systems are well developed.

- But long AC lines may face stability problems.

DC Transmission

- HVDC systems provide controlled and stable power transfer.
- Disturbances can be controlled quickly using converters.
- Fault isolation is faster.
- However, converter stations are complex and expensive.

Advantages of HVDC transmission:

- ➢ During bad weather conditions, the corona loss and radio interference are lower for a HVDC line compared to that in an AC line of the same voltage and same conductor size.
- ➢ Due to the absence of inductance in DC, an HVDC line offers better voltage regulation. Also, HVDC offers greater controllability compared to HVAC.
- ➢ AC power grids are standardized for 50 Hz in some countries and 60 Hz in others. It is impossible to interconnect two power grids working at different frequencies with the help of an AC interconnection. An HVDC link makes this possible.
- ➢ Interference with nearby communication lines is lesser in the case of HVDC overhead lines than that for an HVAC line.
- ➢ In longer distance HVAC transmission, the short circuit current level in the receiving system is high. An HVDC system does not contribute to the short circuit current of the interconnected AC system.
- ➢ Power flow control is easy in the HVDC link.
- ➢ High reliability.

Disadvantages of HVDC transmission:

- ➢ Converter stations needed to connect to AC power grids are very expensive. Converter substations are more complex than HVAC substations.
- ➢ Designing and operating multi-terminal HVDC systems is complex.
- ➢ Converter substations generate current and voltage harmonics, while the conversion process is accompanied by reactive power consumption.
- ➢ As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.
- ➢ During short-circuits in the AC power systems close to connected HVDC substations, power faults also occur in the HVDC transmission system for the duration of the short-circuit.
- ➢ The number of substations within a modern multi-terminal HVDC transmission system can be no larger than six to eight, and large differences in their capacities are not allowed. The larger the number of substations, the smaller may be the differences in their capacities.

- The high-frequency constituents found in direct current transmission systems can cause radio noise in communications lines that are situated near the HVDC transmission line.
- Grounding HVDC transmission involves a complex and difficult installation, as it is necessary to construct a reliable and permanent contact to the Earth for proper operation and to eliminate the possible creation of a dangerous "step voltage."

5. Applications of HVDC transmission:

- Long distance bulk power transmission: Used for transmitting large power over long distances with low losses
- Underground or underwater cables: Suitable for submarine and underground cable transmission, especially across seas, oceans, and densely populated cities where overhead lines are not possible.
- Asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired
- Control and stabilization of power flows in AC ties in an integrated power system.

6. PLANNING FOR HVDC TRANSMISSION

When planning an HVDC transmission system, the system planner mainly considers:

1. Cost
2. Technical Performance
3. Reliability

Usually, technical performance and reliability are treated as requirements, and the system with the lowest cost that satisfies these requirements is selected.

Main Applications of HVDC Planning

1. Long-Distance Bulk Power Transmission

- Used for transmitting large amounts of power over long distances.
- AC and DC systems may provide similar reliability and power carrying capability.
- Therefore, the selection mainly depends on transmission cost and technical requirements.
- DC transmission is generally preferred for very long distances because of lower losses and lower line cost.

2. Interconnection Between Two Adjacent Systems

- Used to connect two nearby AC systems or power grids.

Problems with AC Interconnection

- Synchronization problems
- Stability issues
- Higher transmission capacity requirement

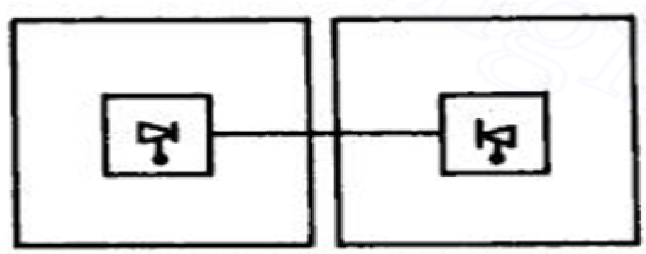
Advantages of DC Interconnection

1. Small fluctuations in voltage and frequency do not affect DC power flow.
2. DC power can be controlled quickly and accurately.
3. System stability and security are improved.

Configurations of HVDC Interconnection

1. **Two-Terminal HVDC Transmission**

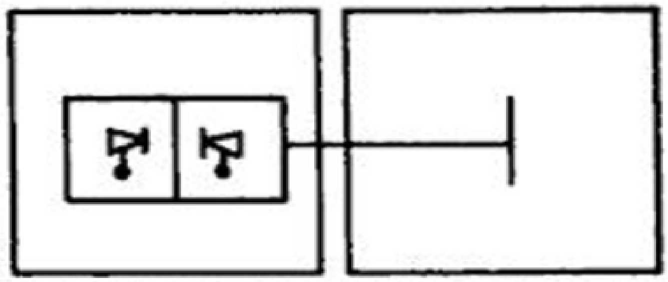
- Two converter stations are connected by:
  - DC overhead line, or
  - DC cable
- Mainly used for long-distance power transmission.



(a) TWO TERMINAL DC LINK

2. **Back-to-Back HVDC Station**

- Both converter stations are located at the same place.
- AC systems are connected through converters without a DC transmission line.
- Used for connecting AC systems operating at different frequencies.



(b) BACK TO BACK DC LINK ALONG WITH AC FEEDER

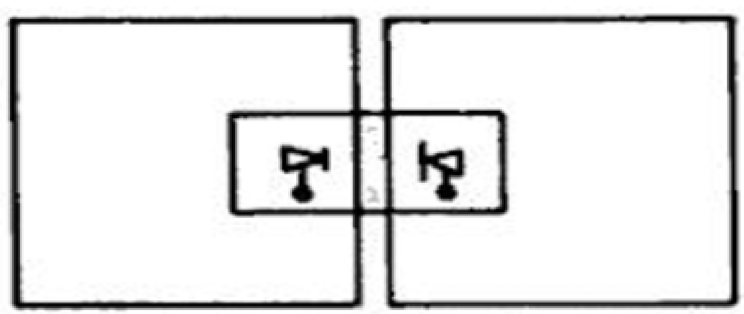
3. **Border Back-to-Back Station**

- This technology is crucial for enhancing grid stability and enabling power transfer across regional or national borders where AC synchronization is impractical or undesirable.
- Most economical if the Short Circuit Ratio (SCR) is acceptable.

The strength of AC systems connected to the terminals of a DC link is measured in terms of short circuit ratio (SCR) which is defined as

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

If SCR is less than 3, the AC system is said to be weak. The conventional constant extinction angle control may not be satisfactory with weak AC system. The recovery of inverters following the clearing of fault in the connected AC system can also be problematic.



(c) BACK TO BACK DC LINK AT BORDER

Important System Studies in HVDC Planning

Detailed studies are required for:

1. Reactive power (VAR) requirements of converter stations
2. Dynamic overvoltages
3. Harmonic generation and filter design
4. Damping of low-frequency oscillations
5. Communication interference caused by converter switching

Role of Converter Control

- Converter control plays a major role in HVDC systems.
- Proper control improves Stability, Reliability, Overall system performance

Tools Used for HVDC Planning

1. Digital simulation
2. HVDC simulators
3. Stability studies
4. Power flow studies

7. Modern trends in D.C. Transmission

The recent developments are expected to improve reliability and reduce the cost of HVDC valves. These are mainly :

- Development in high power semiconductor devices - these include direct light triggered thyristors (LTT) and metal- oxide semiconductor controlled thyristors(MCT)
- Better cooling techniques such as forced vaporization (two phase flow) as a means of reducing thermal resistance between the heat sink and the ambient.
- Suspension of quadrivalve assembly from ceiling to withstand seismic forces.

7. 1. Development in high-power semiconductor devices (LTTs and MCTs) : Direct light-triggered thyristors (LTT) use optical pulses to trigger conduction, eliminating isolated electrical gate circuits. Metal-oxide semiconductor controlled thyristors (MCT) combine MOS gate control with thyristor current capability, allowing easier turn-off or improved gating.

- The light sources used are either gallium arsenide light emitting diodes (LED) or laser diodes.
- Optical triggering (LTT) removes vulnerable gate-isolation hardware
- reduces EMI sensitivity and failure modes associated with long electrical gate wiring.
- MCTs provide more precise gate control and faster, more repeatable switching, reducing stress on devices.
- Both device types simplify valve gate equipment and reduce parts count and cost.

7.2 Improved cooling techniques — forced vaporization (two-phase flow): Two-phase cooling uses a coolant that changes phase (liquid → vapor) as it absorbs heat from semiconductor modules. Forced circulation controls the flow so boiling occurs in designed locations, then vapor is condensed and recirculated.

- Phase-change cooling yields much higher heat removal per unit area and lower thermal resistance between the semiconductor junction and ambient. That keeps device junction temperatures lower and more uniform, reducing thermal cycling, slowing ageing, and lowering failure rates.
- Higher cooling efficiency enables more compact valve design (smaller heat sinks and enclosures), allows higher power density (fewer modules for same power), and reduces forced-air or large liquid-cooled infrastructure needs. Lower maintenance and longer MTBF (mean time between failures) cut operating costs.

7.3. Suspension of quadrivalve assemblies from the ceiling (seismic-resilient mounting): Instead of rigid floor mounting, quadrivalve (four-valve) modules are mechanically suspended from overhead supports or frames designed to decouple seismic motions and control inertial loads.

- Suspended mounting reduces stress transmitted to valve internals and bus connections during earthquakes, decreasing the risk of mechanical damage, electrical contact failures, and misalignment that would cause outages or require repairs. Protecting mechanical and electrical integrity directly improves availability.
- Lower risk of seismic damage means fewer post-event repairs and replacement parts, reduced downtime, and potentially lower insurance and retrofit costs. It also can reduce civil works (heavy anchor foundations) in some designs.

8. Analysis of HVDC Converters

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

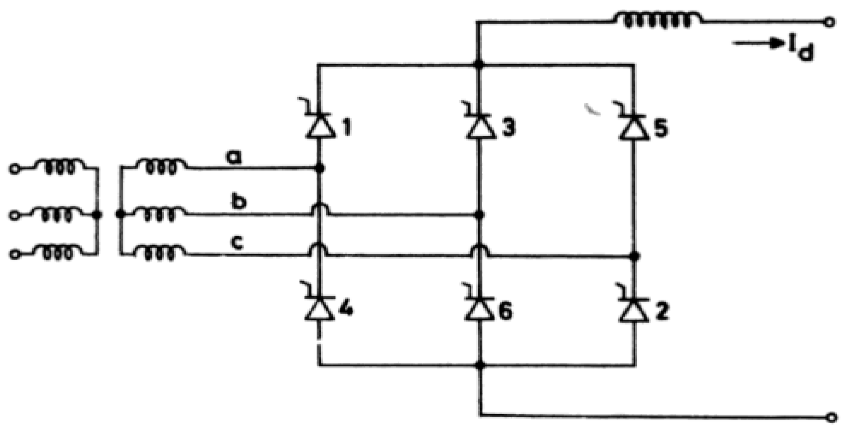


Fig: Graetz circuit

PULSE NUMBER: The pulse number of a converter is defined as the number of pulsations (cycles of ripple) of direct voltage per cycle of alternating voltage. The conversion from AC to DC involves switching sequentially different sinusoidal voltages onto the DC circuit. One possible configuration for a 'p' pulse converter is shown in Fig.

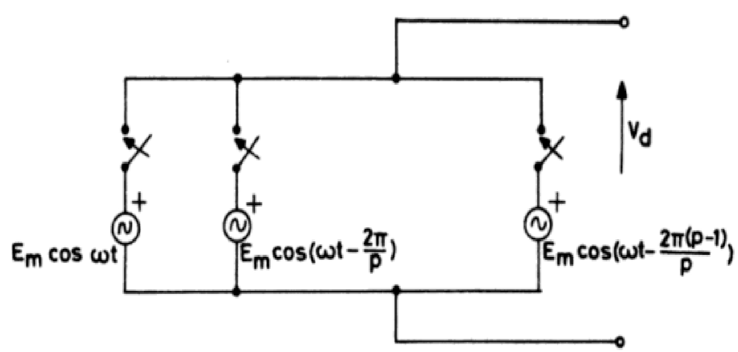


Fig : A "P" pulse converter

A valve can be treated as a (controllable) switch which can be turned on at any instant, provided the voltage across it is positive. A diode is an uncontrolled switch which will turn on immediately after the voltage becomes positive whereas the thyristor switching can be delayed by an angle a (alpha). The voltage sources are actually obtained from the transformer secondary windings. The opening of the switch (both for diode and thyristor) occurs at the current zero (neglecting the turn-off time).

The output voltage Va of the converter consists of a DC component and a ripple whose frequency is determined by the pulse number.

8.1 CHOICE OF CONVERTER CONFIGURATION

The configuration for a given pulse number is selected in such a way that both the valve and transformer (feeding the converter) utilization are maximized. The configuration shown in Fig. is not the best.

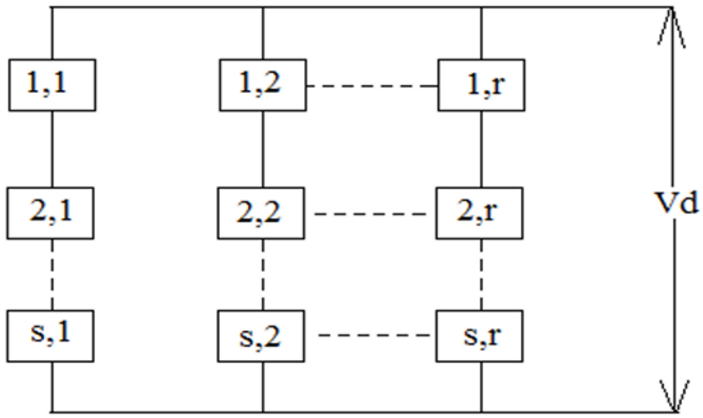


Fig :Converter made up of series and parallel connection of commutation groups

In general, a converter configuration can be defined by the basic commutation group and the number of such groups connected in series and parallel (sce Fig). If there are 'q' valves in a basic commutation group and r of these are connected in parallel and s of them connected in series, then

P =qrs ——------------ (1)

(Note: A commutation group is defined as the group of valves in which only one (neglecting overlap) conducts at a time).

8.1.1 Valve Rating: The valve voltage rating is specified in terms of peak inverse voltage (PIV) it has to withstand. The ratio of PIV to the average dc voltage is an index of the valve utilization.

The average maximum dc voltage across the converter is given by

$$V_{do} = s \frac{q}{2\pi} \int_{-\pi/q}^{\pi/q} E_m \cos\omega t \quad d\omega t$$

$$= \frac{sq}{\pi} E_m \quad \sin\frac{\pi}{q}$$

The peak inverse voltage (PIV) across a valve can be obtained as follows :

If 'q' is even, then the maximum inverse voltage occurs when the valve with a phase displacement of n radian (180°) is conducting and this is given by

$$PIV = 2\,E_m$$

If 'q' is odd, maximum inverse voltage occurs when the valve with a phase shift of

$\pi \pm \frac{\pi}{q}$ is conducting. In this case,

$$PIV = 2E_m \cos\frac{\pi}{2q}$$

The valve utilization factor is given by

$$\frac{PIV}{V_{do}} = \frac{2\pi}{sq\sin\frac{\pi}{q}} \quad \text{for } q \text{ even}$$

$$= \frac{\pi}{sq\sin\frac{\pi}{2q}} \quad \text{for } q \text{ odd}$$

The table shows the valve utilization factor for different six pulse converter configurations. The best valve utilization is obtained for configurations 1 and 3.

Sl.No.	q	r	s	$\frac{PIV}{V_{do}}$
1	2	1	3	1.047
2	2	3	1	3.142
3	3	1	2	1.047
4	3	2	1	2.094
5	6	1	1	2.094

Table: Valve Utilization Factor

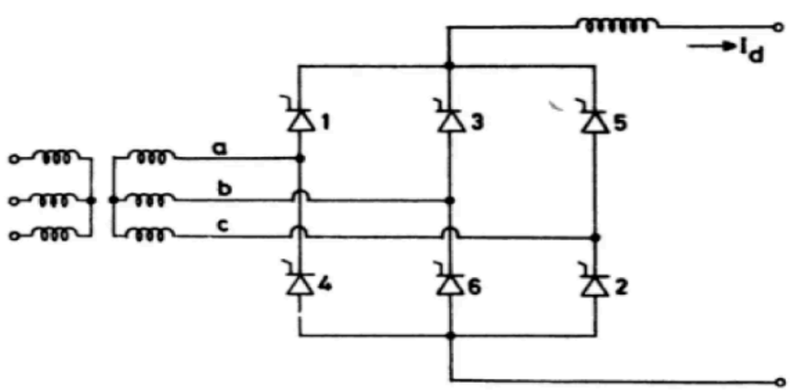
Analysis of Graetz Circuit

It is a 6-pulse converter consisting of two winding transformer where the transformer utilization factor is increased when compared to three winding transformer.

The series conduction of converter groups has been preferred because of controlling and protection as well as the requirements for high voltage ratings. So, a 12 pulse converter is obtained by series connection of two bridges.

The 30° phase displacement between two sets of source voltages is achieved by transformer connections Y-Y for one bridge and Y-Δ for the other bridge.

The use of a 12 pulse converter is preferable over the 6 pulse converter because of the reduced filtering requirements.



Main Functions

- AC to DC conversion (Rectifier mode)
- DC to AC conversion (Inverter mode)
- Voltage and power control in HVDC systems
- Bidirectional power transfer

Analysis of Graetz Circuit without overlap:

At any instant, two valves are conducting in the bridge, one from the upper commutation group and the second from the lower commutation group. The firing of the next valve in a particular group results in the turning OFF of the valve that is already conducting. The valves are numbered in the sequence in which they are fired. Each valve conducts for 120^o and the interval between consecutive firing pulse is 60^o in steady state.

The following assumptions are made to simplify the analysis

a. The DC current is constant.
b. The valves are modeled as ideal switches with zero impedance when ON and with infinite impedance when OFF.
c. The AC voltages at the converter bus are sinusoidal and remain constant.

One period of the AC supply voltage can be divided into 6 intervals – each corresponding to the conduction of a pair of valves. The DC voltage waveform repeats for each interval.

Assuming the firing of valve 3 is delayed by an angle α , the instantaneous DC voltage V_d during the interval is given by

$V_d = e_b - e_c = e_{bc}$ for $\alpha \leq \omega t \leq \alpha + 60^o$

Let $e_{ba} = \sqrt{2} E_{LL} \sin \omega t$

then $e_{bc} = \sqrt{2} E_{LL} \sin(\omega t + 60^o)$

Average DC Voltage = $V_d = \frac{3}{\pi} \int_{\alpha}^{\alpha+60^o} \sqrt{2} E_{LL} \sin(\omega t + 60^o)\, d\omega t$

$$= \frac{3}{\pi} \sqrt{2} E_{LL} [\cos(\alpha + 60^o - \cos(\alpha + 120^o)]$$

$$V_d = \frac{3\sqrt{2}}{\pi} E_{LL} \cos\alpha = 1.35 E_{LL} \cos\alpha$$

$$V_d = V_{do} \cos\alpha \quad \text{-------} \quad (1)$$

The above equation indicates that for different values of α , V_d is variable.

The range of α is 180° and correspondingly V_d can vary from V_{do} to $-V_{do}$. Thus, the same converter can act as a rectifier or inverter depending upon whether the DC voltage is positive or negative.

DC Voltage Waveform:

The DC voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can analyzed in Fourier series and contains harmonics of the order

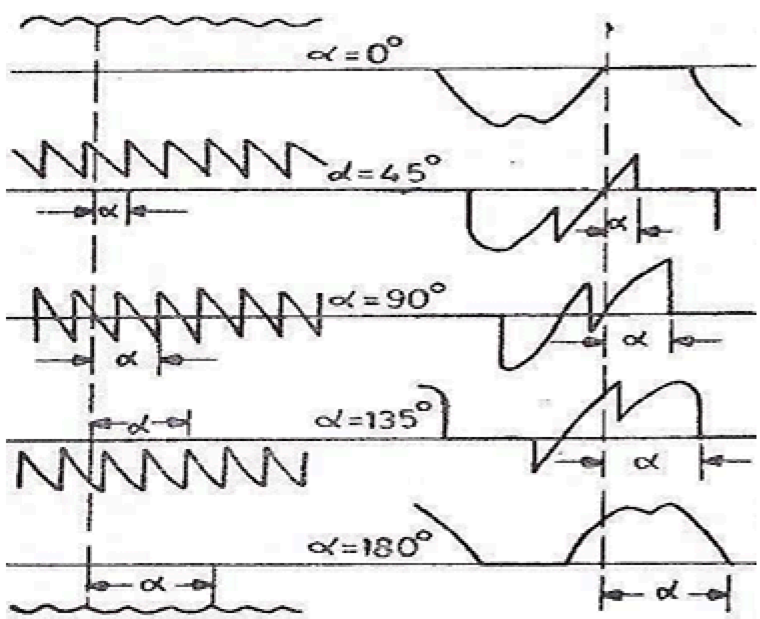
h = np

where, p is the pulse number and n is an integer.

The rms value of the h^{th} order harmonic in DC voltage is given by

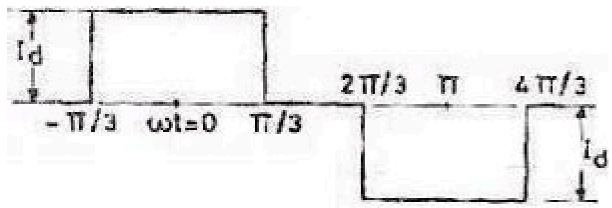
$$V_h = V_{do} \frac{\sqrt{2}}{h^2 - 1} [1 + (h^2 + 1)\sin^2\alpha]^{1/2}$$

The waveforms of the direct voltage and calve voltage are shown for different values of α.



AC Current Waveform:

It is assumed that direct current has no ripple (or harmonics). The AC currents flowing through the valve (secondary) and primary windings of the converter transformer contain harmonics.



The waveform of the current in a valve winding is shown. The rms value of the fundamental component of current is given by

$$I_1 = \frac{1}{\sqrt{2}}\frac{2}{\pi}\int_{-\pi/3}^{\pi/3} I_d \cos\theta . d\theta = \frac{\sqrt{6}}{\pi} I_d \quad \text{---- (2)}$$

where as the rms value of the current is

$$I = \sqrt{\frac{2}{3}}.I_d$$

The harmonics contained in the current waveform are of the order given by

$h = np \pm 1$

Where n is an integer, p is the pulse number. For a six pulse converter, the order of AC harmonics is 5, 7, 11, 13 and higher order. These are filtered out by using tuned filters for each one of the first four harmonics and a high pass filter for the remaining.

The rms value of h^{th} harmonic is given by $I_h = \frac{I_1}{h}$

Power Factor:

The AC power supplied to the converter is given by

$P_{AC} = \sqrt{3} E_{LL} I_1 \cos\phi$

Where $\cos\phi$ is the power factor.

The DC power must match the AC power ignoring the losses in the converter. Thus,

$P_{AC} = P_{DC} = V_{do} I_d = \sqrt{3} E_{LL} I_1 \cos\phi$

Substituting for V_{do} and I_1 from equations (1) and (2) in the above equation, we get

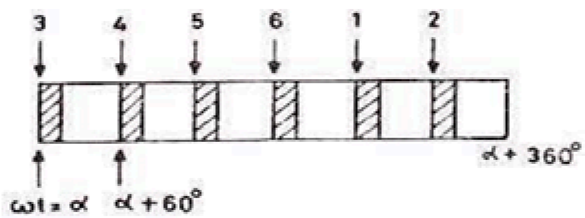
$\cos\phi = \cos\alpha$

The reactive power requirements are increased as α is increased from zero (or reduced from 180^o).

Analysis of Graetz Circuit with overlap

Due to the leakage inductance of the converter transformers and the impedance in the supply network, the current in a valve cannot change suddenly and this commutation from one valve to the next cannot be instantaneous. This is called overlap and its duration is measured by the overlap (commutation) angle 'μ'.

Each interval of the period of supply can be divided into two subintervals as shown in the below timing diagram. In the first subinterval, three valves are conducting and in the second subinterval, two valves are conducting which is based on the assumption that the overlap angle is less than 60^o.



There are three modes of the converter which are

i) Mode 1 – Two and three valve conduction ($\mu<60^o$)
ii) Mode 2 – Three valve conduction ($\mu=60^o$)
iii) Mode 3 – Three and four valve conduction ($\mu>60^o$)

i)Analysis of Two and Three Valve Conduction Mode:

The equivalent circuit for three valve conduction is shown below.

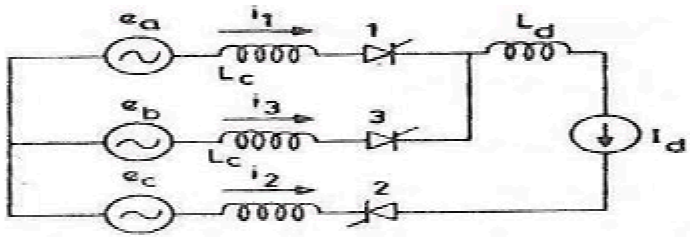
For this circuit,

$$e_b - e_a = L_c\left(\frac{di_3}{dt} - \frac{di_1}{dt}\right)$$

The LHS in the above equation is called the commutating emf whose value is given by

$$e_b - e_a = \sqrt{2}E_{LL}\sin\omega t$$

Which is the voltage across valve 3 just before it starts conducting.



Since, $i_1 = I_d - i_3$

We get,

$$\sqrt{2}E_{LL}\sin\omega t = 2L_c\frac{di_3}{dt}$$

Solving the above equation, we get

$$i_3(t) = I_s(\cos\alpha - \cos\omega t), \alpha \le \omega t \le \alpha + \mu$$

Where,

$$I_s = \frac{\sqrt{2}E_{LL}}{2\omega L_c}$$

At $\omega t=\alpha+\mu$, $i_s = I_d$. This gives $I_d = I_s[\cos\alpha - \cos(\alpha+\mu)]$

The average direct voltage can be obtained as

$$V_d = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\frac{-3}{2}e_c\,d(\omega t) + \int_{\alpha+\mu}^{\alpha+60}(e_b - e_c)\,d(\omega t)\right]$$

$$= V_{do}\cos\alpha - \frac{3}{2\pi}\sqrt{2}E_{LL}[\cos\alpha - \cos(\alpha+\mu)]$$

Since, $\frac{3\sqrt{2}}{\pi}E_{LL} = V_{do}$, we get

$$V_d = \frac{V_{do}}{2}[\cos\alpha + \cos(\alpha+\mu)]$$

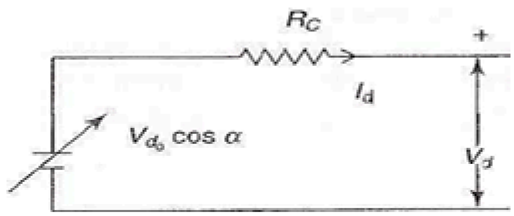
The value of $[\cos\alpha - \cos(\alpha+\mu)]$ can be substituted to get,

$$V_d = V_{do}\left(\cos\alpha - \frac{I_d}{2I_s}\right) = V_{do}\cos\alpha - R_c I_d$$

Where,

$$R_c = \frac{3}{\pi}\omega L_c = \frac{3}{\pi}X_c$$

R_c is called equivalent commutation resistance and the equivalent circuit for a bridge converter is shown below.



Inverter Equations:

For an inverter, advance angle β is given by

$\beta = \pi - \alpha$

and use opposite polarity for the DC voltage with voltage rise opposite to the direction of current. Thus,

$$V_{di} = \frac{-V_{doi}}{2}[\cos\alpha + \cos(\alpha + \mu)]$$

$$= \frac{-V_{doi}}{2}[\cos(\pi - \beta) + \cos(\pi - \gamma)]$$

$$V_{di} = \frac{V_{doi}}{2}[\cos\beta + \cos\gamma]$$

Where, the extinction angle γ is defined as

$\gamma = \beta - \mu = \pi - \alpha - \mu$

Similarly, it can be shown that

$$V_{di} = V_{doi}\cos\beta + R_{ci} I_d$$

$$= V_{doi}\cos\gamma - R_{ci} I_d$$

The subscript "i" refers to the inverter.

ii) Analysis of Three and Four Valve Conduction Mode:

The equivalent circuit for three and four valve conduction is shown below.

For, $\alpha \le \omega t \le \alpha + \mu - 60^o$

$i_1 = I_s \sin(\omega t + 60^o) + A$

$i_6 = I_d - i_2 = I_d - I_s \sin\omega t + C$

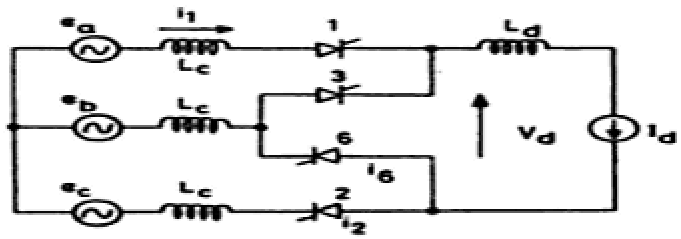
Where, $I_s = \frac{E_m}{\omega L_c} = \frac{2}{\sqrt{3}} I_s$

The constant A can be determined from the initial condition

$i_1 (\omega t = \alpha) = I_d = I_s \sin(\alpha + 60^o) + A$

The constant C can be determined from the final condition

$i_6 (\omega t = \alpha + \mu - 60^o) = 0 = I_d - I_s \sin(\alpha + \mu - 60^o) + C = 0$



For, $\alpha+\mu-60^o \le \omega t \le \alpha+60^0$

$i_1 = I_s \cos\omega t + B$

The constant B can be determined from the continuity equation

$i_1 (\omega t=\alpha+\mu=60^o) = I_s \sin(\alpha+\mu) + A = I_s \cos(\alpha+\mu-60^o) + B$

Finally,

$$I_d = \frac{I_s}{2}[\cos(\alpha - 30^o) - \cos(\alpha + \mu + 30^o)]$$

The expression for average direct voltage is given by

$$V_d = \frac{3}{\pi}\int_{\alpha+\mu-60^o}^{\alpha+60^o} \frac{-3}{2} e_c d(\omega t)$$

Since $e_c = E_m \cos\omega t$

$$V_d = \frac{3}{\pi}\frac{3}{2}E_m[\sin(\alpha+60^o) - \sin(\alpha+\mu-60^o)]$$

$$V_d = \frac{\sqrt{3}}{2}V_{do}[\cos(\alpha-30^o) + \cos(\alpha+\mu+30^o)]$$

Finally

$$V_d = V_{do}[\sqrt{3}\cos(\alpha-30^o) - \frac{3}{2}\frac{I_d}{I_s}] = \sqrt{3}.V_{do}\cos(\alpha-30^o) - 3R_c I_d$$

Converter Bridge Characteristics

A) Rectifier: The rectifier has three modes of operation.

1) First mode: Two and three valve conduction mode ($\mu < 60^o$)

2) Second mode: Three valve conduction mode only for $\alpha < 30^o$ ($\mu = 60^o$)

3) Third mode: Three and four valve conduction mode $\alpha \ge 30^o$ ($60^o \le \mu \le 120^o$)

As the DC current continues to increase, the converter operation changes over from mode 1 to 2 and finally to mode 3.

The DC voltage continues to decrease until it reaches zero.

For $\alpha \geq 30^o$, mode 2 is bypassed.

For Modes 1 and 3, we have

$$\frac{V_d}{V_{do}} = \cos\alpha - \frac{I_d}{2I_s}$$

$$\frac{V_d}{V_{do}} = \sqrt{3}\cos(\alpha - 30^o) - \frac{3I_d}{2I_s}$$

The voltage and current characteristics are linear with different slopes in these cases.

For mode 2, $\mu = 60^o$, μ is constant, so the characteristics are elliptical and is given by

$$\left(\frac{V_d^{|}}{\cos\frac{\mu}{2}}\right)^2 + \left(\frac{I_d^{|}}{\sin\frac{\mu}{2}}\right)^2 = 1$$

where, $V_d^{|} = \frac{V_d}{V_{do}}$ and $I_d^{|} = \frac{I_d}{2I_s}$

B) Inverter:

The inverter characteristics are similar to the rectifier characteristics. However, the operation as an inverter requires a minimum commutation margin angle during which the voltage across the valve is negative. Hence the operating region of an inverter is different from that for a rectifier.

So, the margin angle (ξ) has different relationship to γ depending on the range of operation which are

First Range: $\beta < 60^o$ and $\xi = \gamma$

Second Range: $60^o < \beta < 90^o$ and $\xi = 60^o - \mu = \gamma - (\beta - 60^o)$

Third Range: $\beta > 90^o$ and $\xi = \gamma - 30^o$

In the inverter operation, it is necessary to maintain a certain minimum margin angle ξ_o which results in 3 sub-modes of the 1st mode which are

Mode 1

1(a) $\beta < 60^o$ for values of $\mu < (60^o - \xi_o)$

The characteristics are linear defined by

$$V_d^{|} = \cos\gamma_o - I_d^{|}$$

1(b) $60^o < \beta < 90^o$ for

$$\mu = 60^o - \xi_o = 60^o - \gamma_o = \text{constant}$$

The characteristics are elliptical.

1(c) $90^o < \beta < 90^o + \xi_o$ for values of μ in the range

$$60^o - \xi_o \le \mu \le 60^o$$

The characteristics in this case are line and defined by

$$V_d^| = \cos(\gamma_o + 30^o) - I_d^|$$

Mode 2

For $\mu > 60^o$ corresponding to $\beta > 90^o + \gamma_o$

The characteristics again are linear but with a different slope and is defined by

$$V_d^| = \sqrt{3}\cos\gamma_o - 3I_d^|$$

In the normal operation of the converter $I_d^|$ is in the range of 0.08 to 0.1 .

12-Pulse Converter

A **12-pulse converter** is constructed by connecting two 6-pulse Graetz bridges in **series or parallel** on the DC side, while feeding them from a specialized transformer arrangement on the AC side.

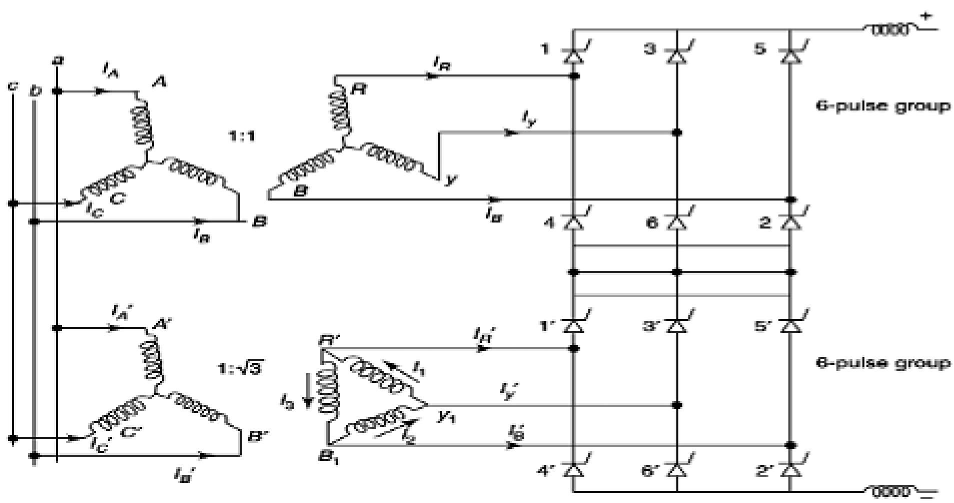


Fig: 12 Pulse converter

As long as the AC voltages at the converter bus remain sinusoidal (with effective filtering), the operation of one bridge is unaffected by the operation of the other bridge connected in series. The region of rectifier operation can be divided into five modes as

Mode 1: 4 and 5 valve conduction

$$0 < \mu < 30^o$$

Mode 2: 5 and 6 valve conduction

$$30^o < \mu < 60^o$$

Mode 3: 6 valve conduction

$$0 < \alpha < 30^o, \mu = 60^o$$

Mode 4: 6 and 7 valve conduction

$$60^o < \mu < 90^o$$

Mode 5: 7 and 8 valve conduction

$$90^o < \mu < 120^o$$

The second mode is a continuation of the first and similarly fifth is a continuation of the fourth.

The equivalent circuit of the twelve pulse converter is the series combination of the equivalent circuits for the two bridges. This is because the two bridges are connected in series on the DC side and in parallel on the AC side. The current waveforms in the primary winding of the star/star and star/delta connected transformers and the line current injected into the converter bus are shown.