HVDC AND FACTS

EET466

SYLLABUS

- **MODULE 1**
- Introduction to HVDC System
- Comparison of AC and DC Transmission - Types of HVDC system - Current Source

Converters - Analysis without and with overlap period. Voltage Source Converters (VSC) -

- VSC with AC current control and VSC with AC voltage control

- **MODULE 2**
- HVDC Controls - Functions of HVDC Controls - Equivalent circuit for a two terminal DC
- Link - Control Basics for a two terminal DC Link - Current Margin Control Method - Current
- Control at the Rectifier - Inverter Extinction Angle Control - Hierarchy of Controls

MODULE 3

- Power flow in Power Systems – Voltage regulation and reactive power flow control in Power
- Systems - Power flow control -Constraints of maximum transmission line loading - Needs
- and emergence of FACTS - Types of FACTS controllers-Advantages and disadvantages
- Transmission line compensation- Uncompensated line -shunt compensation - Series
- compensation –Phase angle control

MODULE 4

- Static shunt Compensator - Objectives of shunt compensations - Variable impedance type
- VAR Generators -TCR, TSR, TSC, FC-TCR (Principle of operation and schematic) and -
- STATCOM (Principle of operation and schematic).
- Static Series compensator - Objectives of series compensations-Variable impedance type
- series compensators - GCSC. TCSC, TSSC (Principle of operation and schematic)
- Switching converter type Series Compensators-(SSSC) (Principle of operation and
- schematic)

MODULE 5

- Unified Power Flow Controller: Circuit Arrangement, Operation of UPFC- Basic principle of
- P and Q control- independent real and reactive power flow control- Applications
- Introduction to interline power flow controller (IPFC) (Principle of operation and schematic)
- Thyristor controlled Voltage and Phase angle Regulators (Principle of operation and
- schematic)
- Note: Simulation assignments may be given in MATLAB, SCILAB, PSAT, ETAP, PSCAD, etc.

REFERENCES

- Text Books
- 1. Vijay K Sood, “HVDC and FACTS Controllers”, Springer, 2004
- 2. **N.G. Hingorani and L.Gyugyi, “Understanding FACTS”, IEEE Press 2000**
- References:
- 1**. K.R.Padiyar, “High Voltage DC Transmission”, Wiley 1993**
- 2. Y.H. Song and A.T.Jones, “Flexible AC Transmission systems (FACTS)”, IEEE
- Press 1999.
- **3. K.R.Padiyar, “FACTS Controllers in Power Transmission and distribution”, New age**
- **international Publishers 2007.**
- 4. T.J.E. Miller, “Reactive Power control in Power systems”, John Wiley 1982.
- 5**. C.L.Wadhwa, “Electric Power Systems”, New Academic Science Limited, 1992**

INTRODUCTION

- DC Transmission now became practical when long distances were to be covered or where cables were required

- 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.

- Highest functional DC voltage for DC transmission is +/- 600kV. D.C

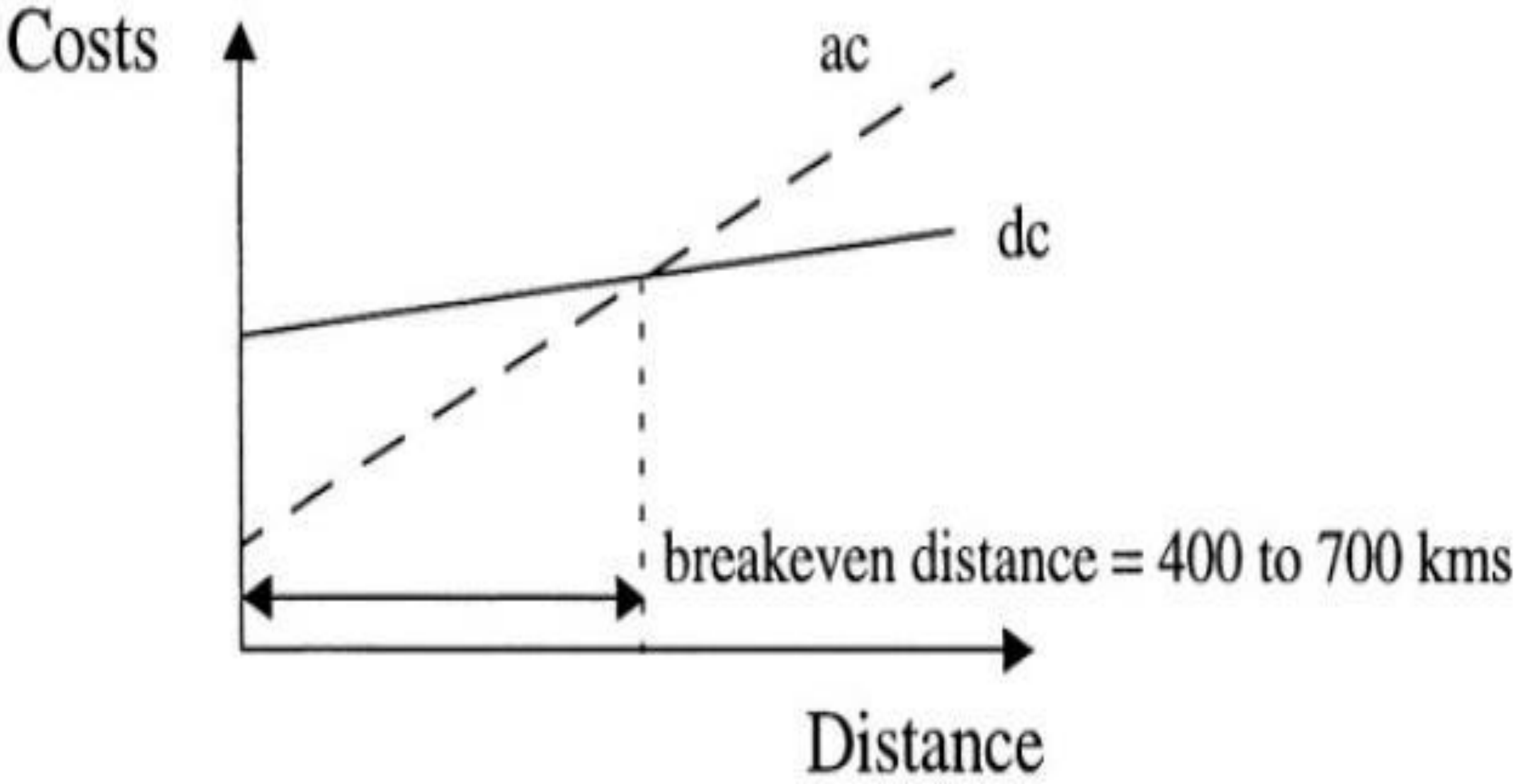
Comparison of AC and DC Transmission

1) Economics of transmission

2) Technical Performance

3) Reliability

Economics of Power Transmission



AC TRANSMISSION	DC TRANSMISSION
Many conductors are used for transmission line	Two conductors are used for transmission
Corona loss is more	No corona loss
Line inductance, capacitance, phase displacement and surge problems occur which cause voltage drop	No inductance, capacitance, phase displacement and surge problems which cause no voltage problem
In transmission line loss is high	In transmission line loss is less
Skin effect are present	Skin effect are not present
This transmission line have stability problem	Less stability problem
Maintenance of AC sub station is easy and cheaper	Maintenance of DC transmission in not easy and cheaper

Technical Performance:

- ❑Due to its fast controllability, a DC transmission has full control over transmitted power,

- ❑An ability to enhance transient and small signal stability in associated AC networks

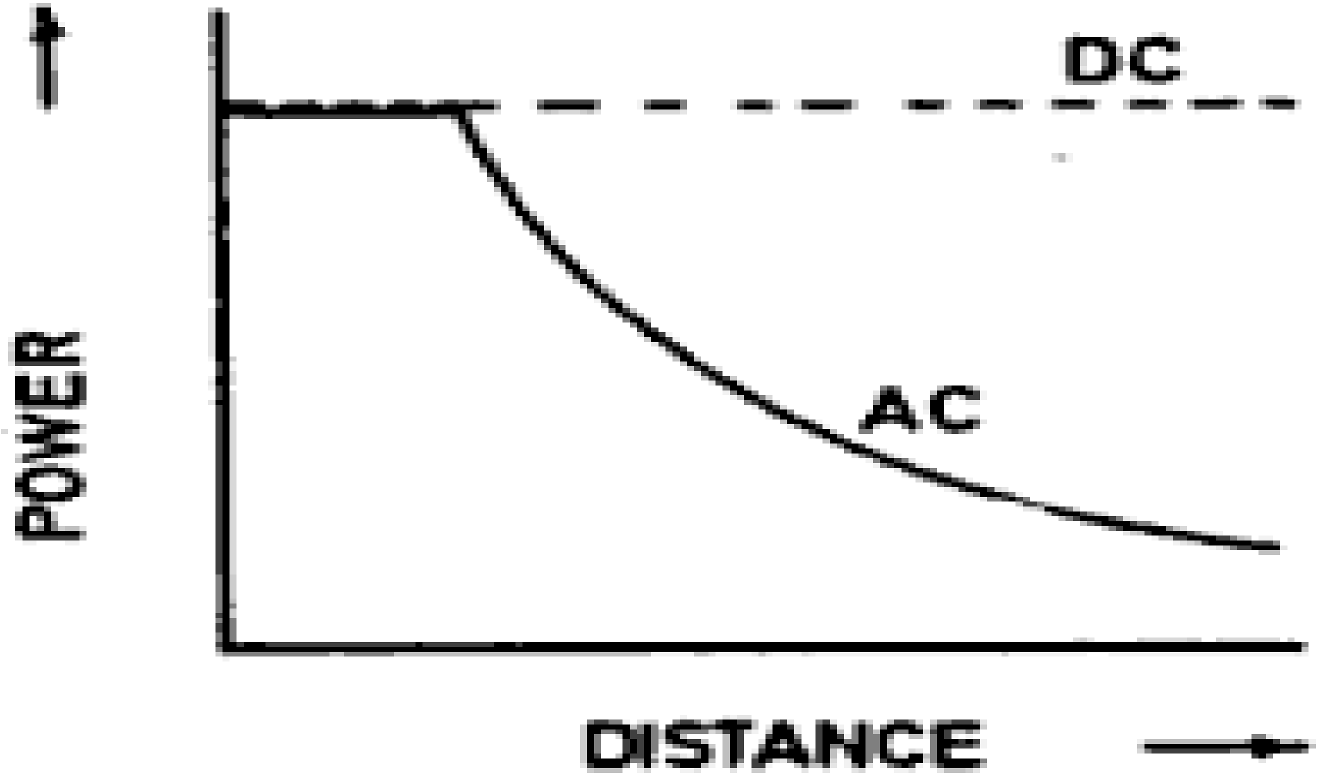
- ❑Fast control to limit fault current in DC lines.

Stability Limits:

- ❖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 whereas the power carrying ability of DC lines is unaffected by the distance of transmission.



Power transfer capability vs. distance

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).

- Although DC converter stations require reactive power related to the power transmitted, the DC line itself does not require any reactive power

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.

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:

1. The presence of large power oscillations which can lead to frequent tripping,
2. Increase in fault level, and
3. 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.

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

Disadvantages of DC Transmission

1. High cost of conversion equipment.
2. Inability to use transformers to alter voltage levels.
3. Requirement of reactive power and
4. Complexity of controls.

The disadvantages can be overcomes by

- Increase in the ratings of a thyristor cell that makes up a valve.

1. Modular construction of thyristor valves.
2. Twelve-pulse (and higher) operation of converters.
3. Use of forced commutation.
4. Application of digital electronics and fiber optics in the control of converters.

RELIABILITY

- The reliability of DC transmission systems is good and comparable to that of AC systems.

- The reliability of DC links has also been very good.

- There are two measures of overall system reliability-energy availability and transient reliability.

- ***Energy availability:***

Energy availability= 100(1- equivalent outage time/ total time)%

Equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage

- **Transient reliability**

- This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems

- Transient reliability = 100 X No. of times HVDC systems performed as designed /number of recordable AC faults

- Recordable AC system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault.

Application of DC Transmission

- Underground or underwater cables

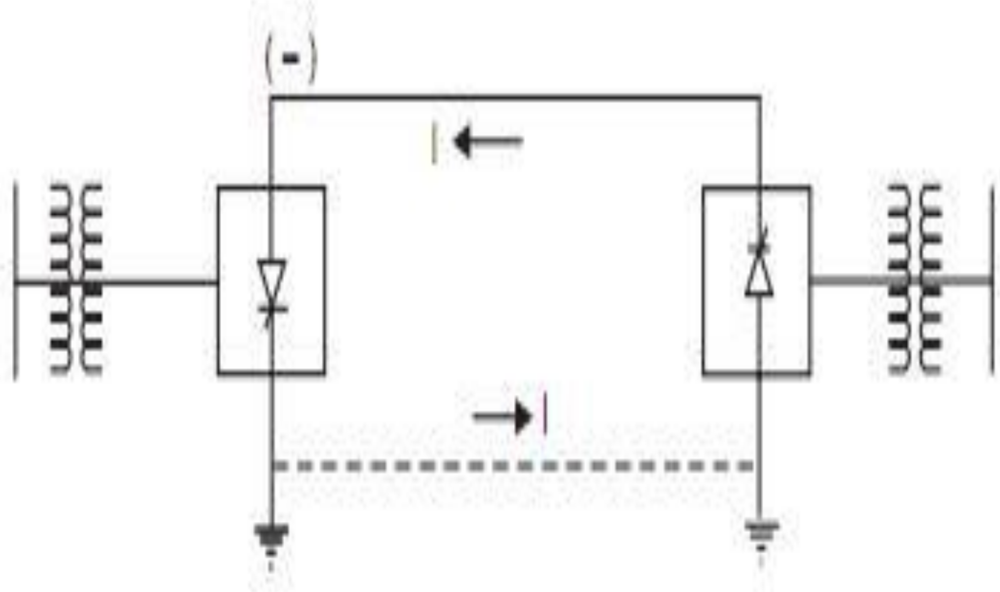
- Long distance bulk power transmission

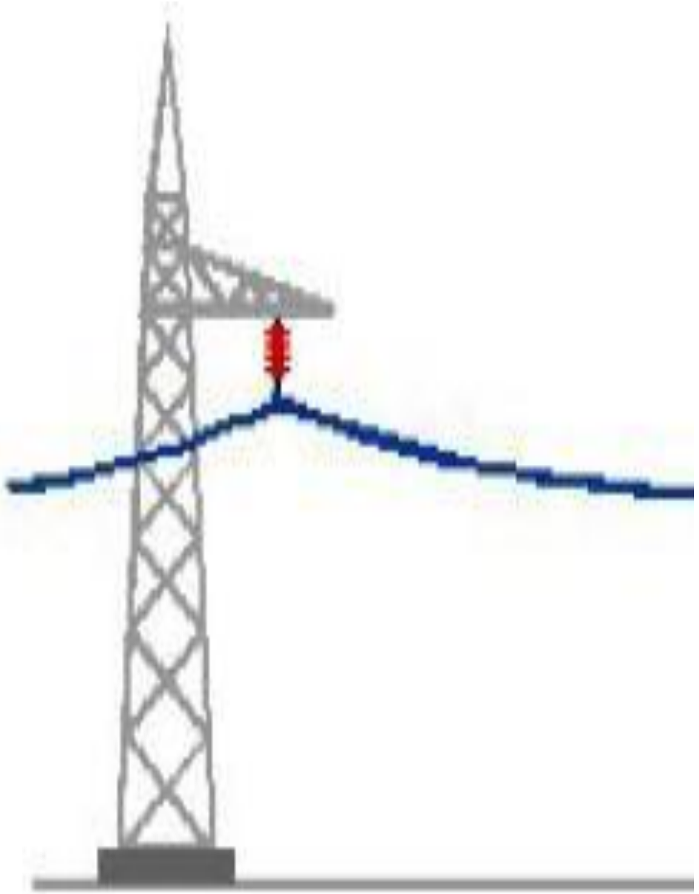
- Stabilization of power flows in integrated power system:

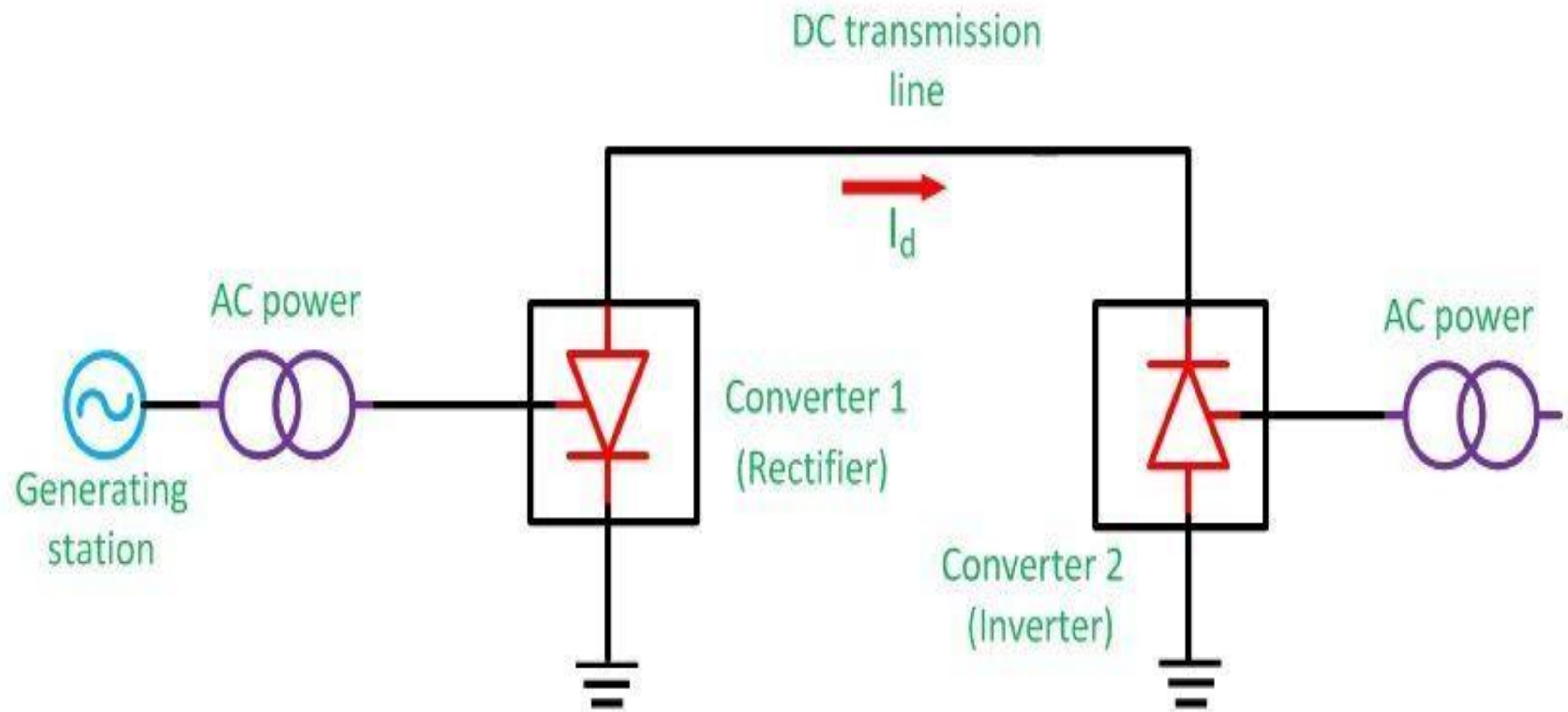
TYPES OF HVDC LINK

- MONOPOLAR LINK

- A monopolar link has one conductor and uses either ground and/or sea return.
- A metallic return can also be used where concerns for harmonic interference and/or corrosion exist.
- In applications with DC cables (i.e., HVDC Light), a cable return is used.
- Since the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity, a monopolar link is normally operated with negative polarity.



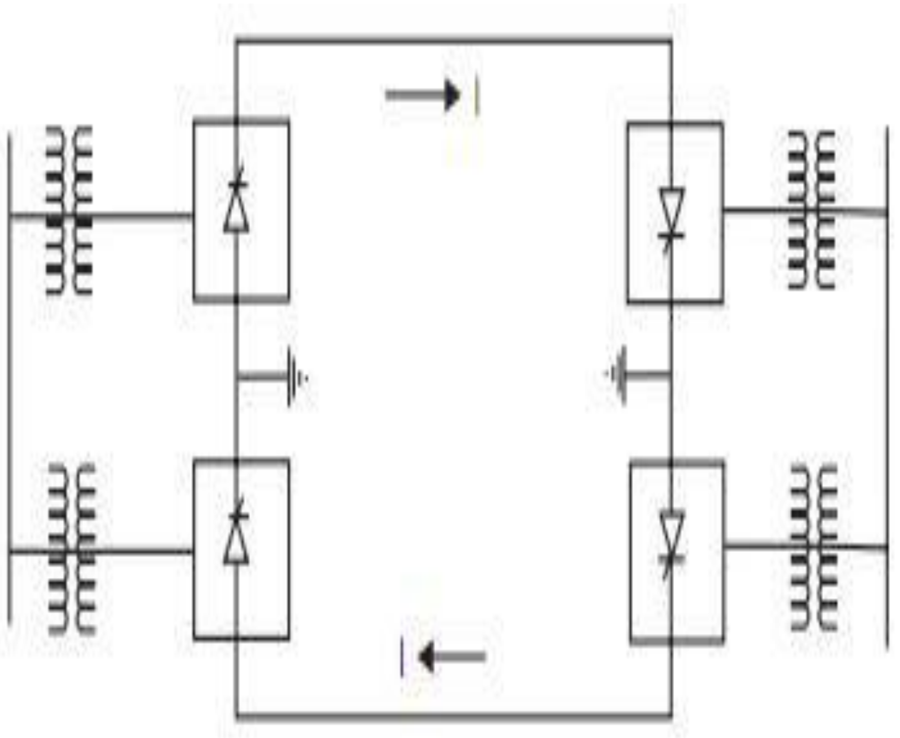


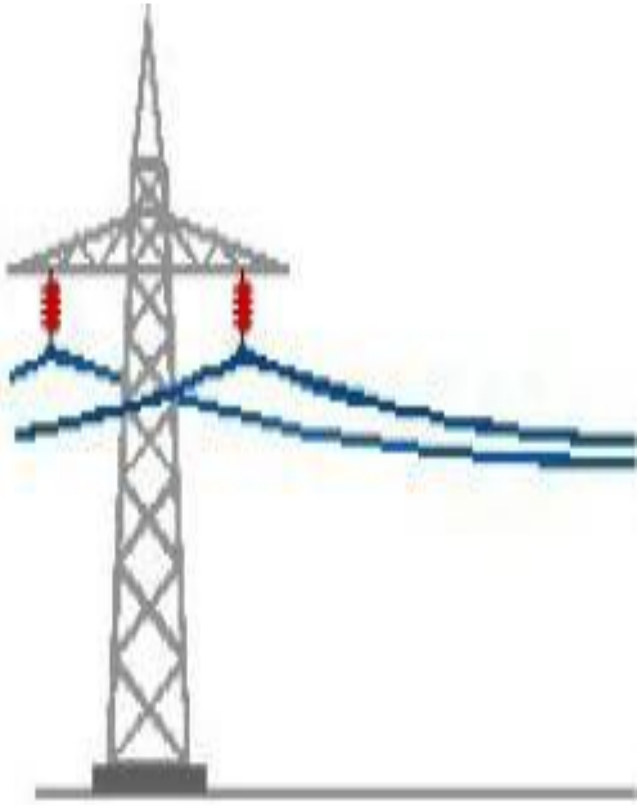


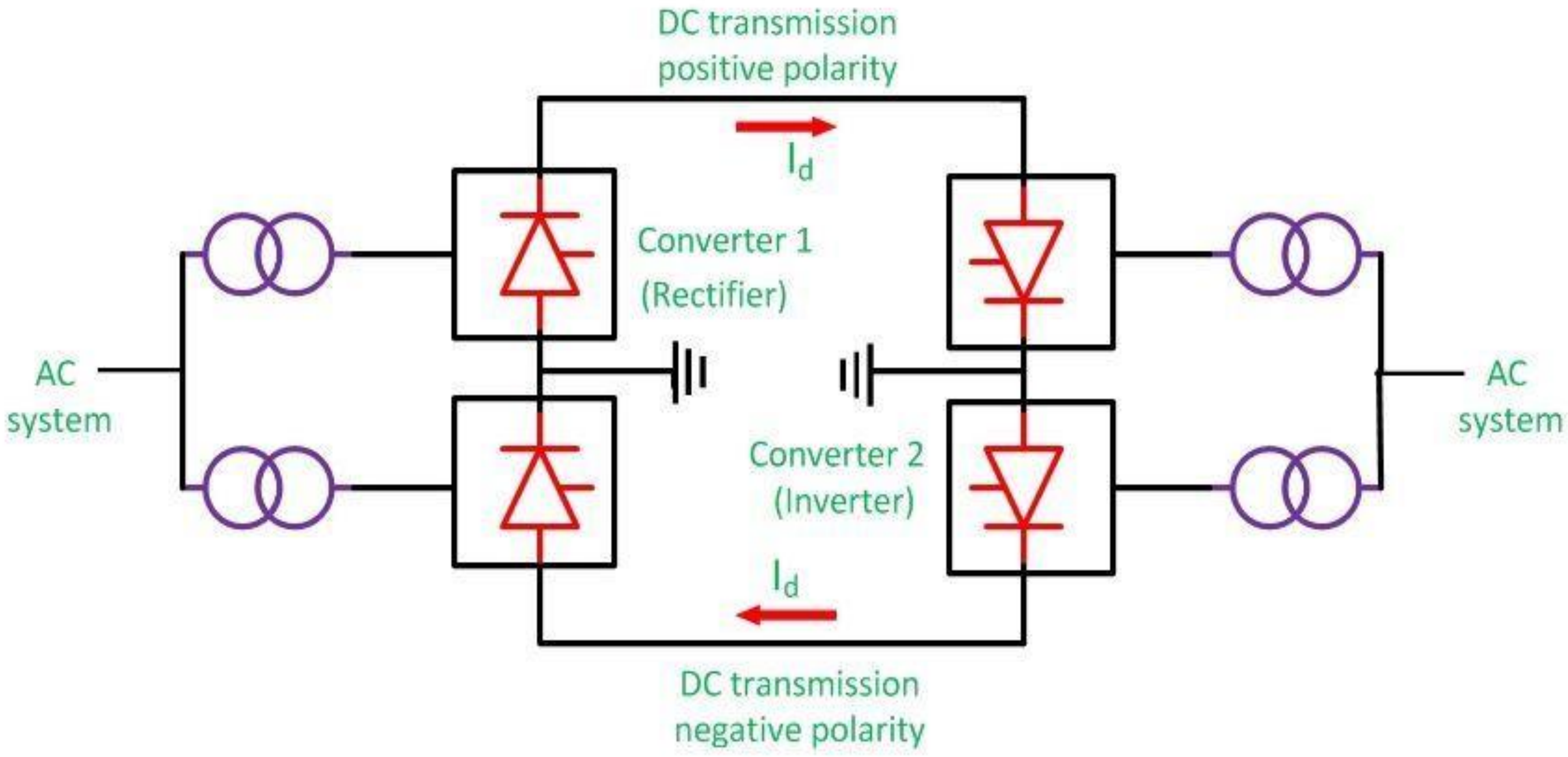
Monopolar link

BIPOLAR LINK

- A bipolar link as has two conductors, one positive and the other negative.
- Each terminal has two sets of converters of equal rating, in series on the DC side.
- The junction between the two sets of converters is grounded at one or both ends by the use of a short electrode line.
- Since both poles operate with equal currents under normal operation, there is zero ground current flowing under these conditions.
- Monopolar operation can also be used in the first stages of the development of a bipolar link.
- Alternatively, under faulty converter conditions, one DC line may be temporarily used as a metallic return with the use of suitable switching.



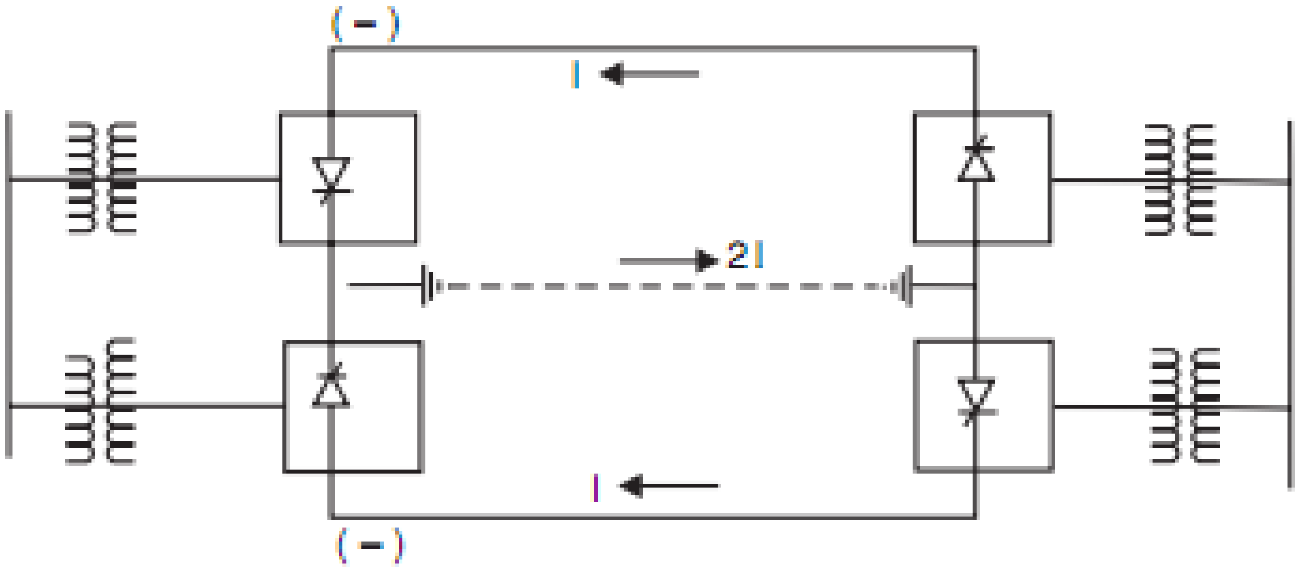


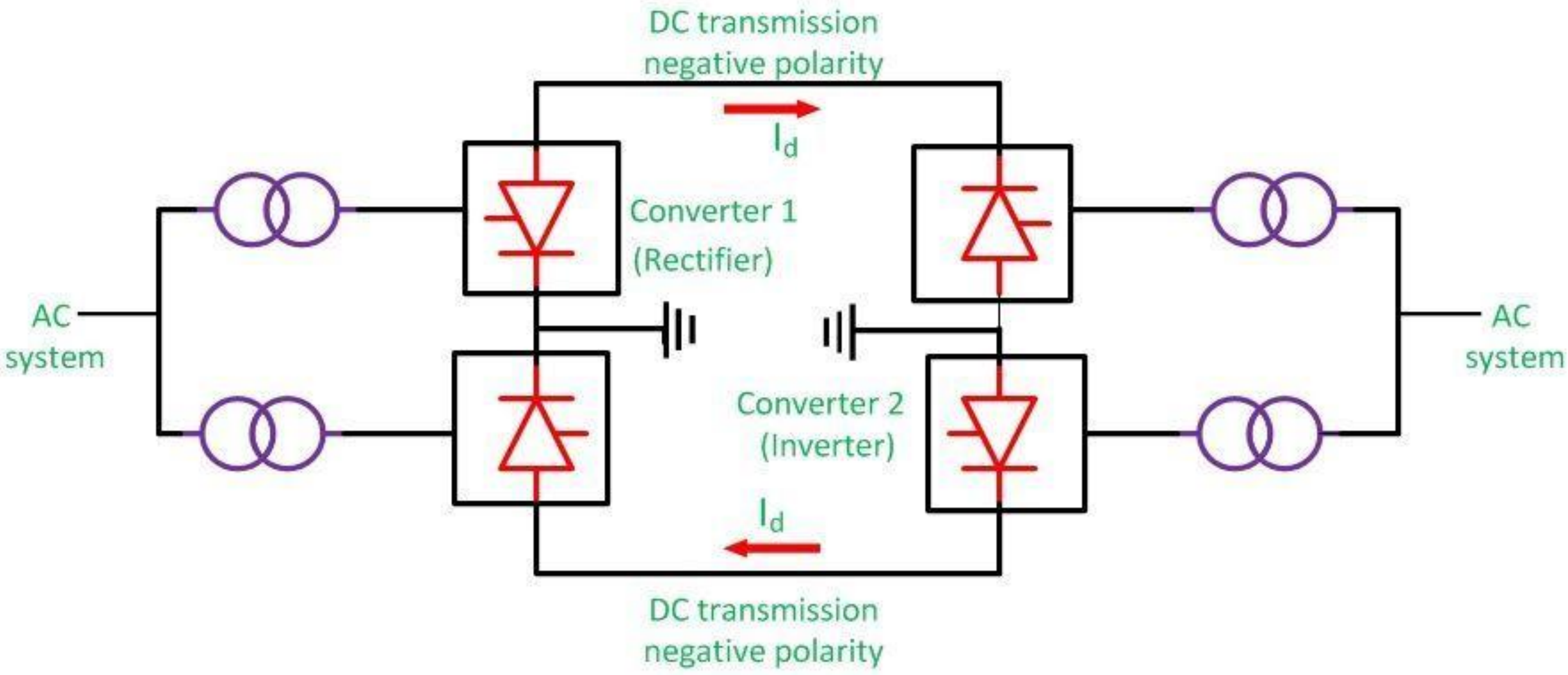


Bipolar link

Homopolar link

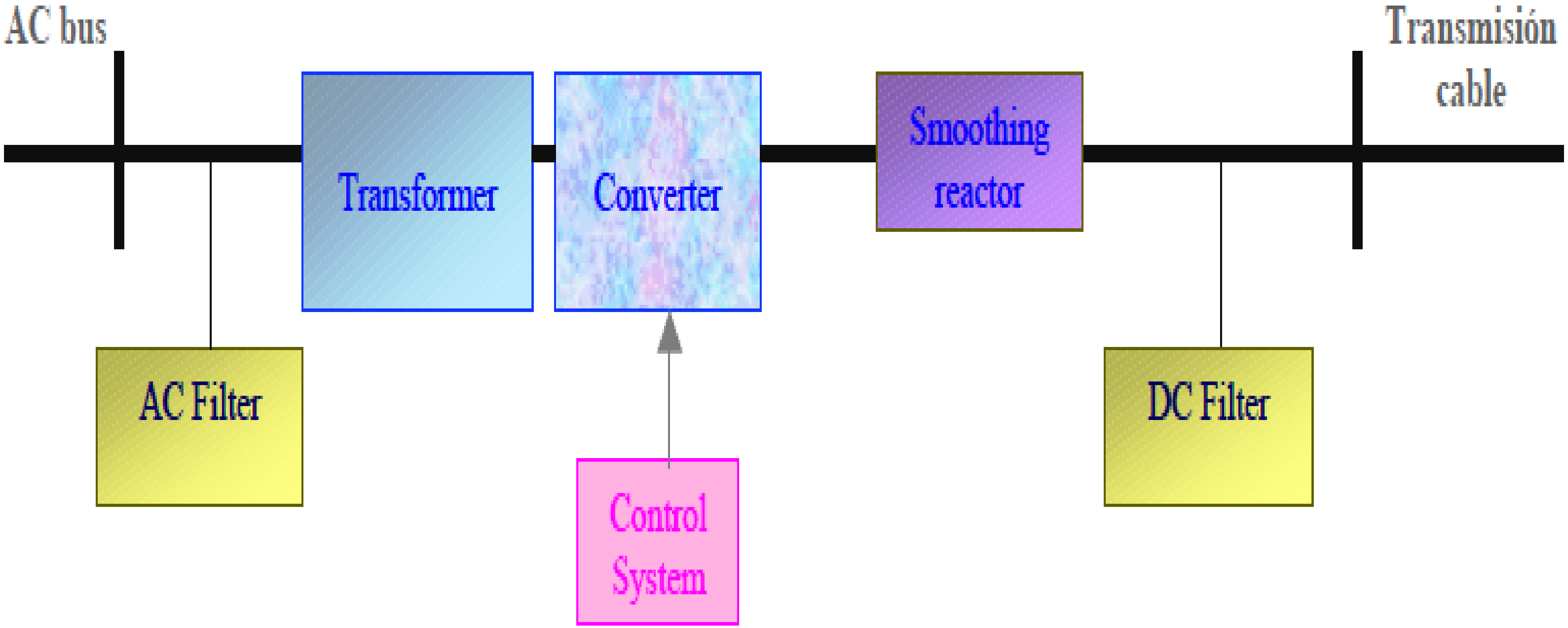
- In this type of link two conductors having the same polarity (usually negative) can be operated with ground or metallic return.
- Due to the undesirability of operating a DC link with ground return, bipolar links are mostly used.
- A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantage
- s.





Homopolar link

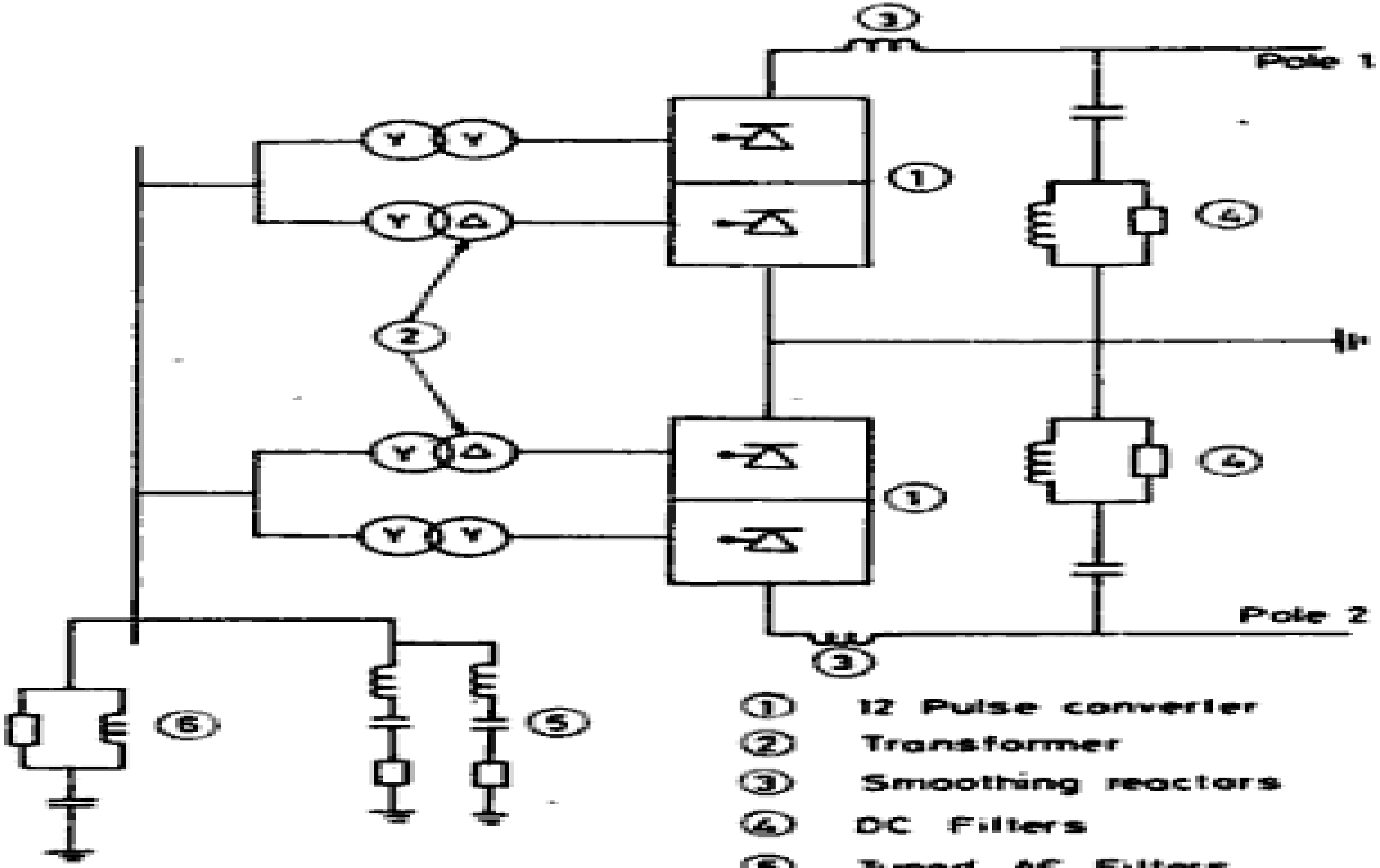
HVDC CONVERTER STATION



- The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed.

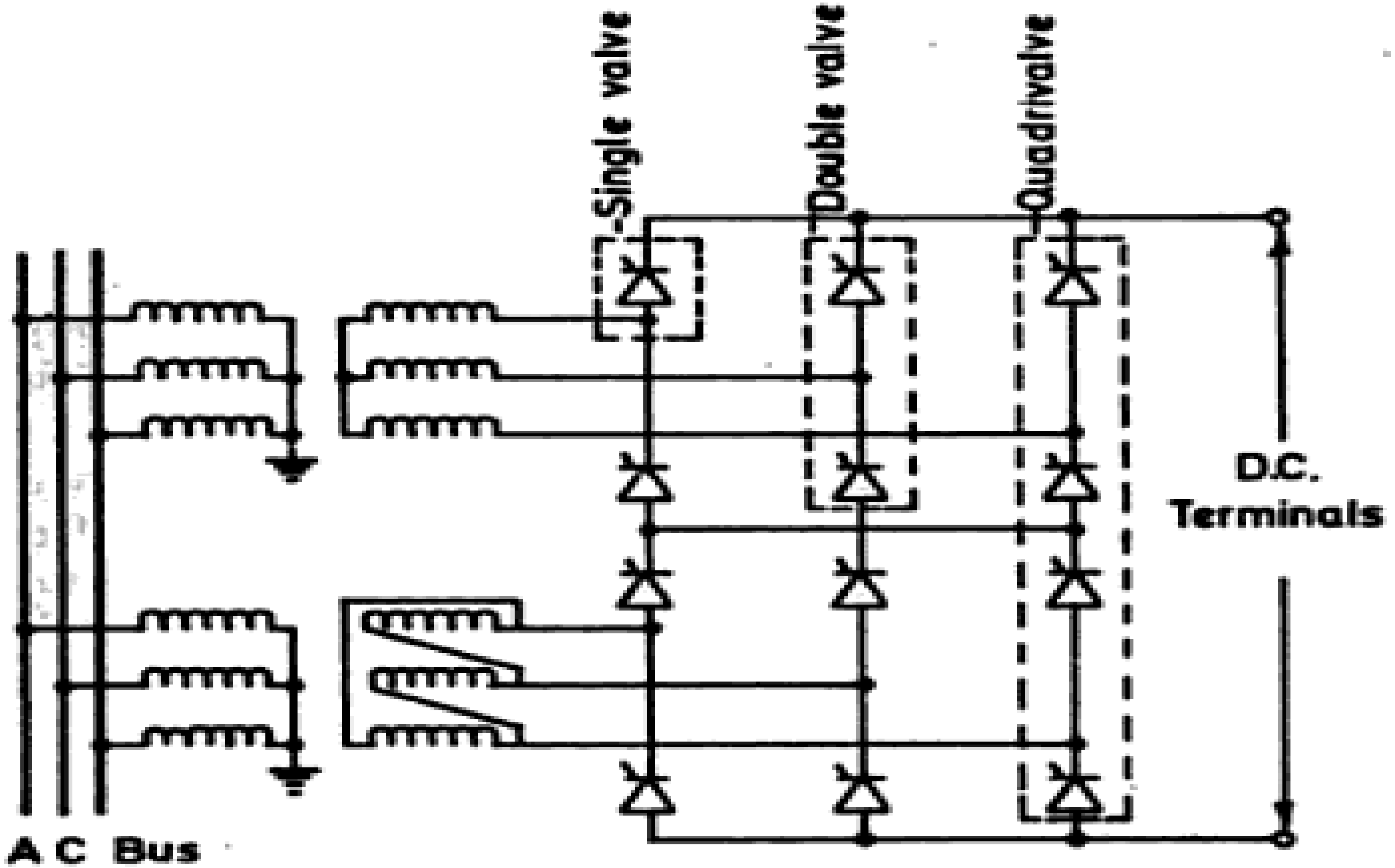
- A point to point transmission requires two converter stations.

- The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control



① 12 Pulse converter
② Transformer
③ Smoothing reactors
④ DC Filters
⑤ Tuned AC Filters
⑥ HP AC Filters

CONVERTER UNIT



- This usually consists of two three phase converter bridges connected in series to form a 12 pulse converter

- The total number of valves in such a unit is twelve. The valves can be packaged as single valve, double valve or quadrivalve arrangements. Each valve is used to switch in segment of an AC voltage waveform. The converter is fed by converter transformers connected in star/star and star/delta arrangements.

- The valves are cooled by air, oil, water of freon. Liquid cooling using deionized water is more efficient
- Valve firing signals are generated in the converter control at ground potential and are transmitted to each thyristor in the valve through a fiber optic light guide system.

- The valves are protected using snubber circuits, protective firing and gapless surge arrestors.

CONVERTER TRANSFORMEER

- The converter transformer has three different configurations-

(i) three phase, two winding,

(ii) single phase, three winding and

(iii)single phase, two winding

- The valve side windings are connected in parallel with neutral grounded.
- On the AC side transformers are connected in parallel with neutral grounded
- The leakage reactance of the transformer is chosen to limit the short circuit currents through any valves.
- The converter transformers are designed to withstand DC voltage stresses and increased eddy current losses due to harmonic currents. One problem that can arise is due to the DC magnetization of the core due to unsymmetrical firing of valves

FILTERS

- There are three types of filters used which are

1. AC Filters:

- These are passive circuits used to provide Low impedance, shunt paths for AC harmonic currents.

2. DC Filters:

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

3. 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

Reactive power source

- Part of the reactive power requirement is provided by AC filters. In addition, shunt capacitors, synchronous condensors and static VAR systems are used depending on the speed of control
- **Smoothing Reactor:**
- A sufficiently large series reactor is used on DC side to smooth DC current and also for protection.
- The reactor is designed as a linear reactor and is connected on the line side, neutral side or at intermediate location.
- **DC Switchgear:**
- It is modified AC equipment used to interrupt small DC currents. DC breakers or Metallic Return Transfer Breakers (MRTB) are used, if required for interruption of rated load currents.
- In addition to the DC switchgear, AC switchgear and associated equipment for protection and measurement are also part of the converter station.

Modern Trends in DC Transmission

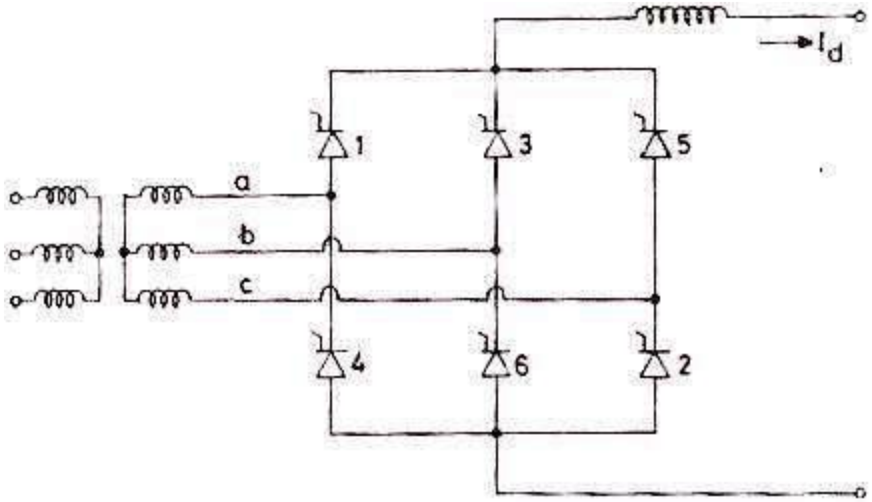
- **Power semiconductors and valves**
- **Converter Control**
- **DC Breakers**
- **Conversion of existing AC lines:**
- **Operation with weak AC systems:**

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= Short circuit level at the converter bus/Rated DC power

SIX PULSE 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 a six pulse converter
- 12 pulse converter is composed of two bridges in series supplied from two different (three-phase) transformers with voltages differing in phase by 30 degree



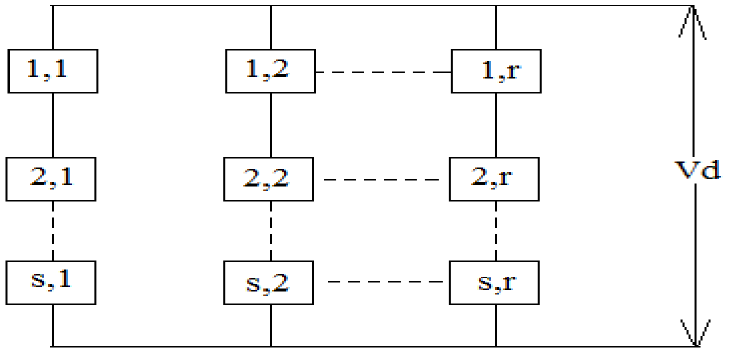
- **Pulse Number**
- The pulse number of a converter is defined as the number of pulsations (cycles of ripple) of direct voltage per cycle of alternating voltage

- Conversion from AC to DC involves switching sequentially different sinusoidal voltage on DC circuit

CHOICE OF CONVERTER CONFIGURATION

- For any given pulse number select the configuration such a way that both the valve and transformer utilization are maximized
- In general converter configuration can be selected by the basic commutation group and the no. of such groups connected in series and parallel.
- Commutation groups means set of valves in which only one valve conducts at a time.
- If there are 'q' valves in a basic commutation group and r of those are connected in parallel and s of them in series then total no. of valves= qrs

CONVERTER MADE UP OF SERIES AND PARALLEL CONNECTION OF COMMUTATION GROUP



VALVE VOLTAGE RATING

- The valve rating is specified in terms of Peak Inverse Voltage (PIV).
- The ratio of PIV to average DC voltage is an index of valve utilization.
- So, average maximum DC voltage across the converter is given by,
- □

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

$$= s\frac{q}{2\pi}E_m(\sin\omega t)_{-\pi/q}^{\pi/q} = \frac{sq}{2\pi}E_m\left[\sin\frac{\pi}{q} - \sin\left(-\frac{\pi}{q}\right)\right] = \frac{sq}{2\pi}E_m.2\sin\frac{\pi}{q}$$

$$V_{do} = \frac{sq}{\pi}E_m \sin\frac{\pi}{q} \text{ ----- } (1)$$

- If ‘q’ is even, then maximum peak inverse voltage

PIV = 2Em

If ‘q’ is odd, then maximum inverse voltage

PIV = 2Em cos(π/2q)

$$\text{For q even, } \frac{PIV}{V_{do}} = \frac{2E_m}{\frac{sq}{\pi} E_m \sin\frac{\pi}{q}} = \frac{2\pi}{s.q.\sin\frac{\pi}{q}}$$

$$\text{For q odd, } \frac{PIV}{V_{do}} = \frac{2E_m \cos\frac{\pi}{2q}}{\frac{sq}{\pi} E_m \sin\frac{\pi}{q}} = \frac{2\pi.\cos\frac{\pi}{2q}}{sq.\sin\frac{\pi}{q}} = \frac{2\pi.\cos\frac{\pi}{2q}}{sq.2\cos\frac{\pi}{2q}\sin\frac{\pi}{2q}}$$

$$\left(\text{Since } \sin 2\theta = 2\sin\theta\cos\theta \text{ and } 2\cos\frac{\pi}{2q}\sin\frac{\pi}{2q} = \sin\frac{2\pi}{2q} = \sin\frac{\pi}{q}\right)$$

$$\frac{PIV}{V_{do}} = \frac{\pi}{sq.\sin\frac{\pi}{2q}} \quad \text{(For q odd)}$$

TRANSFORMER RATING

$$I_v = \frac{I_d}{r\sqrt{q}} \quad \text{------} \ (2)$$

- The current rating of a valve is given by above equation.

- The transformer rating on the valve side (in VA) is given by,

$$S_{tv} = p\frac{E_m}{\sqrt{2}}I_v$$

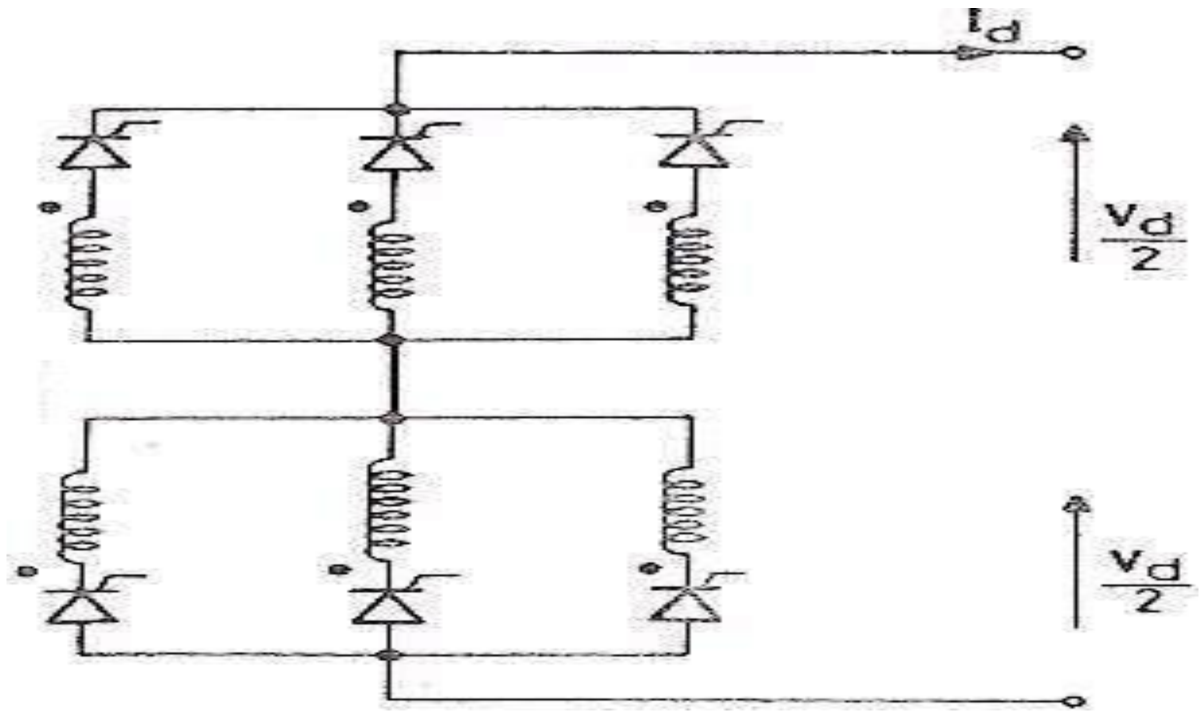
- From equations (1), (2) & p=qrs, we have

$$S_{tv} = p\frac{V_{do}.\pi}{\sqrt{2}.sq.\sin\frac{\pi}{q}}.\frac{I_d}{r\sqrt{q}}$$

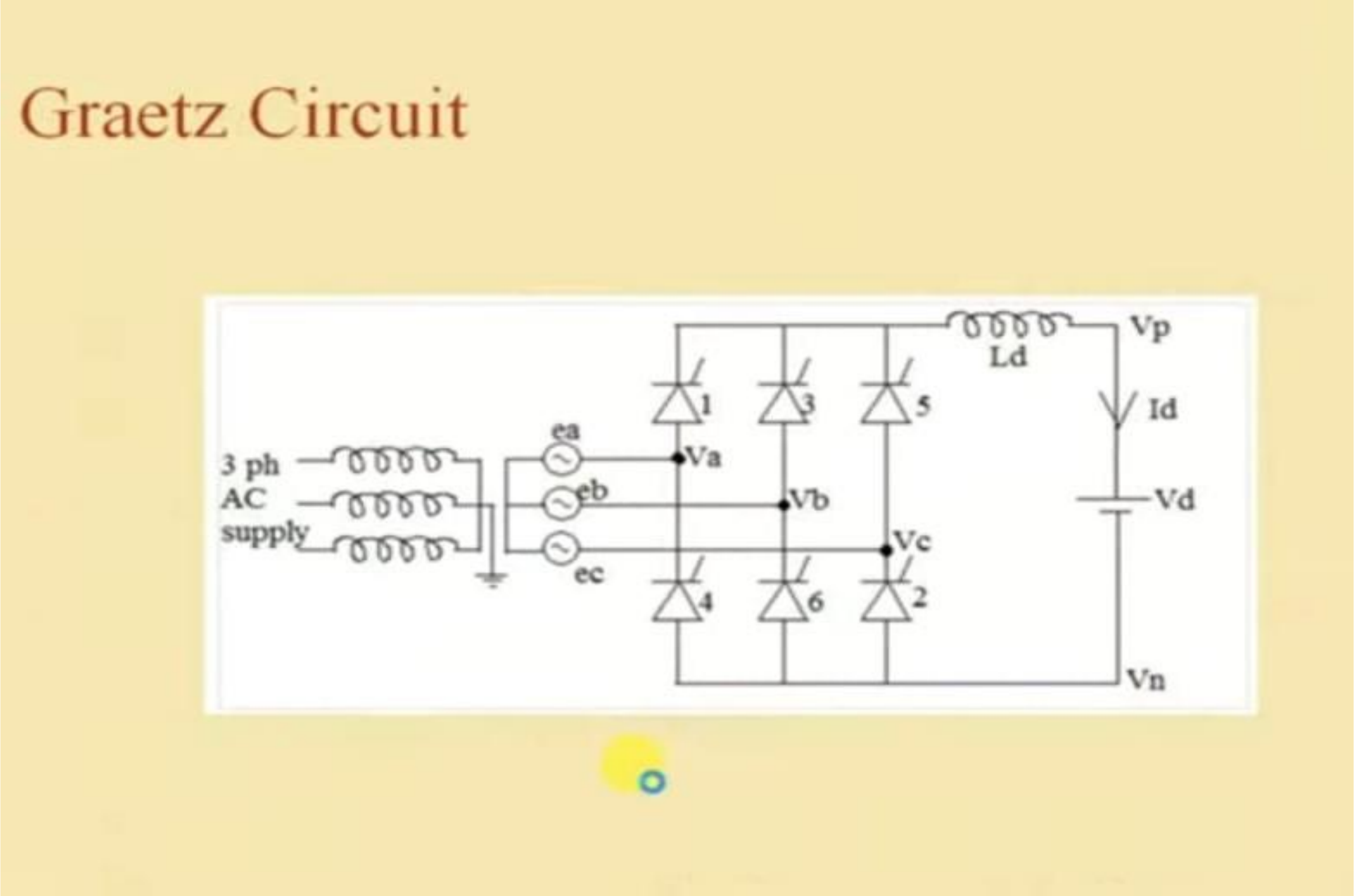
$$S_{tv} = \frac{\pi}{\sqrt{2}}.\frac{V_{do}I_d}{\sqrt{q}.\sin\frac{\pi}{q}}$$

Transformer utilization factor $\left(\frac{S_{tv}}{V_{do}I_d}\right)$ is a function of q.

- Both from valve and transformer utilization considered gratez circuit is the best circuit for six pulse converter



Gratez circuit



- It utilizes the transformer and the converter unit to at most level and it maintains low voltage across the valve when not in conduction.
- Due to this it dominates all other alternative circuits from being implemented in HVDC converter
- The low voltage across the valve is the peak inverse voltage which the valve should withstand
- It consists of 6 valves arranged in bridge type and the converter transformer having tappings on the AC side for voltage control
- AC supply is given for the three windings of the converter transformer connected in star with ground neutral
- Valve side winding are either connected in star or delta with ungrounded neutral
- Valves are fired in definite and fixed order and DC output contain SIX DC pulses per one cycle of AC voltage

ANALYSIS OF GRATEZ 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 degree and the interval between consecutive firing pulse is 60degree 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.

Operation without overlap:

- The six pulse converter without over lapping valve conduction sequence are 1–2, 2–3, 3–4, 4–5, 5–6, 6–1.
- At any instant two valves are conducting in the bridge. One from the upper group and other from the lower group.
- Each valve arm conducts for a period of one third of half cycle i.e., 60 degrees.
- In one full cycle of AC supply there are six pulses in the DC waveform. **Hence the bridge is called as six pulse converter.**

Conditions

- when $\alpha = 0$, the commutation takes place naturally and the converter acts as a rectifier.
- when $\alpha > 60$ deg, the voltage with negative spikes appears and the direction of power flow is from AC to DC system without change in magnitude of current.
- when $\alpha = 90$ deg, the negative and positive portions of the voltage are equal and because of above fact, the DC voltage per cycle is zero. Hence the energy transferred is zero.
- when $\alpha > 90$ deg, the converter acts as an inverter and the flow of power is from DC system to AC system.

Conditions

- Although α can vary from 0 to 180 degrees, the full range cannot be utilized. In order to ensure the firing of all the series connected thyristors, it is necessary to provide a minimum limit of α greater than zero, say 5 deg.
- Also in order to allow for the turn off time of a valve, it is necessary to provide an upper limit less than 180 deg.
- The delay angle α is not allowed to go beyond $180-\gamma$ where γ is called the extinction angle (sometimes also called the marginal angle).
- The minimum value of the extinction angle is typically 10 deg, although in normal operation as an inverter, it is not allowed to go below 15deg or 18deg

Let valve 3 is fired at an angle of α.

the DC output voltage is given by

Vdc = Vdo Cos α

$$V_d = e_b - e_c = e_{bc}$$

$$e_{bc} = \sqrt{2}V_{LL} Sin(\omega t + 60^0)$$

$$\therefore V_{dc} = \frac{6}{2\pi}\int_{\alpha}^{\alpha+60^0} e_{bc}.d\,\omega t$$

$$V_{dc} = \frac{3}{\pi}\int_{\alpha}^{\alpha+60^0} \sqrt{2}V_{LL} Sin(\omega t + 60^0).d\,\omega t$$

$$= \frac{3\sqrt{2}}{\pi}V_{LL}\left(Cos(\alpha + 60^0) - Cos(\alpha + 120^0)\right)$$

$$= \frac{3\sqrt{2}}{\pi}V_{LL} Cos\alpha$$

$$= 1.35 V_{LL} Cos\alpha$$

From above equation we can say that if firing angle varies, the DC output voltage varies

DC Voltage Waveform

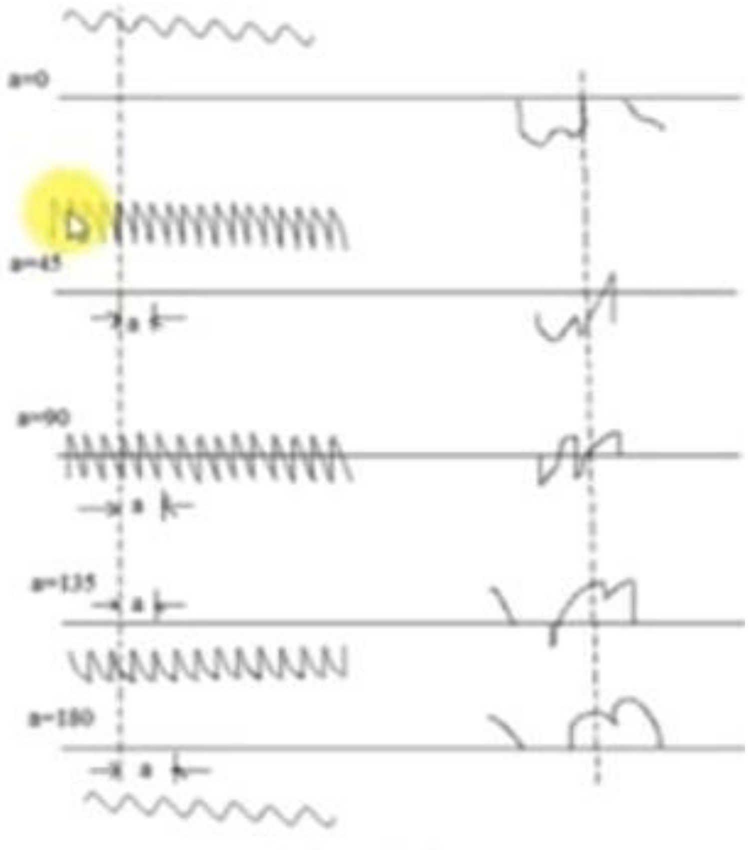
The dc voltage waveform contains a ripple whose frequency is six times the supply frequency.

This can be analysed in Fourier series and contains harmonics of the order $h = np$

Where p is the pulse number and n is an integer.

The r.m.s value of the h^{th} order harmonic in dc voltage is given by

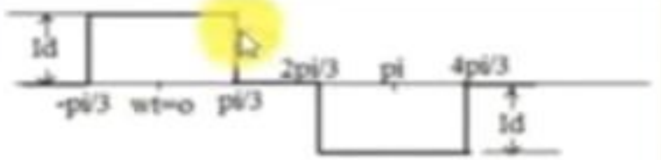
$$V_h = V_{do} \frac{\sqrt{2}}{h^2 - 1}\left[1 + \left(h^2 - 1\right)\sin^2 \alpha\right]^{1/2}$$



Voltage waveforms

AC Current Waveform

- It is assumed that the direct current has no ripple (or harmonics) because of the smoothing reactor provided in series with the bridge circuit.
- The AC currents flowing through the valve (secondary) and primary windings of the converter transformer contain harmonics.



AC Current waveforms

BY FOURIER ANALYSIS

analysis, the peak value of a line current of
tal frequency component is given by.

$$I_p = \frac{2}{\pi}\int_{-\pi/3}^{\pi/3} I_d.\cos\theta.d\theta$$

$$\Rightarrow I_p = \frac{2}{\pi}.I_d\int_{-\pi/3}^{\pi/3}\cos\theta.d\theta$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}[\sin\theta]_{-\pi/3}^{\pi/3}$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\sin\left(\frac{\pi}{3}\right)-\sin(-\pi/3)\right]$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\frac{\sqrt{3}}{2}+\frac{\sqrt{3}}{2}\right]\left[\because \sin(-\theta) = -\sin\theta\right]$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\frac{2\sqrt{3}}{2}\right]$$

$$\Rightarrow I_p = \frac{2\sqrt{3}}{\pi}.I_d$$

Now the rms value of line current of fundamental frequency component is given by

$$I_{rms} = \frac{I_p}{\sqrt{2}}$$

$$\Rightarrow I_{rms} = \frac{\frac{2\sqrt{3}}{\pi}.I_d}{\sqrt{2}}$$

$$\Rightarrow I_{rms} = \frac{2\sqrt{3}I_d}{\sqrt{2}\pi}$$

$$\therefore I_{rms} = \frac{\sqrt{6}}{\pi}.I_d$$

Generally, the RMS value of nth harmonic is given by, $I_n = \frac{I}{n}$

where I = Fundamental current
n = nth order harmonic.

The harmonics contained in the current waveform are of the order given by
h = np ± 1
where n is an integer, p is the pulse number.
For a 6 pulse bridge converter, the order of AC harmonics are 5, 7, 11, 13 and higher order.

Power Factor

The AC power supplied to the converter is given by

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

where cosΦ is the power factor.

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

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

Substituting for Vdc = Vdo Cos α, and I1= $\frac{\sqrt{6}}{\pi}I_d$, we obtain

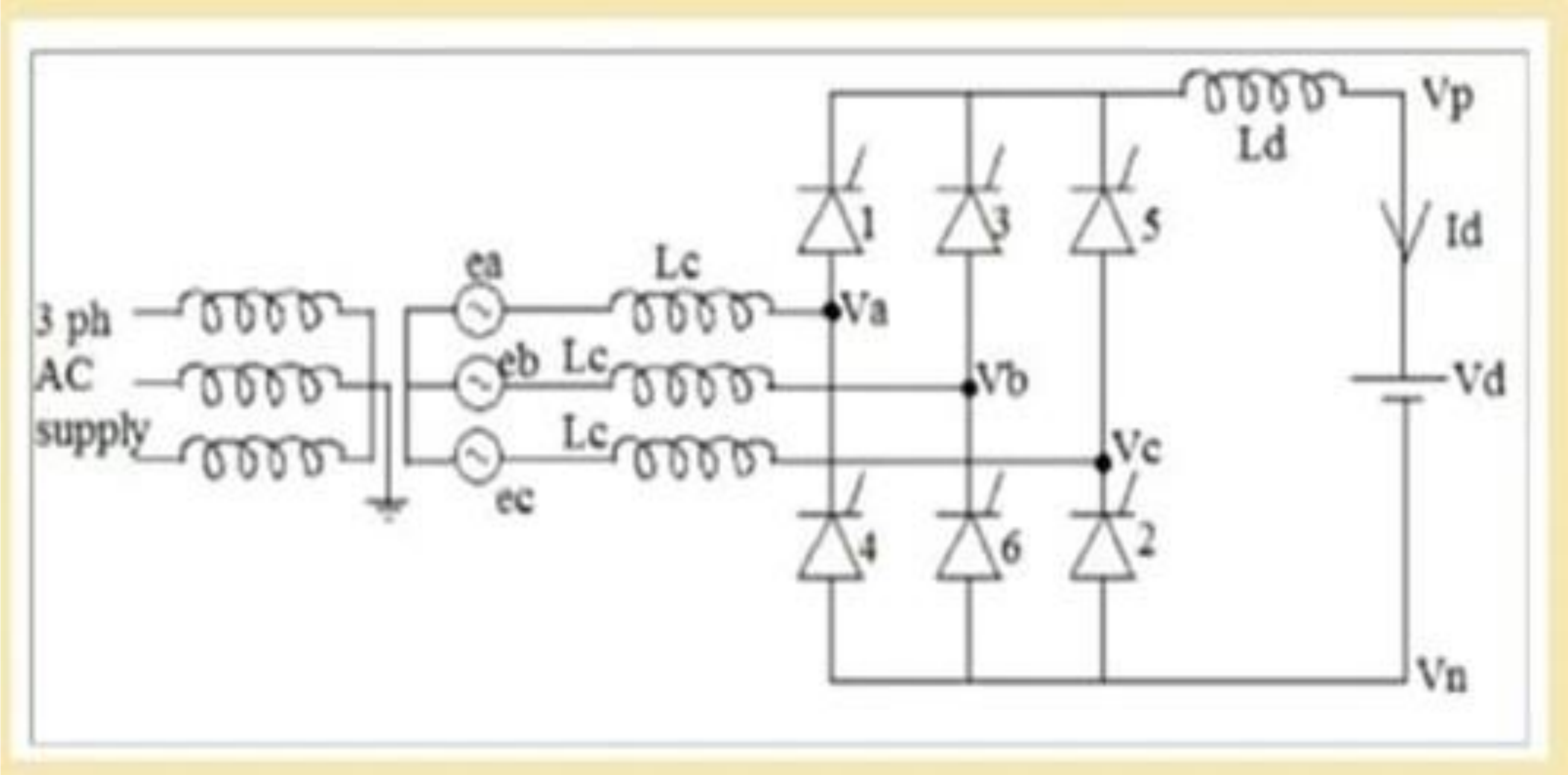
cos Φ = cos α

The reactive power requirements are increased as α is increased from 0

When α = 90 deg, the power factor is zero and only reactive power is consumed.

LINE COMMUTATED CONVERTERS WITH OVERLAP

- Lc indicates inductance of transformer
- Vd and Id= DC voltage and current flowing in the line
- Ld=DC side reactance
- 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 thus commutation from one valve to next valve cannot be instantaneous



3 ph
AC
supply
ea
eb
ec
Lc
Lc
Lc
Va
Vb
Vc
1
3
5
4
6
2
Ld
Vp
Id
Vd
Vn

Commutation Delay

- The process of transfer of current from one path to another path with both paths carrying current simultaneously is known overlap.
- The time required for commutation or overlapping which is expressed in electrical degrees is done with commutation angle, denoted by μ.
- During normal operating conditions the overlap angle is in the range of 0 to 60 degrees, in which two (or) three valves are conducting.
- However, if the overlap angle is the range of 60 to 120 degrees, then three to four valves are in conducting state which is known as abnormal operation mode.
- During commutation period, the current increases from 0 to I din the incoming valve and reduces to zero from Id in the outgoing valve.
- The commutation process begins with delay angle and ends with extinction angle ie., it starts when $\omega t = \alpha$ and ends when $\omega t = \alpha+\mu = \delta$, where δ is known as an extinction angle.

Mode of Operation

- Mode-1-Two and three valve conduction (μ<60 deg)
- Mode-2-Three valve conduction (μ=60 deg)
- Mode-3- Three and four valve conduction (μ>60 deg)
- Depending upon the delay angle α, the mode 2 must be just a point on the boundary of modes 1 and 3.

ANALYSIS OF TWO AND THREE VALVE CONDUCTION MODE

- Generally overlap angle will be less than 60 degree
- In this mode each interval of the period of supply can be divided into two subintervals
- In the first subinterval three valves are conducting and in the second subinterval two valves are conducting

Analysis

Let us assume the input voltages

$$e_a = E_m \cos | \omega t + 60^0 |$$
$$e_b = E_m \cos | \omega t - 60^0 |$$
$$e_c = E_m \cos | \omega t - 180^0 |$$

Corresponding line voltages are e_{ac} , e_{ba}, e_{cb}

$$e_{ac} = e_a - e_c$$
$$= E_m \cos(\omega t + 60^0) - E_m \cos(\omega t - 180^0)$$
$$= E_m (\cos(\omega t + 60^0) - \cos(\omega t - 180^0))$$
$$= E_m \left[| \cos \omega t . \frac{1}{2} - \sin \omega t . \frac{\sqrt{3}}{2} + \cos \omega t | \right]$$
$$= E_m \left[\frac{3}{2} \cos \omega t - \frac{\sqrt{3}}{2} \sin \omega t \right]$$
$$= \sqrt{3} E_m | \frac{\sqrt{3}}{2} \cos \omega t - \frac{1}{2} \sin \omega t |$$
$$= \sqrt{3} E_m \left[\cos 30^0 \cos \omega t - \frac{1}{2} \sin \omega t \right]$$
$$e_{ac} = \sqrt{3} E_m \cos(\omega t + 30^0)$$

Analysis contd…

- Each valve will conduct for 120 degrees and each pair will conduct for 60 degrees, if there is no overlap.
- Let us consider non-overlap of only valve 1,2 conducting followed by overlap of 3 with 1 i.e., 1,2 and 3 conducting.
- When only valve 1 and 2 conducting

$$i_a = -i_c = I_1 = I_2 = I_d$$

$$i_b = I_3 = I_4 = I_5 = I_6 = 0$$

$$V_a = V_p = e_a = E_m \cos(\omega t + 60^0)$$

$$V_b = e_b = E_m \cos(\omega t - 60^0)$$

$$V_c = V_n = e_c = E_m \cos(\omega t - 180^0)$$

$$V_d = V_p - V_n = e_a - e_c = e_{ac} = \sqrt{3}E_m \cos(\omega t + 30^0)$$

$$V_1 = V_2 = 0$$

$$V_3 = e_{ba} = \sqrt{3}E_m \sin\omega t$$

$$V_4 = V_n - V_p = -V_d$$

$$V_5 = V_n - V_p - V_d$$

$$V_6 = e_c - e_b = e_{cb} = \sqrt{3}E_m \cos(\omega t + 150^0)$$

Analysis contd… (3 Valve conducting)

- When valve 3 is fired then 3 will overlap with 1 and it will be 3 valve conduction periods ie., 1, 2 and 3.
- For this period the voltage and current waveforms are different

Consider that valve 3 is ignited at angle ‘α’ and for overlap angle both 1 and 3 conduct together.

The duration of overlap 1 and 3 will conduct top with 2 at the bottom as shown in the fig.

Just at the beginning, ωt = α

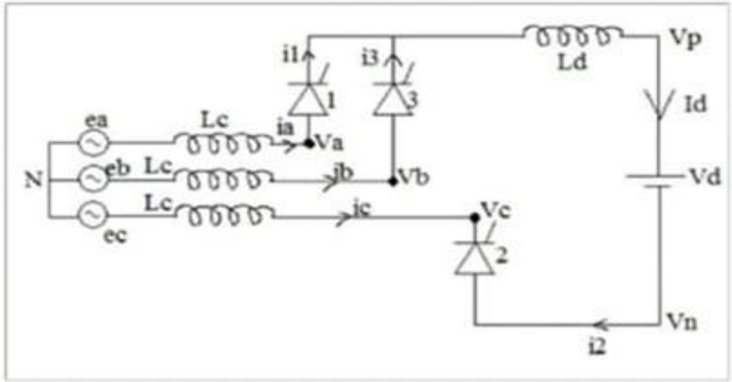
At ωt = α $\quad i_1 = I_d$

$i_3 = 0$

When the overlap ends at an angle (α+μ)

At ωt = (α+μ) $\quad i_1 = 0$

$i_3 = I_d$



The angle (α+μ) is called extinction angle During overlap a loop is formed as N-3-1-N

For this loop,

$$e_b - e_a = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt}$$

$$\sqrt{3}E_m \sin \omega t = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt}$$

Assuming the dc current either i1 alone conduct, i3 alone when 3 alone conducts should be equal to Id

So both 1 and 3 conduct overlap $i_1 + i_3 = I_d$

$$i_1 = I_d - i_3$$

So

$$\sqrt{3}E_m \sin \omega t = L_c \frac{di_3}{dt} - L_c \frac{di}{dt}(i_d - i_3)$$

$$\sqrt{3}E_m \sin \omega t = 2L_c \frac{di_3}{dt}$$

$$\sqrt{3}E_m \int \sin \omega t.dt = 2L_c \int di_3$$

$$\sqrt{3}E_m \int_{\alpha/\omega}^{t} \sin \omega t.dt = 2L_c \int_{\alpha/\omega}^{t} di_3$$

$$\frac{\sqrt{3}E_m}{2L_c\omega}(-\cos \omega t)_{\alpha/\omega}^{t} = i_3$$

At $\omega t = (\alpha+\mu)$;

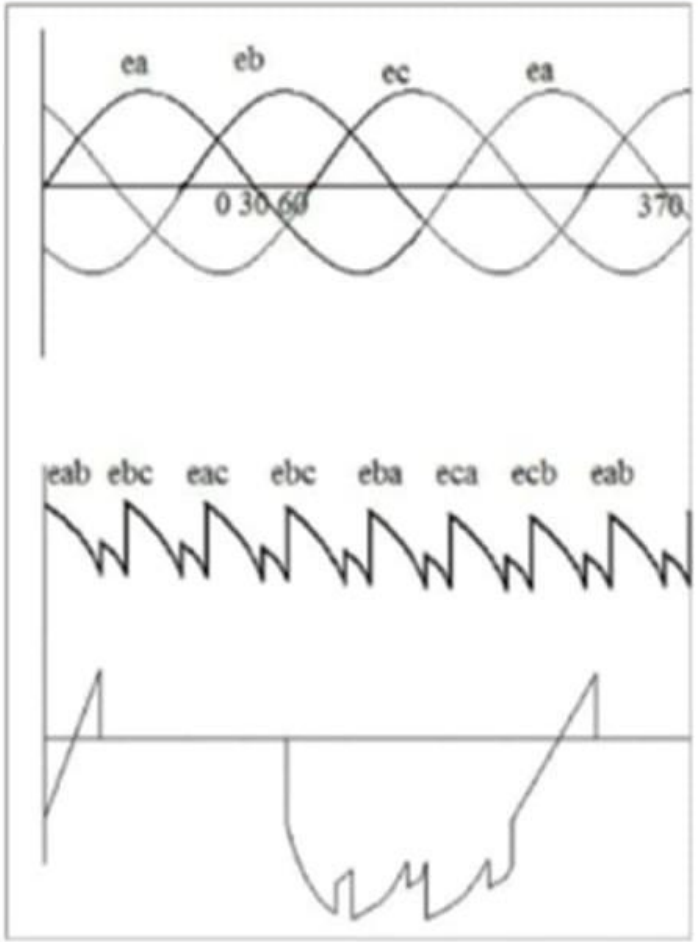
$$i_3 = I_d$$

$$\therefore I_d = \frac{\sqrt{3}E_m}{2\omega L_c}\left(\cos\alpha - \cos(\alpha+\mu)\right)$$

$$\therefore I_d = I_{s2}\left(\cos\alpha - \cos(\alpha+\mu)\right)$$

$$i_3 = I_d - i_1 = \frac{\sqrt{3}E_m}{2\omega L_c}\left(\cos\alpha - \cos\omega t\right)$$

$$I_{s2} = \frac{\sqrt{3}E_m}{2\omega L_c}$$



DC voltage and valve voltage waveforms for rectifier when α=15 deg, μ = 15 deg, δ = 30 deg

ANALYSIS OF VOLTAGE SOURCE CONVERTER