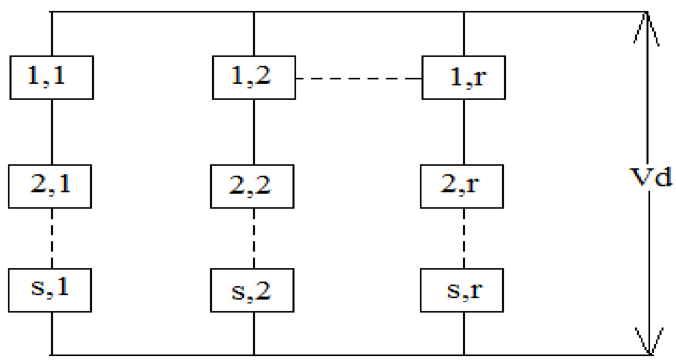
Introduction:

- HVDC converters converts AC to DC and transfer the DC power, then DC is again converted to AC by using inverter station.
- HVDC system mainly consists of two stations, one in rectifier station which transfers from AC to DC network and other is inverter station which transfers from DC to AC network.
- For all HVDC converters twelve pulse bridge converters are used. Same converter can act as both rectifier as well as an inverter depending on the firing angle 'α'.
- If firing angle α is less than 90 degrees the converter acts in rectifier mode and if the firing angle α is greater than 90 degrees the converter acts in inverter mode.

Choice of Converter configuration



Converter Configuration

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

Valve Voltage Rating:

Valve voltage rating is specified in terms of peak inverse voltage (PIV) it can withstand.
The valve utilization is the ratio of PIV to average dc voltage.
Converter average DC voltage is

$$\boxed{V_{do} = \frac{sq}{\pi} V_m . \sin\frac{\pi}{q}}$$

$$V_{do} = s.\frac{q}{2\pi}\int_{-\frac{\pi}{q}}^{\frac{\pi}{q}} V_m Cos\omega t.d\omega t$$

$$= \frac{sq}{2\pi} V_m \left[Sin\omega t\right]_{-\pi/q}^{\pi/q}$$

$$= \frac{sq}{2\pi} V_m .2.Sin\frac{\pi}{q}$$

i) Peak inverse voltage(PIV):

If q is even:

then the maximum inverse voltage occurs when the valve with a phase displacement of π radian in conducting and this is given by **PIV = 2Vm**

If q is odd:

the maximum inverse voltage occurs when the valve with a phase shift of π±π/q in conducting and this is given by **PIV = 2Vm Cosπ/2q**

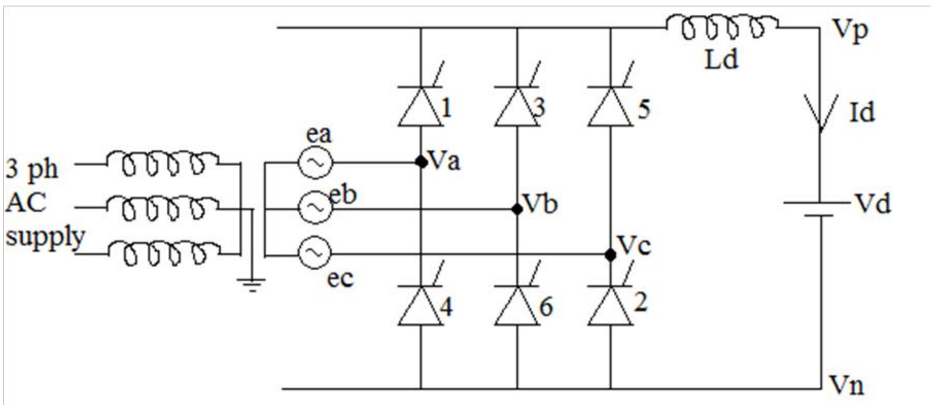
ii) Utilization factor:

Utilization factor = $\frac{PIV}{V_{do}} = \frac{2\pi}{sq.\sin\frac{\pi}{q}},$ for q is even

$= \frac{\pi}{sq.\sin\frac{\pi}{2q}},$ for q is odd

Analysis of Graetz circuit (6-pulse converter bridge):

The schematic diagram of a six-pulse Graetz circuit is shown in the fig.



- This Graetz circuit 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 quality present in Graetz circuit, it dominates all other alternative circuits from being implemented in HVDC converter.
- The low voltage across the valves is nothing but the peak inverse voltage which the valve should withstand.
- The six-pulse Graetz circuit consists of 6 valves arranged in bridge type and the converter transformer having tapings on the AC side for voltage control.
- AC supply is given for the three winding of the converter transformer connected in star with grounded neutral.
- The windings on the valve side are either connected in star or delta with ungrounded neutral.
- The six valves of the circuit are fired in a definite and fixed order and the DC output obtained contains six DC pulses per one cycle of AC voltage wave.

a)**Operation without overlap:**

- The six pulse converter without over lapping valve construction 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.

For simple analysis following assumptions are much:

i) AC voltage at the converter input is sinusoidal and constant

ii) DC current is constant

iii) Valves are assumed as ideal switches with zero impedance when on(conducting) and with infinite impedance when off(not conducting)

In one full cycle of AC supply we will get 6-pulses in the output. Each pair of the devices will conduct 60 degrees. The dc output voltage waveform repeats every 60 degrees interval.

Therefore for calculation of average output voltages only consider one pulse and multiply with six for one full cycle. In this case each device will fire for 120 deg.

Firing angle delay:

Delay angle is the time required for firing the pulses in a converter for its conduction.

- It is generally expressed in electrical degrees.
- In other words, it is the time between zero crossing of commutation voltage and starting point of forward current conduction.
- The mean value of DC voltage can be reduced by decreasing the conduction duration, which can be achieved by delaying the pulses ie., by increasing the delay angle we can reduce the DC voltage and also the power transmission form one valve to another valve can also be reduced.

- ✓ when α = 0, the commutation takes place naturally and the converter acts as a rectifier.
- ✓ when α > 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 α = 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 α > 90 deg, the converter acts as an inverter and the flow of power is from DC system to AC system.

Let valve 3 is fired at an angle of α.

the DC output voltage is given by

Vdc = Vdo Cos α

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

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

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

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

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

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

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

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.

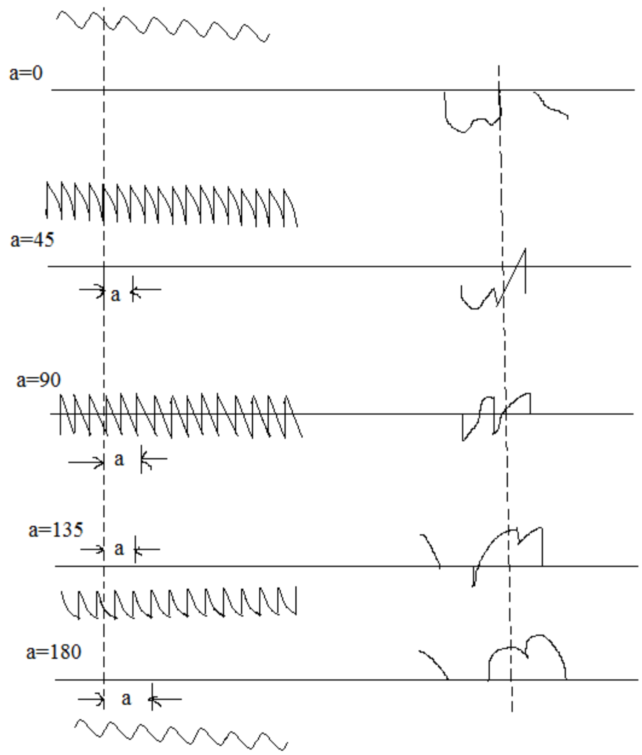
This can be analysed in Fourier series and contains harmonics of the order h=np

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

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

- 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-γ 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.



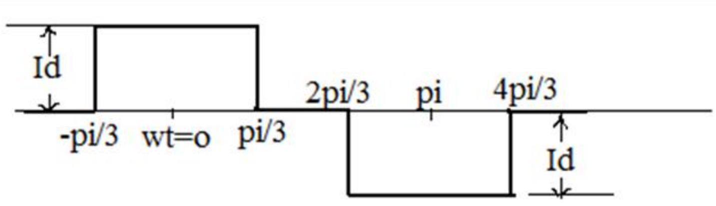
Voltage waveforms

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.

The waveform of the current in a valve winding is shown in fig.



AC Current waveforms

By Fourier analysis, the peak value of a line current of fundamental 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 $\pm$ 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.
They are filtered out by using tuned filters for each one of the first four harmonics and a high pass filter for the rest.

<u>The Power Factor:</u>

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

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

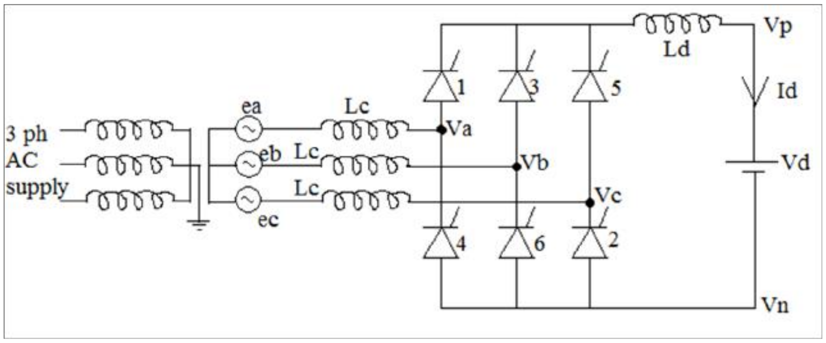
Substituting for Vdc = Vdo Cos α, and I1= $\frac{\sqrt{6}}{\pi} I_d$, we obtain

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.

ii) With overlap:



Lc indicates leakage inductance of transformer

Vd, Id = DC voltage and current flowing in the line

Ld = DC side reactance

V1 = voltage across the thyristors

p,n = positive and negative pole on the line

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 the next cannot be instantaneous.

For example, when valve 3 is fired, the current transformer from valve 1 to valve 3, takes a finite period during which both valves are conducting. This is called overlap and its duration is measured by the overlap (commutation) angle 'μ'.

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.

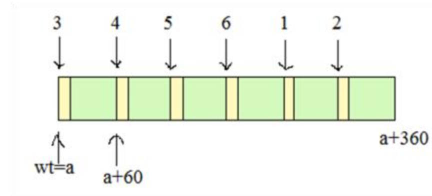
During normal operating conditions the overlap angle is in the range of 0 to 60 degrees, in which two (or) three valves are conducting.

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_d in 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 ωt = α and ends when ωt = α+μ = δ, where δ is known as an extinction angle.

There are three modes of the converter as follows:



1. Mode-1----Two and three valve conduction (μ<60 deg)
2. Mode-2----Three valve conduction (μ=60 deg)
3. 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.

i) Analysis of Two and Three valve conduction mode:

Generally overlap angle will be less than 60 deg, so let us analyse this mode.

Timing diagram

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.

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}

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

$$\begin{aligned}
e_{ba} &= E_m \cos(\omega t - 60^0) - E_m \cos(\omega t + 60^0) \\
&= E_m((\cos \omega t \cos 60^0 + \sin \omega t \sin 60^0) - (\cos \omega t \cos 60^0 \sin \omega t \sin 60^0)) \\
&= E_m \left[\cos \omega t.\frac{1}{2} + \sin \omega t.\frac{\sqrt{3}}{2} - \cos \omega t.\frac{1}{2} + \sin \omega t.\frac{\sqrt{3}}{2} \right] = \sqrt{3}E_m(\sin \omega t) \\
\therefore e_{ba} &= \sqrt{3}E_m \sin \omega t
\end{aligned}$$

$$\begin{aligned}
e_{cb} &= E_m(\cos(\omega t - 180) - \cos(\omega t - 60^0)) \\
&= E_m(\cos \omega t.\cos 180^0 + \sin \omega t \sin 180^0 - \cos \omega t \cos 60^0 - \sin \omega t \sin 60^0) \\
&= E_m \left[\frac{-3}{2}\cos \omega t - \frac{\sqrt{3}}{2}\sin \omega t \right] \\
&= \sqrt{3}E_m \left[\frac{-\sqrt{3}}{2}\cos \omega t - \frac{1}{2}\sin \omega t \right] \\
\therefore e_{cb} &= \sqrt{3}E_m \cos(\omega t + 150^0)
\end{aligned}$$

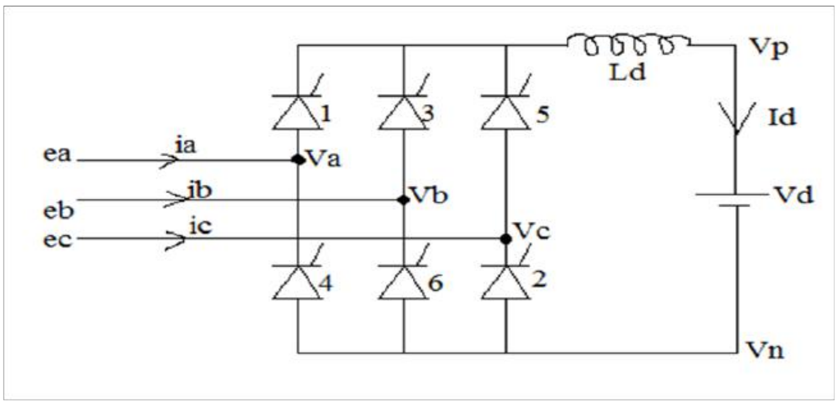
$$e_{cb} = E_m(\cos(\omega t - 180) - \cos(\omega t - 60^0))$$
$$= E_m(\cos\omega t.\cos 180^0 + \sin\omega t \sin 180^0 - \cos\omega t \cos 60^0 - \sin\omega t \sin 60^0)$$
$$= E_m\left[\frac{-3}{2}\cos\omega t - \frac{\sqrt{3}}{2}\sin\omega t\right]$$
$$= \sqrt{3}E_m\left[\frac{-\sqrt{3}}{2}\cos\omega t - \frac{1}{2}\sin\omega t\right]$$
$$\therefore e_{cb} = \sqrt{3}E_m\cos(\omega t + 150^0)$$

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.

Ie., 1,2 and 3 conducting.

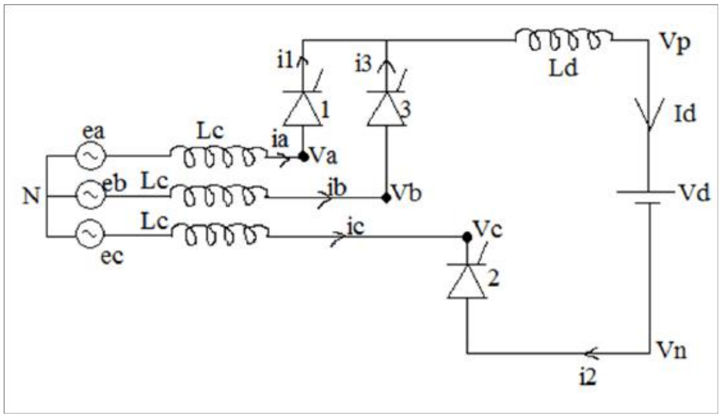
When only valve 1 and 2 conducting



$$i_a = -i_c = I_1 = I_2 = I_d$$
$$i_b = I_3 = I_4 = I_5 = I_6 = 0$$
$$V_a = V_p = e_a = E_m\cos(\omega t + 60^0)$$
$$V_b = e_b = E_m\cos(\omega t - 60^0)$$
$$V_c = V_n = e_c = E_m\cos(\omega t - 180^0)$$
$$V_d = V_p - V_n = e_a - e_c = e_{ac} = \sqrt{3}E_m\cos(\omega t + 30^0)$$
$$V_1 = V_2 = 0$$
$$V_3 = e_{ba} = \sqrt{3}E_m\sin\omega t$$
$$V_4 = V_n - V_p = -V_d$$
$$V_5 = V_n - V_p - V_d$$
$$V_6 = e_c - e_b = e_{cb} = \sqrt{3}E_m\cos(\omega t + 150^0)$$

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 emanation for the voltage and current are different and thus can be obtained as follows:



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 $i_1 = I_d$

$i_3 = 0$

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

At ωt = (α+μ) $i_1 = 0$

$i_3 = I_d$

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

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

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

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

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

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

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

At ωt = (α+μ);

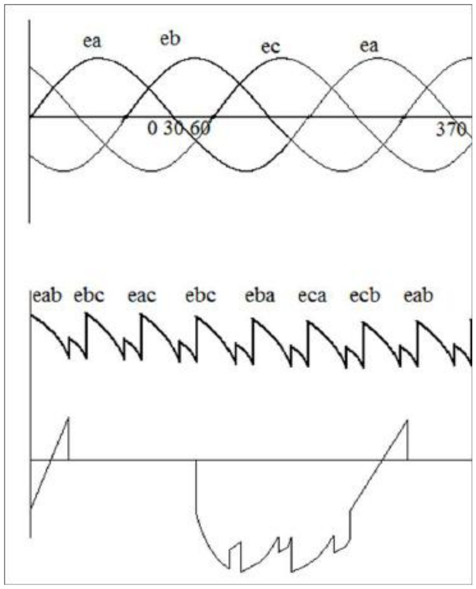
$$i_3 = I_d$$

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

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

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

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



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

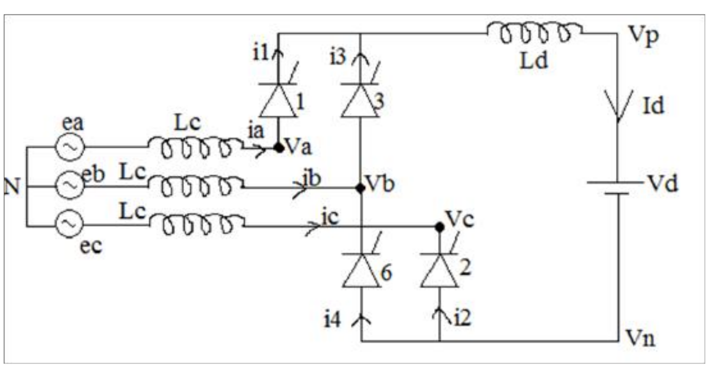
ii) Overlap Angle greater than 60 degrees:

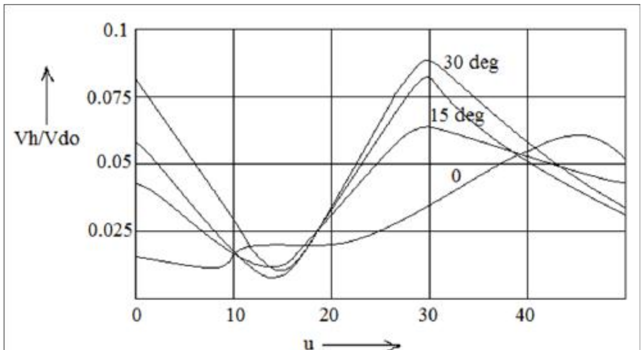
Overlap angle is in greater than 60 deg is abnormal, this will occur only at low alternating voltage.

In this case minimum no. of valves conducting are 3, and there are intervals when four valves are conducting.

This is because when commutation process started, the previous valves are not yet completed.

When four valves are conducting they constitute a three-phase short circuit on the ac source and a pole-to-pole short circuit on the dc terminals.





DC voltage harmonics with overlap

$$\frac{V_h}{V_{do}} = \left[\frac{1}{2}\left[C^2 + D^2 - 2CD\cos(2\alpha+\mu)\right]\right]^{\frac{1}{2}}$$

$$C = \frac{\cos(h+1)\frac{\mu}{2}}{h+1}$$

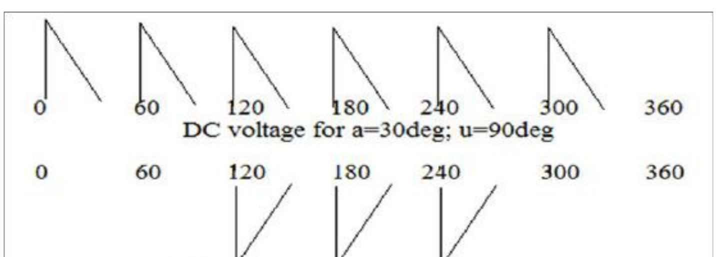
$$D = \frac{\cos(h-1)\frac{\mu}{2}}{h-1}$$

Equivalent circuit for four valve conduction

$$I_d = \frac{I_{s2}}{\sqrt{3}}\left(\cos\left(\alpha - 30^0\right) - \cos\left(\delta + 30^0\right)\right)$$

Average Direct voltage

$$V_d = V_{do}\left[\sqrt{3}\cos\left(\alpha - 30^0\right) - \frac{3}{2}\frac{I_d}{I_{s2}}\right]$$



Comparision of waveforms of Rectifiers and Inverters:

i) Rectifier average voltage across valve is negative, average voltage across inverter valve is positive.

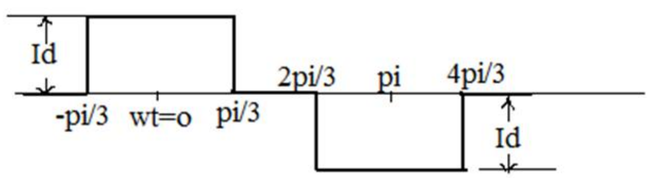
ii) Both rectifier and inverter modes of operation, the voltage across the valve is negative immediately after extinction of the arc, but in case of inverter valve voltage in negative much shorter duration than in the rectifier.

iii) In both modes of operation, voltage across valve is positive just before conduction begins, but in the rectifier it is positive for short duration than in the inverter

iv) Four minor voltage jumps per cycle, two of which are half as at ignition and other half of that at extinction.

AC current and DC voltage Harmonics:

The current waveform of the valve is distorted. The actual expression for the current can be derived from fourier analyses.



AC Current waveforms

The fundamental current, $I_1 = \left[I_{11}^2 + I_{12}^2 \right]^{1/2}$

where

$$I_{11} = I_1 \cos\phi = \frac{\sqrt{6}}{\pi} I_d \left[\frac{\cos\alpha + \cos(\alpha+\mu)}{2} \right]$$

$$I_{11} = I_1 \sin\phi = \frac{\sqrt{6}}{\pi} I_d \left[\frac{2\mu + \sin 2\alpha - \sin 2\delta}{4(\cos\alpha - \cos\delta)} \right]$$

where Φ is the power factor angle

$$\delta = \alpha + \mu$$

From the equations, the power factor angle is

$$\tan\phi = \frac{2\mu + \sin 2\alpha - \sin 2\delta}{\cos 2\alpha - \cos 2\delta}$$

$$\therefore \frac{I_h}{I_{ho}} = \frac{1}{2n}\left[A^2 + B^2 - 2AB\cos(2\alpha+\mu) \right]^{1/2}$$

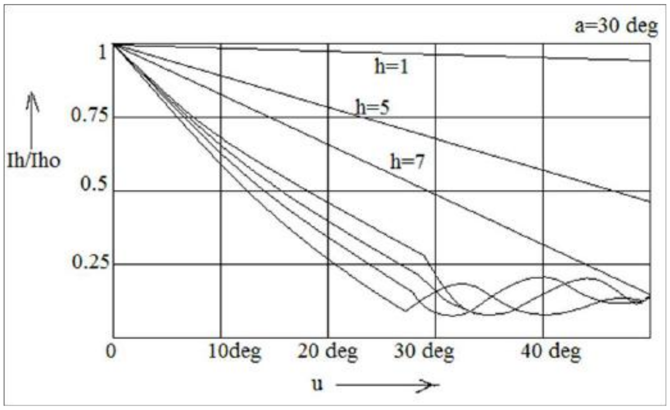
$$A = \frac{\sin(h+1)\frac{\mu}{2}}{h+1}, \quad B = \frac{\sin(h-1)\frac{\mu}{2}}{h-1}$$

$$n = \frac{1}{2}\left(\cos\alpha - \cos|\alpha+\mu|\right)$$

$$I_{ho} = \frac{\sqrt{6}}{\pi}\frac{I_d}{h}$$

Harmonic component with no overlap

From the fig all the harmonics especially of higher order, decreases sharply with increases of μ and the reduction factor lies in the range 0.1 to 0.2



The DC voltage harmonics are altered due to overlap is