Date 1/7/2015

Fundamentals of HVDC & FACTS devices

AC—[DC]—AC   AC—[AC]—AC

Corona
Interference
Skin effect

HVDC → high voltage Direct current
FACTS → Flexible ac transmission system

UNIT - I

Introduction

The industial growth of a nation requires increased consumption of energy, particularly electrical energy.

This has led to increase in generation & transmission facilities to meet the increasing demand.

The problems of AC transmission particularly in long distance transmission has led to the development of DC transmission

Generation and utilisation of energy AC is still economical & feasible, Transmission of electrical energy DC can be used.

AC—[DC]—AC
long distance bulk power

V. Imp.
14m

* **Comparision of AC & DC transmission:-** (or Advantages, comparision, differences.)

Depends on the following factors.

7m (i) Economics of Transmission / cost
7m (ii) Technical performance
(iii) Reliability

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(i) Economics of Transmission:-

* The cost of Transmission includes investment cost & Operational cost (cost of losses)

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* The investment cost includes cost of Transmission towers, insulators, conductors, technical equipment.

* The operational costs includes mainly cost of losses.

* No. of conductors required in AC are 3.
  No. of insulators required in AC are 3.
  No. of conductors required in DC are 2.
  No. of insulators required in DC are 2.

* Two conductor DC line can carry as much power as a three conductor AC line for same conductor size and voltage level.

Same conductor size = Same current

$$\boxed{I_d = I_a}$$

* power losses in dc line $(2I_d^2R)$ are less when compared power loss in ac $(3I_a^2R)$.
* Skin effect and corona are absent in DC line.

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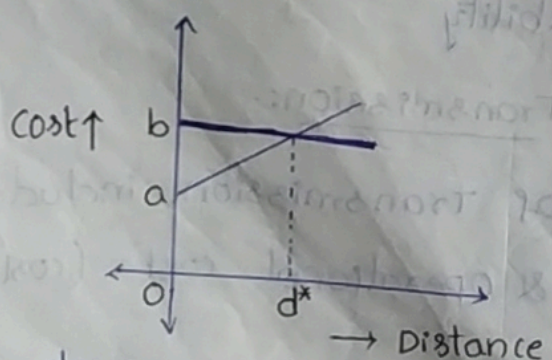
Terminal Equipment

AC	DC
Transformers	Transformers, converters, filters etc.
cost are fixed for given power transfer	costlier



Oa – Terminal equipment cost of ac line
Ob – Terminal equipment cost of DC line
d^* – break even distance

fig shows : variation of cost of transmission with distance for AC & DC transmission. AC tends to be more economical for distances less than break even distance & costlier for longer distances.

$d^* \rightarrow$ 500 - 800 km for over head lines
48 - 96 km for underground cables
24 - 48 km for submarine cables.

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(ii) Technical performance:

DC transmission has the following advantages over AC transmission.

(i) Full control over the power transmitted.
(ii) The ability to enhance Transient & dynamic stability in associated AC Networks.
(iii) Fast control to limit fault currents in DC lines.

In addition to this DC transmission overcomes some of the problems in AC transmission. They are as follows:

(i) Stability limit: (power transfer) (or) (power carrying capability)

power transfer in ac lines is dependent on the angle difference between the voltage phasors at the two ends.

For a given power level this angle increases with the distance.

$$P = \frac{E_1 E_2}{X} \sin\delta$$

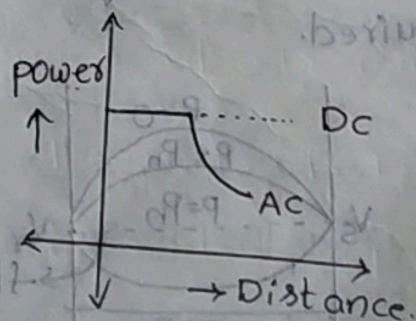


figure shows power carrying capability of DC line is unaffected by the distance let I_d = Current in each DC conductor

I_a = current in each ac conductor.

V_d = Voltage of a dc conductor

V_a = voltage of a ac conductor.

$\cos\phi$ = powerfactor of ac line

$I_d = I_a$ - for conductors of same size.

consider a 2 conductor dc line and 3 conductor ac line with same conductor size & insulation level.

power of a dc line,

$$P_d = 2 V_d I_d$$

power of a ac line,

$$P_a = 3 V_a I_a \cos\phi$$

$$\frac{P_d}{P_a} = \frac{2 V_d I_d}{3 V_a I_a \cos\phi} = \frac{2\sqrt{2} V_a I_d}{3 V_a I_a \cos\phi} = \frac{2\sqrt{2}}{3\cos\phi}$$

$$\cos\phi = 0.945$$

$$P_d = P_a$$

Two conductor dc line carry power ↑ is more, when compared to 3 conductor ac power. line (power factor < 0.945)
$(P_d > P_a)$

(ii) <u>Voltage</u> <u>control</u>:

Voltage control is not needed in case of dc lines, since the voltage drop is due to only resistance.

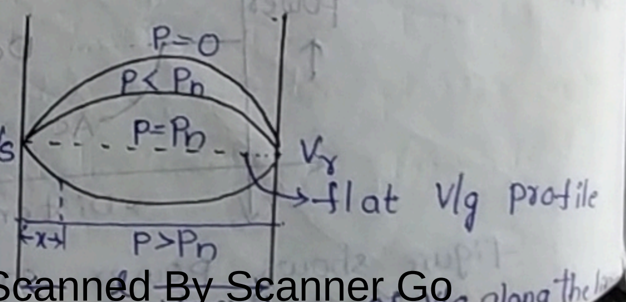
In case of ac lines voltage control as load varies is required.

l = length of the line

x = distance from the

P_n - surge impedance loading $= \frac{|V|^2}{Z_0}$

$(|V_s| = |V_r| = |V|)$



variation of V/g along the line

P - actual (loading) Power flow.

Swing curves – ac ∴ $P < P_n$ reactive power absorption
flat – dc ∴ $P > P_n$,, ,, injection

(iii) <u>compensation:</u>

AC line requires shunt and series compensation.
No such compensation is required in case of dc lines.

(iv) <u>problems</u> <u>of</u> <u>AC</u> <u>Interconnection:</u> (SCADA in ac line supervisory control and data acceleration)

when two power systems are connected by ac lines it is called as synchronous inter-connection. The problems are

(i) presence of large power oscillations which ~~has~~ can lead to frequent tripping.

Telephone interference

(ii) Increase in fault level.

(iii) Transmission of disturbances from one system to other coordinated control of interconnected systems is needed.

The controllability of power flow in dc line eliminates all the above problems.

AC — AC
synchronous

AC — DC — AC
HVDC
Asynchronous

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(v) <u>Ground</u> <u>Return:-</u>

In AC lines the Ground is not used as Return because

i) The Impedance Offered by it is high.

ii) Interference with communication lines.

In DC lines, when ground is used as a return path, the following advantage is there

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In a 2 conductor dc line if there is a fault on one conductor power can be transferred using other healthy conductor & ground.

(iii) **Reliability:** (probability of success / failure)

The reliability of DC transmission system is quite good & comparable to that of AC systems.

performance of thyristor values is much more reliable than mercury arc values.

There are two measures for overall system Reliability.

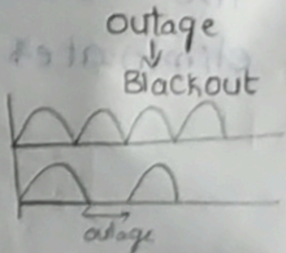
(i) Energy availability
(ii) Transient Reliability

(i) **Energy availability:-**

$$E.A = 100\left[1 - \frac{\text{equivalent outage time}}{\text{total time}}\right]\%$$

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

Interruption in ac cycle or dc. Short (period) is called outage. in interval of time



(ii) **Transient Reliability:-**

$$T.R = \frac{100 \times \text{No. of times HVDC system performed as designed}}{\text{No of recordable AC faults}}$$

Recordable AC faults are those faults which cause one (or) more AC bus phase v/g's to drop below 90% of the voltage prior to the fault

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Both energy availability & Transient reliability of existing DC systems with thyristor values is 95%. (or) more.

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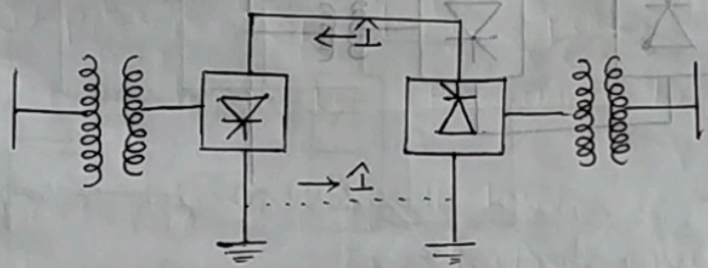
Types of DC links: (Asynchronous)

(i) Monopolar link
(ii) Bipolar link
(iii) Homopolar link

(i) Monopolar link:

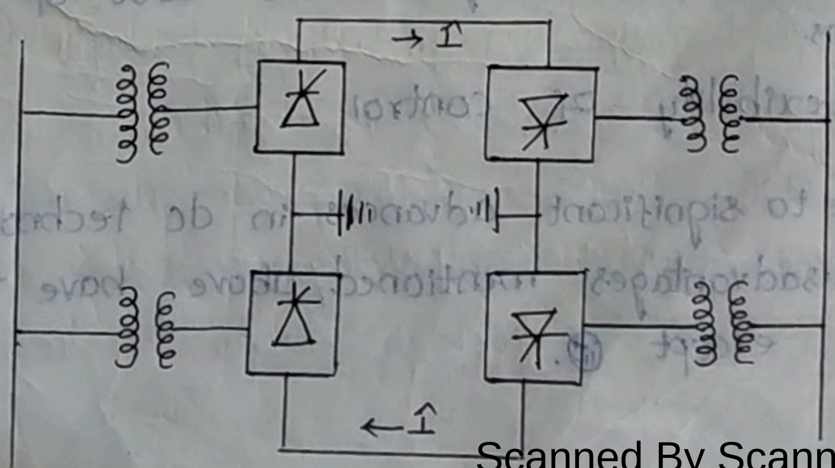
It has one conductor usually of negative polarity & uses ground (or) Sea as return path.
- Sometimes metallic return is also used.



(ii) Bipolar link:

It has two conductors one positive and other negative. Each may be double conductor in EHV (Extra high voltage) lines. Each terminal has two sets of converters of identical ratings in series on DC side.

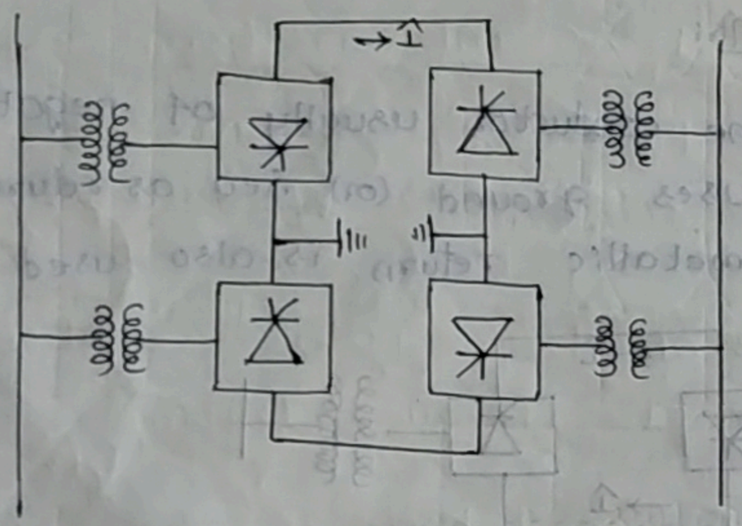
The junction between two sets of converters is grounded at one end (or) both the ends.



Both poles operate at equal currents & hence there is zero ground current flowing under these conditions.

(iii) Homopolar link:-

It has two (or) more conductors all having the same polarity usually negative. And always operated with ground (or) metallic return.



Corona less with -ve polarity compare +ve polarity

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Disadvantages of DC transmission:

(i) The difficulty of breaking DC currents which results in high cost of DC breakers.

(ii) Inability to use transformers to change v/g levels.

(iii) High cost of conversion equipment.

(iv) Generation of Harmonics which requires AC & DC filters adding to the cost of converter stations.

(v) complexibility of control.

Due to significant advances in dc technology all the disadvantages mentioned above have tried to overcome except (ii).

(i) Development of DC breakers.

(ii) Modular construction of thyristor value.

(iii) Increase in the ratings of cells that make up a value.

(iv) Twelve pulse operation of converters.

(v) Use of metaloxide, gapless arresters.

(vi) Application of Digital electronics & fibre optics in control of converters.

Some of these advances has improves the reliability and reduce the cost of conversion equipment.

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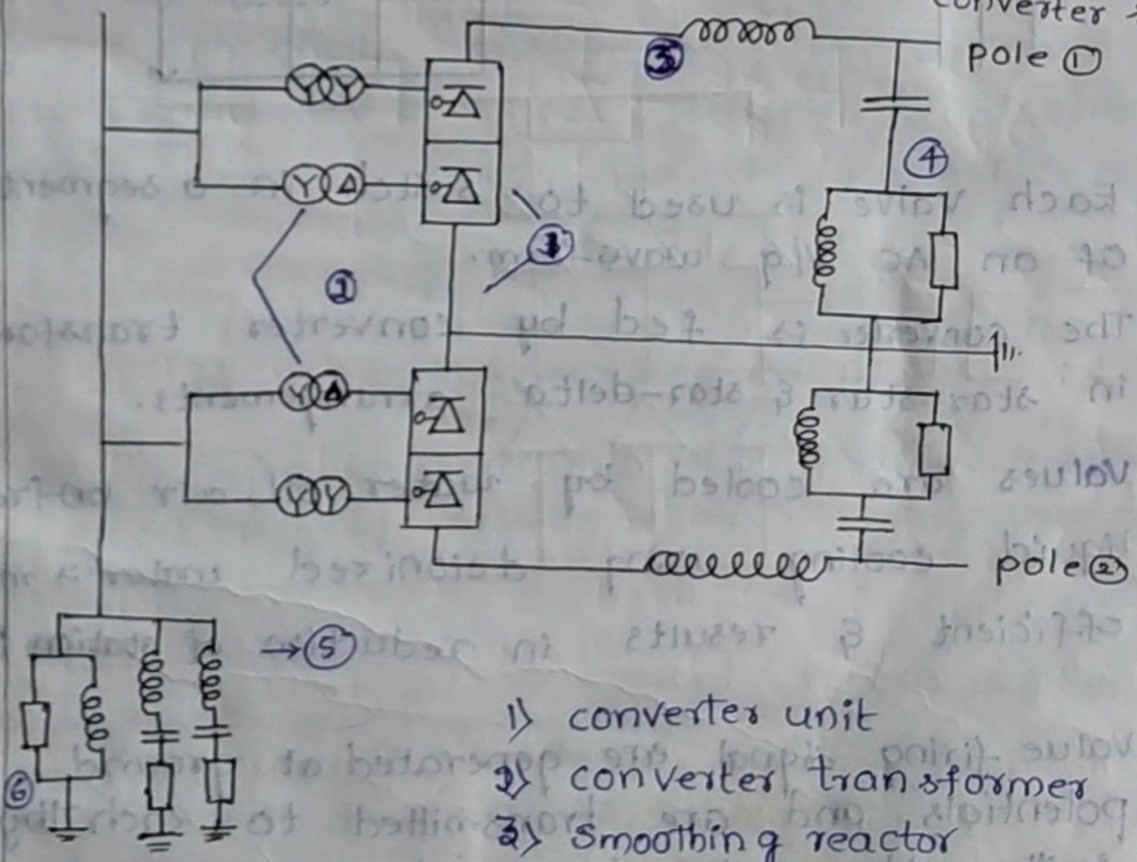
#7115 **Typical layout of a HVDC converter station:-**

major components in a HVDC converter station



1) converter unit

2) converter transformer

3) Smoothing reactor

4) DC filter

5) Tuned AC filters

6) Highpass AC filters.

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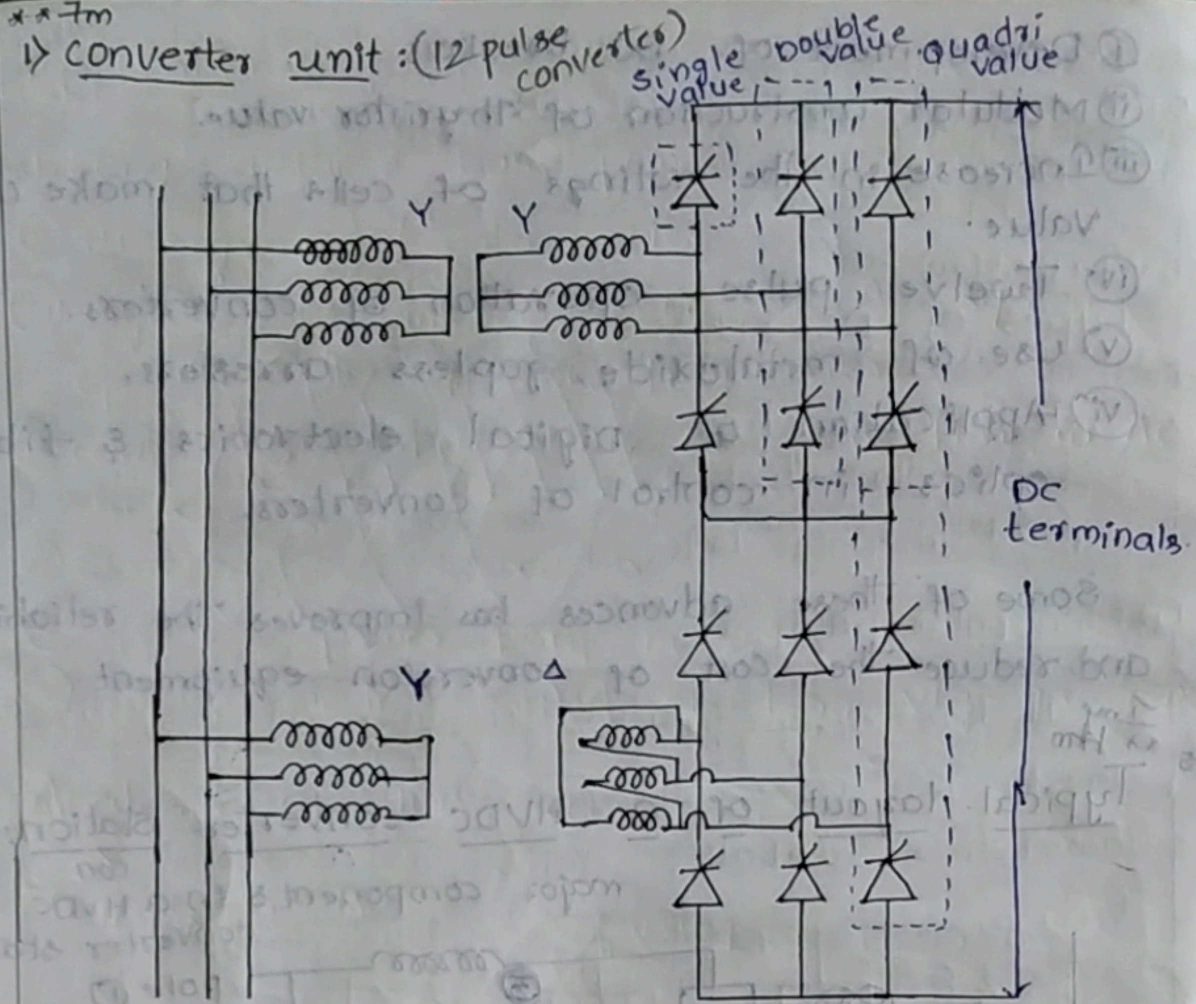
1) Converter unit : (12 pulse converter)



- Each valve is used to switch in a segment of an AC v/g waveform.
- The converter is fed by converter transformers in star-star & star-delta arrangements.
- Values are cooled by water, oil, air (or) freon
- liquid cooling using deionized water is more efficient & results in reduction of station loses.
- Value firing signal are generated at ground potentials and are transmitted to each thyristor in the value group through fiber optics. light signal.
- light signal is converted to electrical signal using gate drive amplifier and pulse T/f.
- Values are protected by using snubber ckt as well as and Zince oxide gapless surge arresters.

under ground cables are prefered for light signals

LTT (light

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2) converter Transformer: (diagram compulsory)

converter Transformer can have different configurations.

(i) Three phase two winding
(ii) single phase two winding
(iii) Single phase three winding

The value side windings are connected in Y and Δ with neutral point undergrounded on the AC side the transformers are connected in parallel with neutral grounded. The leakage reactance of the transformer is choosen to find short circuits. currents through any value.

- The converter transformers are designed to with stand the DC voltage stresses & increased eddy current losses due to harmonic currents.

3) Smoothing reactor:

It is connected between dc line & dc filter.

It is used to smoothen dc current & provide protection by limiting short circuit currents.

4) Filters:

There are two types of filters

(i) AC filters are used to filter out harmonics of ac
(ii) DC filters are used to filter out harmonics of dc

High frequency filters are used to supress high frequency surges.

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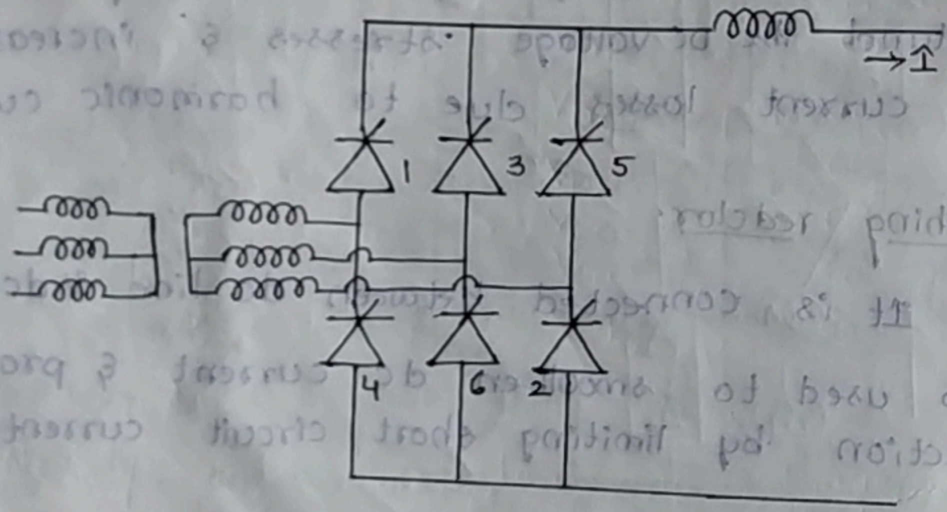
Applications:

(i) Long distance bulk power transmission.
(ii) underground / water cables.
(iii) synchronous interconnection of AC system operating at different frequencies.
(iv) control & stabilization of power flow in AC tie lines.
(v) Simple line construction
(vi) Greater power per conductor.
(vii) cable can be worked at high v/g gradients.

Analysis of HUDC converters:

Graetz circuit: ⇒ six pulse converter ⇒ 3ϕ full bridge converter



- The conversion from AC to DC & DC to AC is done in HVDC converter stations by using 3ϕ bridge converters.
- The configuration of the bridge also called as "Graetz circuit"
- It is a six pulse converter
- 12 pulse converter consists of two 3ϕ bridges connected in series.
- No.of pulsation (no.of cycles ripple) of direct v/g per cycle of alternating voltages

A commutation group is defined as group of values in which only one thyristor conducts at a time. If there are 'q' values competition in commutation ground and all are them are connected in parallel, r of them s in series.

Then the pulse no. is given by

$$\boxed{p = qrs} = 3 \times 2 \times 1 = 6$$

No of thyristor, series, parallel

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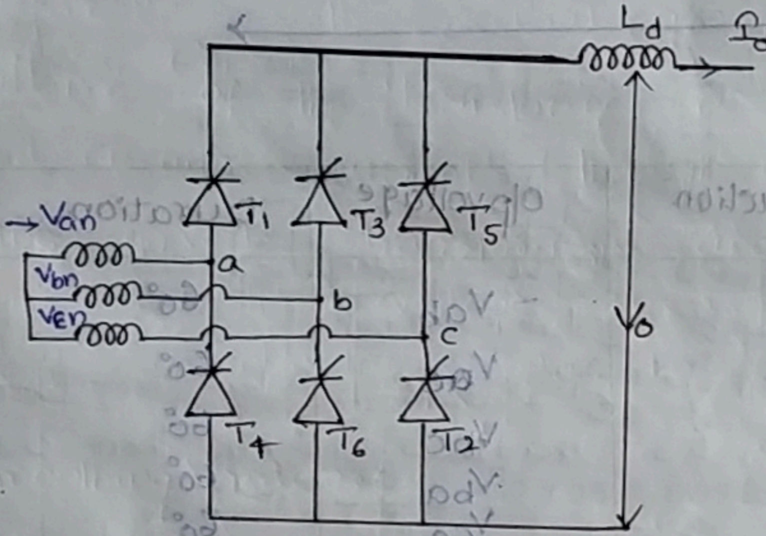
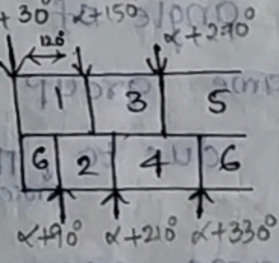
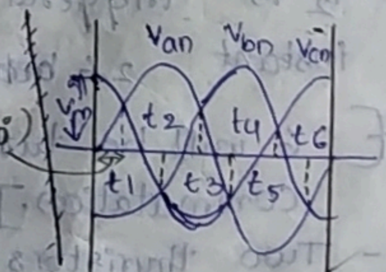


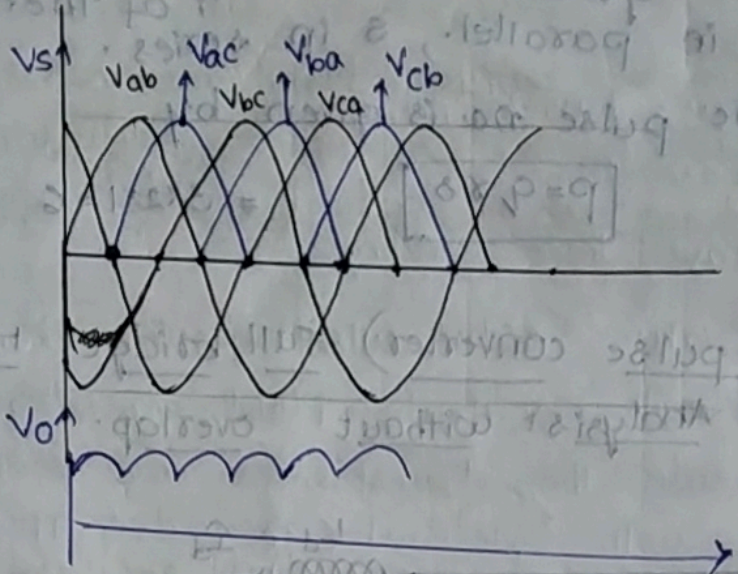
- The thyristor values are six in number and are connected as shown.
- The values are fired in the sequence according to their numbering. period of conductor for each thyristor is 120°
- Each thyristor is thyristor triggered at an angle of 60°





- Thyristors are divided into upper half group as well as the lower half group.
- upper half group (T_1, T_3, T_5) as +ve group and lower half group (T_4, T_6, T_2)

- T_1, T_3, T_5 are firing instants for +ve group of thyristors.
- T_4, T_6, T_2 are firing instants for -ve group of thyristors.



Thyristor conduction	O/p voltage	Duration
T_1, T_6	V_{ab}	$60°$
1, 2	V_{ac}	$60°$
3, 2	V_{bc}	$60°$
3, 4	V_{ba}	$60°$
5, 4	V_{ca}	$60°$
5, 6	V_{cb}	$60°$

- Already T_6 is conduction, T_1 is triggered at an angle of $\alpha+30°$. so at this instant 1, 6 are in conduction.
- T_2 is triggered at an angle of $\alpha+90°$. So at this instant 2, 6 belongs to same group.
[6 will be turn off due to the natural process commutation.]
- Two thyristors of same group comes into conduction i.e. closed loop is formed due to short ckt currents flows.
- In that short ckt current reverse current flows due to thyristor turn ON.

Average o/p voltage $V_0 = \frac{1}{T}\int_{T_{ON}}^{T_{OFF}} V_S \, dt$

$V_{an} = V_m \sin\omega t$

$V_{bn} = V_m \sin(\omega t - 120)$

$V_{cn} = V_m \sin(\omega t - 240)$

$V_{ab} = V_{an} - V_{bn} = \sqrt{3} V_m \sin(\theta + 30^\circ) = \sqrt{3} V_m \sin(\omega t + 30^\circ)$

$$V_0 = \frac{1}{\frac{\pi}{3}} \int_{\alpha+30^\circ}^{\alpha+90^\circ} \sqrt{3} V_m \sin(\omega t + 30^\circ) \, d(\omega t)$$

$$= \frac{3\sqrt{3} V_m}{\pi} \left[-\cos(\omega t + 30^\circ)\right]_{\alpha+30^\circ}^{\alpha+90^\circ}$$

$$= \frac{3\sqrt{3} V_m}{\pi} \left[-\cos(\alpha + 90^\circ + 30^\circ) + \cos(\alpha + 30^\circ + 30^\circ)\right]$$

$$= \frac{3\sqrt{3} V_m}{\pi} \left[-\cos(\alpha + 120^\circ) + \cos(\alpha + 60^\circ)\right]$$

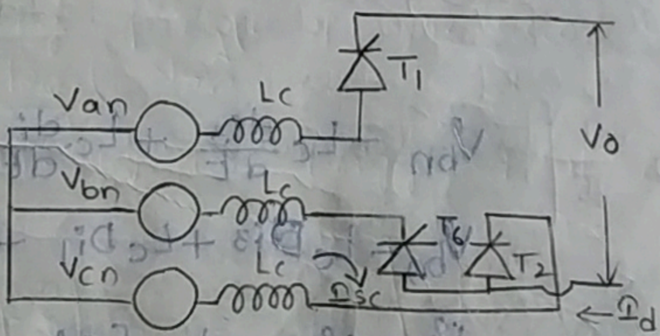
$\alpha < 90^\circ$ $V_0 = \frac{3\sqrt{3} V_m}{\pi} \left[-\cos(180^\circ + (\alpha + 60^\circ)) + \cos(\alpha + 60^\circ)\right]$

$$= \frac{3\sqrt{3} V_m}{\pi} \left[\cos(\alpha + 60^\circ) + \cos(\alpha - 60^\circ)\right]$$

$\alpha > 90^\circ$ $V_0 = \frac{3\sqrt{3} V_m}{\pi} \left[2 \cos\alpha \cdot \cos 60^\circ\right]$

$$\boxed{V_0 = \frac{3\sqrt{3} V_m}{\pi} \cos\alpha.}$$

Inverter $V_0 = -\frac{3\sqrt{3} V_m}{\pi} \cos\alpha.$



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Analysis of 3 phase bridge circuit with Overlap: (Effect of source inductance) ($u < 60^\circ$) overlap angle.

(3 value conduction mode)

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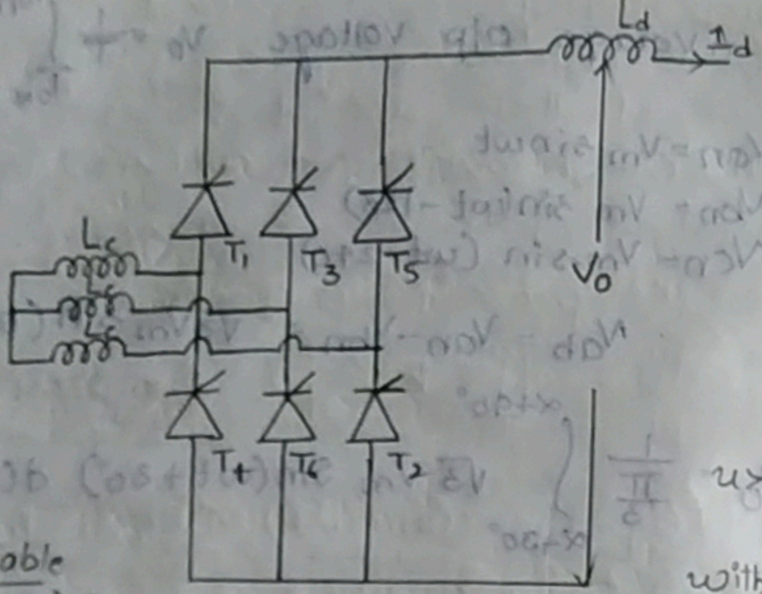

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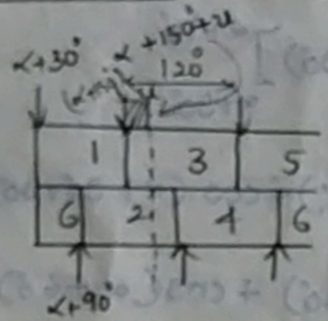


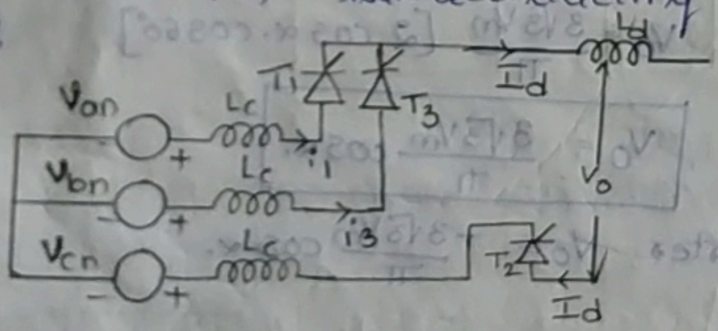
$u > 60°$ - 4 value conduction

$(u < 60)$

with overlap - 3 value conduction

without over lap - Two value conduction

→ consider 1, 2 are in conduction 3 is trigger at an angle of $\alpha + 150°$ value 1 doesn't stop conduction due to leakage inductance of the Transformer. Then values 1, 3, 2 should be conducting then overlap $u < 60°$



$I_d = i_1 + i_3$

without overlap

$I_d = i_3$.

$$V_{bn} - L_c \frac{di_3}{dt} + L_c \frac{di_1}{dt} - V_{an} = 0$$

$$V_{bn} - L_c Di_3 + L_c Di_1 - V_{an} = 0$$

$$V_{bn} - V_{an} = L_c [Di_3 - Di_1]$$

$$V_{bn} - V_{an} = L_c [Di_3 - D(I_d - i_3)]$$

$$V_{ba} = 2L_c Di_3$$

$$Di_3 = \frac{V_{ba}}{2L_c} \quad \text{--- (1)}$$

Integrating on both sides $\left[\because V_{ba} = \sqrt{3} V_m \sin(\omega t+30^\circ)\right.$
$\left. V_{ba} = -V_{ab}\right]$

$$\int D i_3 = \int \frac{V_{ba}}{2L_c}\, dt$$

$$i_3 = \frac{1}{2L_c}\int -\sqrt{3} V_m \sin(\omega t+30^\circ)\, dt$$

$$i_3 = +\frac{\sqrt{3}V_m}{2}\,\frac{[\cos(\omega t+30^\circ)+k]}{\omega L_c}$$

$$i_3 = \frac{\sqrt{3}V_m}{2\omega L_c}\cos(\omega t+30^\circ) + \underbrace{K}_{\text{Auxiliary constant}} \quad \text{--- (2)}$$

$K - ? \Rightarrow i_3 = 0$

$\omega t = \alpha + 150^\circ$ $\qquad \alpha + 150^\circ + u.$

At the begining of overlap.

$$0 = \frac{\sqrt{3}V_m}{2\omega L_c}\cos(\alpha+150+30) + K$$

$$K = \frac{-\sqrt{3}V_m}{2\omega L_c}\cos(\alpha+180)$$

$$K = \frac{\sqrt{3}V_m}{2\omega L_c}\cos\alpha.$$

$$i_3 = \frac{\sqrt{3}V_m}{2\omega L_c}\cos(\omega t+30^\circ) + \frac{\sqrt{3}V_m}{2\omega L_c}\cos\alpha$$

$$i_3 = \frac{\sqrt{3}V_m}{2\omega L_c}\left[\cos(\omega t+30^\circ) + \cos\alpha\right] \quad \text{--- (3)}$$

$$i_1 = I_d - i_3$$

At the end of over lap $\qquad \omega t = \alpha + 150 + u$
$\qquad\qquad = \delta + 150^\circ$

$$0 = \frac{\sqrt{3}V_m}{2\omega L_c}(\cos(\delta+150+30) + K$$

$$K = \frac{-\sqrt{3}V_m}{2\omega L_c}\cos(\delta+180) \qquad K = \frac{-\sqrt{3}V_m}{2\omega L_c}\cos(\delta+180)$$

$$K = \frac{\sqrt{3}V_m}{2\omega L_c}\cos\delta. \qquad K = +\frac{\sqrt{3}V_m}{2\omega L_c}\cos\delta$$

$[\because \delta = \alpha + u]$

$$i_3 = \frac{\sqrt{3}V_m}{2\omega L_c}\left[\cos\alpha - \cos\delta\right] \quad \text{--- (4)}$$

$$i_3 = I_d$$

Average output voltage (V_0) =

$$V_0 = V_{bn} - L_c \frac{di_3}{dt} - v_{cn} = V_{bn} - L_c Di_3 - V_{cn}$$

$$V_0 = V_{bc} - \cancel{L_c} \cdot \frac{V_{ba}}{2\cancel{L_c}}$$

$$V_0 = V_{bc} - \frac{V_{ba}}{2}$$

$$V_{bc} = V_{bn} - V_{cn} = V_m \sin(\omega t - 120) - V_m \sin(\omega t - 240)$$

$$= V_m \sin(\omega t - 120) - V_m \sin(\omega t + 120)$$

$$= V_m [\sin(\omega t - 120^\circ) - \sin(\omega t + 120^\circ)]$$

$$= V_m [\cancel{\sin \omega t \cdot \cos 120^\circ} - \cos \omega t \cdot \sin 120^\circ - \cancel{\sin \omega t \cdot \cos 120^\circ} - \cos \omega t \cdot \sin 120^\circ]$$

$$V_{bc} = V_m [-\cancel{2}\cos \omega t \cdot \frac{\sqrt{3}}{\cancel{2}}]$$

$$V_{bc} = -\sqrt{3} V_m \cos \omega t$$

$$V_{bc} = +\sqrt{3} V_m \sin(\omega t - 90^\circ)$$

$$V_0 = V_{bc} - \frac{V_{ba}}{2}$$

$$V_0 = \sqrt{3} V_m \sin(\omega t - 90^\circ) - \frac{1}{2}(-\sqrt{3} V_m \sin(\omega t + 30^\circ))$$

$$V_0 = \sqrt{3} V_m \sin(\omega t - 90^\circ) + \frac{\sqrt{3} V_m \sin(\omega t + 30)}{2}$$

$$\left[V_0 = \frac{1}{T}\int v_s \, dt\right]$$

$$V_0 = \frac{1}{\frac{\pi}{3}}\left[\sqrt{3} V_m \int_{\alpha+150^\circ}^{\alpha+210^\circ} \sin(\omega t - 90^\circ)\, d(\omega t) + \frac{\sqrt{3}}{2} V_m \int_{\alpha+150^\circ}^{\alpha+150^\circ+u} \sin(\omega t + 30^\circ)\, d(\omega t)\right]$$

$$V_0 = \frac{1}{\frac{\pi}{3}}\left[\sqrt{3} V_m \int_{\alpha+150}^{\alpha+210^\circ} \sin(\omega t - 90^\circ)\, d(\omega t) + \frac{\sqrt{3} V_m}{2} \int_{\alpha+150^\circ}^{\delta+150^\circ} \sin(\omega t + 30^\circ)\, d(\omega t)\right]$$

$$V_0 = \frac{\sqrt{3} V_m}{\frac{\pi}{3}} \int_{\alpha+150}^{\alpha+210^\circ} \left[\sin(\omega t - 90^\circ)\, d(\omega t) + \frac{1}{2} \int_{\alpha+150^\circ}^{\delta+150^\circ} \sin(\omega t + 30^\circ)\, d(\omega t)\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[\left[-\cos(\omega t-90^\circ)\right]_{\alpha+150^\circ}^{\alpha+210^\circ} + \frac{1}{2}\left[-\cos(\omega t+30^\circ)\right]_{\alpha+150^\circ}^{\delta+150^\circ}\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[-\cos(\alpha+120^\circ)+\cos(\alpha+60^\circ)+\frac{1}{2}\left[\cos(\delta+180^\circ) - \cos(\alpha+180^\circ)\right]\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[-\cos(180^\circ+(\alpha-60^\circ))+\cos(\alpha+60^\circ)+\frac{1}{2}\left[\cos(\delta+180^\circ)-\cos(\alpha+180^\circ)\right]\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[+\cos(\alpha-60^\circ)+\cos(\alpha+60^\circ)+\frac{1}{2}\left(\cos(\delta+180^\circ)-\cos(\alpha+180^\circ)\right)\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[2\cos\alpha\cdot\cos 60^\circ + \frac{1}{2}\cos\delta - \frac{\cos\alpha}{2}\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[\cancel{2}\cos\alpha\cdot\frac{1}{\cancel{2}} + \frac{1}{2}\cos\delta - \frac{1}{2}\cos\alpha\right]$$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}\left[\cos\alpha - \frac{1}{2}\cos\alpha + \frac{1}{2}\cos\delta\right]$$

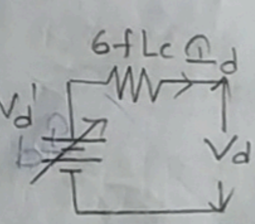
$$V_0 = \frac{3\sqrt{3}V_m}{2\pi}\left[\cos\alpha + \cos\delta\right]$$

Equivalent circuit of Rectifier: $(\alpha < 90^\circ)$

$$V_d = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha - \frac{3\sqrt{3}V_m}{\pi}\left[\frac{\cos\alpha - \cos\delta}{2}\right]$$

$$V_d = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha - \frac{3\sqrt{3}V_m}{2\pi}\left[\cos\alpha - \cos\delta\right]$$

$$V_d = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha - \frac{3\sqrt{3}V_m}{\cancel{2}\pi}\cdot\frac{\cancel{2}\omega L_c I_d}{\sqrt{3}V_m}$$



$$V_d = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha - 6fL_c I_d$$

$$V_d = V_d' - 6fL_c I_d$$

$$\boxed{V_d = V_{do}\cos\alpha - R_c I_d}$$

$6fL_c = V_d' - R_c I_d$

$R_c = \frac{3\omega L_c}{\pi}$ (or) $6fL_c$

V_d' = Average o/p voltage without overlap.

***

$$Di_3 = \frac{V_{ba}}{2L_c}$$

$$i_3 = \frac{\sqrt{3}V_m}{2\omega L_c}[\cos\alpha - \cos\delta] - I_d$$

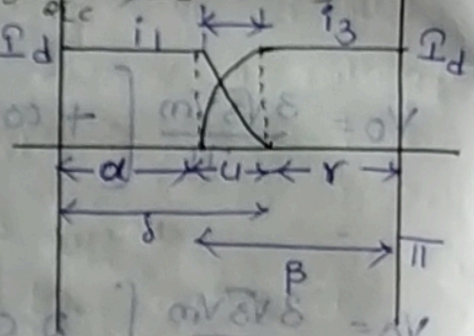
$$V_0 = \frac{3\sqrt{3}V_m}{2\pi}[\cos\alpha + \cos\delta]$$

13th

* **Inverter equation:** ($\alpha > 90^\circ$)

→ Ckt diagram (six pulse operation $u < 60^\circ$)

[$Di_3 = \frac{V_{ba}}{2L_c}$, $I_d = i_3$, V_d]



For a converter with overlap 'u' less than 60° ($u < 60^\circ$), the mean dc o/p voltage is given by

$$V_d = \frac{3\sqrt{3}V_m}{\pi}\left[\frac{\cos\alpha + \cos\delta}{2}\right]$$

$$\delta = \alpha + u.$$

For an inverter V_{d_i} = '−ve' of V_d

$$= -\frac{3\sqrt{3}V_m}{2\pi}[\cos\alpha + \cos\delta]$$

Inverter
- $\beta = \pi - \alpha$
- β = advance firing angle
- $\gamma = \pi - \delta = \pi - (\alpha + u)$

γ = Extension angle

Rectifier α = firing angle.

$$V_{d_i} = -\frac{3\sqrt{3}V_m}{2\pi}[\cos(\pi - \beta) + \cos(\pi - \gamma)]$$

$$V_{d_i} = +\frac{3\sqrt{3}V_m}{\pi}\left[\frac{\cos\beta + \cos\gamma}{2}\right] \quad \text{— (1)}$$

$$I_d = \frac{\sqrt{3}V_m}{2\omega L_c}[\cos\alpha - \cos\delta]$$

$$I_d = \frac{\sqrt{3}V_m}{2\omega L_c}[\cos(\pi - \beta) + \cos(\pi - \gamma)] \quad \left[\because I_s = \frac{\sqrt{3}V_m}{2\omega L_c}\right]$$

$$I_d = I_s[\cos\gamma - \cos\beta] \quad \text{— (2)}$$

14/7/15

$$V_{di} = V_{doi}\left[\frac{\cos\beta+\cos\gamma}{2}\right] \quad -(1)$$

$$V_{doi} = \frac{3\sqrt{3}\,V_m}{\pi}$$

$$\frac{I_d}{I_s} = \left[\cos\gamma - \cos\beta\right] \quad -(2) \qquad I_s = \frac{\sqrt{3}\,V_m}{2\omega L_c}$$

Interms of β:

From (2) $\cos\gamma = \cos\beta + \frac{I_d}{I_s}$

substituting this value in (1)

$$V_{di} = \frac{V_{doi}}{2}\left[\cos\beta + \cos\beta + \frac{I_d}{I_s}\right]$$

$$V_{di} = \frac{V_{doi}}{2}\left[2\cos\beta + \frac{I_d}{I_s}\right]$$

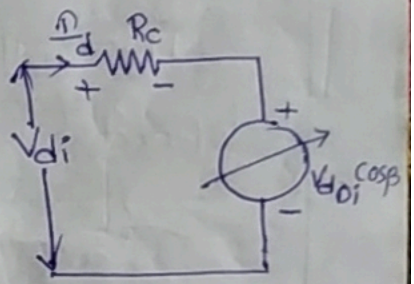
$$= V_{di}\cos\beta + \frac{V_{doi}}{2} \times \frac{I_d}{I_s}$$

$$= V_{doi}\cos\beta + \frac{3\sqrt{3}V_m}{2\pi} \times \frac{I_d}{\sqrt{3}V_m}\cdot 2\omega L_c$$

$$= V_{doi}\cos\beta + \left(\frac{3\omega L_c}{\pi}\right) I_d$$

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

Equivalent circuit



Without overlap

$$\left[\therefore I_d = \frac{\pi}{\sqrt{6}} I_s \text{ or } \frac{\pi}{\sqrt{6}} I_L\right]$$

Interms of $\cos\gamma$:

$$\cos\beta = \cos\gamma - \frac{I_d}{I_s}$$

substituting this value in (1)

$$V_{di} = \frac{V_{doi}}{2}\left[\cos\gamma - \frac{I_d}{I_s} + \cos\gamma\right]$$

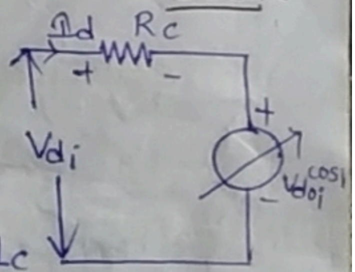
$$V_{di} = \frac{V_{doi}}{2}\left[2\cos\gamma - \frac{I_d}{I_s}\right]$$

$$V_{di} = V_{doi}\cos\gamma - \frac{V_{doi}}{2} \times \frac{I_d}{I_s}$$

$$= V_{doi}\cos\gamma - \frac{3\sqrt{3}V_m}{2\pi} \times \frac{I_d}{\sqrt{3}V_m}\, 2\omega L_c$$

$$V_{di} = V_{doi}\cos\gamma - R_c I_d$$

Equivalent circuit



$V_d = V_{d0} \cos\alpha - R_c I_d$ Rectifier

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

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

Graetz circuit is universally used for HVDC transmission. the reasons are:

1. PIV is less
2. Requires less transformer secondary rating.
3. Simplest transformer connection
4. power ratings of values is lower.
5. Secondary windings may be connected
6. Either in Y (or) Δ.