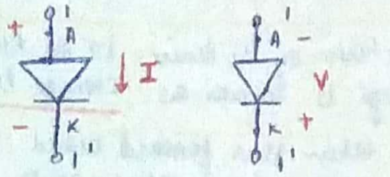
# Power Electronics

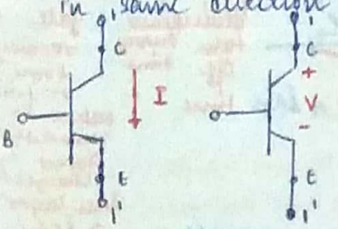
## Switches :

→ Diode blocks voltage of opp. polarity or in reverse direction. (One quadrant)

(current Always flows in A to K direction)

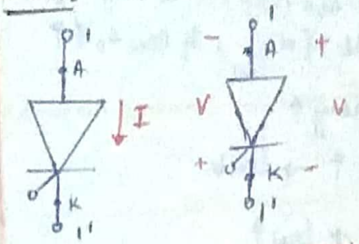



→ BJT block voltage of same polarity or in same direction. (One quadrant)




→ Same is the case for MOSFET and IGBT.

### → SCR :




→ SCR can develop blocking voltage in both direction +ve and -ve.

→ It is bipolar unidirection

→ Two quadrant switch.

→ Operates in R.B.M (OFF), F.B.M (OFF), F.C.M (ON).

→ In F.C.M and F.B.M, $J_1, J_3$ → S.C or F.B; $J_2$ → O.C or R.B.

→ Half controlled device.

→ When the S.C.R is conducting or in F.C.M then the junction $J_2$ breaks down but it is not getting forward biased.

→ at R.B.M, $I_{AK} = 0$ $V_{AK} = -V$

at F.B.M, $I_{AK} = 0$ $V_{AK} = +V$

at F.C.M, $I_{AK} = +ve$, $V_{AK} = 0$. (∵ S.C hoga diode).

→ VBO (Forward Break over voltage or forward break down voltage) is always specified by manufacture

→ VBO is the final voltage rating of the S.C.R

→ Under Gate Triggering : $q = I_g \times t$

$I_g \propto \frac{1}{VBO}$

$I_g \propto \frac{1}{\text{Depth in layer}}$

$\frac{dv}{dt}$ Triggering : Same voltage across capacitor ke sath time ka change hota hai. Here $V = V_{AK}$.

$\frac{dv}{dt} = I_{charging} \times \frac{1}{C_j}$

→ $\frac{dv}{dt}$ is always related with noise signal not with the actual supply voltage.

→ $I_{charging} > I_L$ (Latching current) ⇒ SCR-ON

→ $\left(\frac{dv}{dt}\right)_{operated} > \left(\frac{dv}{dt}\right)_{specified}$ ⇒ SCR-ON

] main condition to fulfill the ON of SCR.

→ $I_{AK} > I_L$ → SCR ON

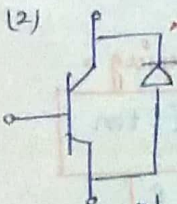
→ $I_{AK} < I_H$ → SCR OFF

→ $t_{ON}$ (Pulse width) = $\frac{L \times \text{Inductor current}}{\text{Source voltage}}$

## Two Quadrant Example :

(1) SCR

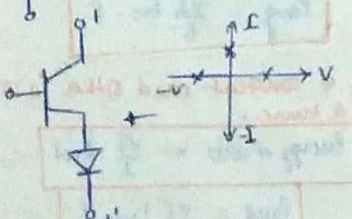
(2)



(voltage source Inverter me application)

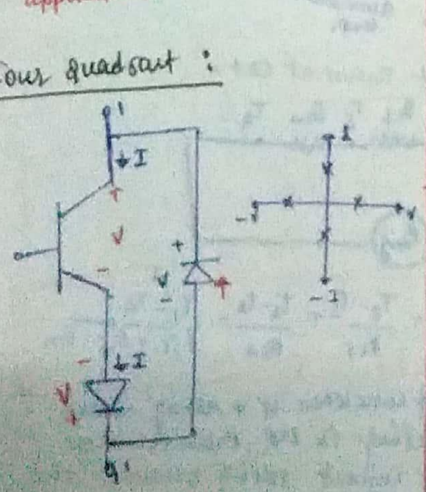
Similarly with MOSFET and IGBT.

(3)




(current source Inverter me application)

## Four Quadrant :




→ Bipolar

→ Bidirectional

## Switching characteristics during Turn ON Process :-

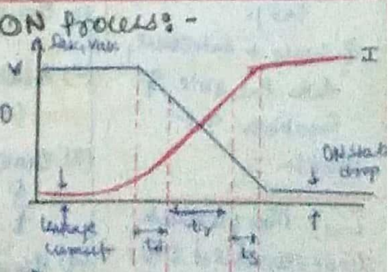
→ SCR (OFF) —TURN ON PROCESS→ SCR (ON)

$V_{AK}$ → max, $I_{AK}$ → zero/min

$V_{AK}$ → Min or 0, $I_{AK}$ → max

→ $T_{ON} = t_d + t_r + t_s$

($t_d$ = delay time, $t_r$ = rise time, $t_s$ = Spread time)




Switching characteristics during Turn ON Process

$t_{ON} = t_d + t_r + t_s$

→ $t_r$ is most dominating, and to Reduce $t_{ON}$, we need to Reduce $t_r$ and that can be done by controlling $\left(\frac{di}{dt}\right)$. As $f \propto \frac{1}{t_{ON}}$, if $t_{ON}\downarrow$, $f\uparrow$ and switching frequency ↑.

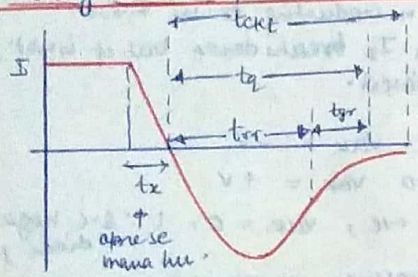
→ high $\left(\frac{di}{dt}\right)$ → $f\uparrow$ → $t_{ON}\downarrow$

→ low $\left(\frac{di}{dt}\right)$ → $f\downarrow$ → $t_{ON}\uparrow$

But if $\left(\frac{di}{dt}\right)_{operated} > \left(\frac{di}{dt}\right)_{specified}$ → SCR damage

if $\left(\frac{di}{dt}\right)_{operated} < \left(\frac{di}{dt}\right)_{specified}$ → SCR will be safe.

→ During rise time, Power loss will be maximum




→ Total turn off time = $t_x + t_{rr}$

→ Device turn off time = $t_{rr} + t_{gr}$

## Switching characteristic during Turn OFF process:-

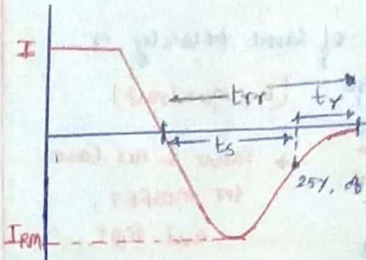
→ Agar Ideal condition hai, aur Reverse biased kiе ki to turant P-N Junction open switch tarah kam nai karega. Toda time lega off hone me.

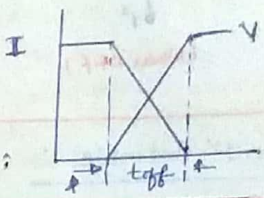
→ The time taken by the device for the Removal of the stored charge is known as storage time.

→ The time taken from forward biased steady state condition to reverse biased steady state condition is known as Reverse recovery time $t_{rr}$.

$t_q = t_{rr} + t_{gr}$

- $t_q$: device turn off time
- $t_{rr}$: Reverse recovery time
- $t_{gr}$: gate recovery time, or time taken to remove the stored charges in inner layer of SCR.




→ In ideal situation, $t_{rr}$ and $t_{gr} = 0$, characteristic will look like:

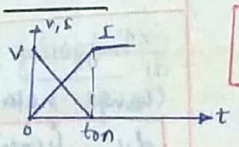
**Note:** (1) Agar diode ko reverse biased kiе, aur Storage time $(t_s)$ ya rise time $(t_r)$ ka bat kia to $V_{AK} \neq 0$ balki diode ko short kiya reverse upto $t_s$ aur current nikalenge ckt me.

(2) The switching characteristics of SCR, BJT, MOSFET, IGBT or diode are all same.

→ Switch ON ya OFF hona, current dekh ke voltage na ki voltage.

$$P_{avg} = \frac{1}{T}\int P\,dt$$

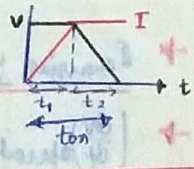
**Case 1:** When I and V both are varying.




$$\text{Energy or } W(t) = \frac{VI}{6}\cdot t_{on}$$

$$P_{avg} = \frac{VI}{6}\, t_{on}\cdot f$$

**Case 2:** When one is constant and other is varying at a time.




$$\text{Energy or } W(t) = \frac{VI}{2}\, t_{ON}$$

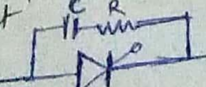
$$P_{avg} = \frac{VI}{2}\, t_{on}\cdot f$$

→ surge current, fault current, overcurrent are related to overcurrent-Protection. use $I^2t = \text{constant}$

$T_j > T_c > T_s > T_a$

(Junction temp, case temp, Sink temp, atmospheric temp.)

$\frac{dv}{dt}$ Protection:




(voltage Snubber ckt).

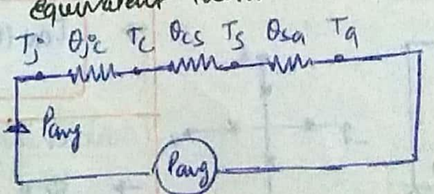
If noise is introduced, then the role of snubber ckt starts.

### Thermal Protection:

Analogy b/w Electrical and Thermal Quantity.

| Electrical | Thermal Quantity |
|---|---|
| (1) Charge (C) | (1) Heat (J) or watt-sec |
| (2) Potential diff (V) | (2) Temperature difference (°C) |
| (3) current (I) $= \frac{Q}{t} = C/sec$ | (3) Power = Avg Power = watt or J/sec |
| (4) Resistance $= \frac{V}{I}$ | (4) Thermal resistance = °C/watt. |

Equivalent Thermal ckt.




$$P_{avg} = \frac{T_j - T_c}{\theta_{jc}} = \frac{T_c - T_s}{\theta_{cs}} = \frac{T_s - T_a}{\theta_{sa}} = \frac{T_j - T_a}{\theta_{jc} + \theta_{cs} + \theta_{sa}}$$

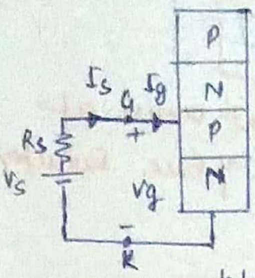
**Imp Note:** If somewhere it is asking about the device rating in SCR, then always calculate its current rating because the Power is associated with current (Practically).

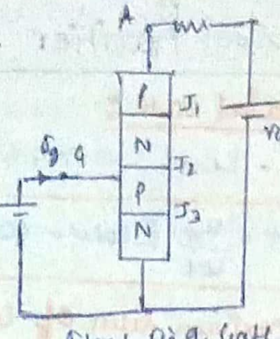
$T_{ON}$: time for which Diode remained ON.

$t_{ON}$: time for which [illegible]

## Gate Characteristics of SCR :

### Complete gate driving ckt :

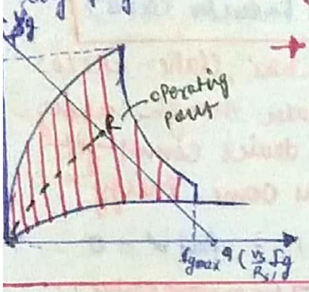



Ideal fig of Gate

yad rakhna hai agar 'G' aur 'K' ke bich me Resistance lag gaya to fir $I_g \neq I_s$.

→ "Slope of load line is −ve of $R_s$."




## String Efficiency for series and Parallel operation :

$$\eta_{string} = \frac{\text{Voltage across the string}}{(\text{Individual rating of SCR}) \times (\text{No. of SCR})}$$

$$\eta_{string} = \frac{\text{current through the string}}{(\text{Individual current rating of SCR}) \times \text{No. of SCR}}$$

Derating factor (D.F) = $1 - \eta_{string}$

Negative temp coefficient device :- BJT, SCR.

→ **Continuous Gate Triggering :-**

- In FCM, we apply continuous Gate Triggering.
- For High Inductive Load, we use continuous gate triggering
- If nothing is mentioned or nothing is available for calculation of turn ON time then we go for $t_{on} \approx$ Gate Pulse width

**Condition of Continuous Gate Triggering :**

$$P_{g\,avg} = V_g I_g = P_{g\,max}$$

→ **Pulse Gate Triggering :**

$$P_{g\,(avg)} = P_{g\,max} \times D = P_{g\,max} \times \frac{T_{ON}}{T}$$

$$P_{g\,max} = V_g I_g$$

- If $T_{ON} < 100\,\mu sec$, then we will always use Pulse Triggering
- If $T_{ON} > 100\,\mu sec$, then we will always use Continuous Gate Triggering.
- Kabhi bhi $I_g$ ki do value ayi to ue value ko select karna hai jo 2 to 3 times $I_{g\,min}$ ho.

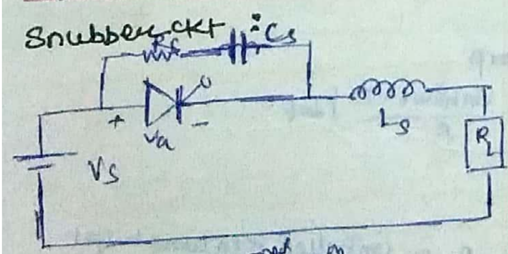
$$R = \frac{nV_1 - V_s}{(n-1)\Delta I_l}$$

$$C = \frac{\Delta Q\,(n-1)}{V_1 n - V_s}$$

$n$ = no. of SCR in series.
$V_s$ = Source voltage
$V_1$ = Individual rating of SCR
$\Delta I_l$ = leakage current $= I_{l\,max} - I_{l\,min}$
$\Delta Q$ = Charge in charge.

**Special note :** Jab diode ya SCR capacitor ke parallel me laga hai to during charging of capacitor, SCR will be OFF and once capacitor is fully charged then while discharging, SCR will be ON.

### Snubber ckt




$$L_s = \frac{V_s}{\left(\frac{di}{dt}\right)_{rating}}$$

most value of $V_s$

$$R_s = \frac{\left(\frac{dV_a}{dt}\right)}{\left(\frac{di}{dt}\right)}$$

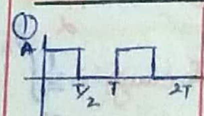
$$C_s = \frac{4\xi_1^2 L_s}{(R_s + R_L)^2}$$

### Trick for finding dc RMS and Avg value :

$$\text{Avg} = \text{Amplitude} \times \frac{\text{Duration of signal exist}}{\text{Time period}}$$

$$\text{RMS} = \text{Amplitude} \times \sqrt{\frac{\text{Duration of signal exist}}{\text{Time period}}}$$

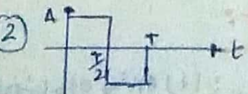
(1)




$$\text{Avg} = A \times \frac{T/2}{T} = A/2.$$

$$\text{RMS} = \frac{A}{\sqrt{2}}.$$

(2)




→ Symmetrical Square pulse waveform me half ko lo bus aur phir Time period bhi half hojaega aur usse RMS and Avg nikalo.

~~$\text{Avg} = A \times \frac{T/2}{T/2} = A$~~ → Symmetrical waveform ke avg. value = 0

$$\text{RMS} = A \times \sqrt{\frac{T/2}{T/2}} = A.$$

# Single Phase Control Rectifier

## Single phase Half wave controlled and uncontrolled Rectifier :-

### (1) R - Load :

→ $\boxed{i_o(t) = \frac{V_m \sin\omega t}{R}}$ → $\beta = \pi$

→ $\alpha$ = firing Angle

→ $V_o(t) = V_m \sin\omega t$

→ for uncontrolled $\alpha = 0$ – in case of R-Load.

*** → PIV = $V_m$

### (2) R-L Load :

(a) **controlled :** Note : Jab Jab Inductor Reverse bias hone ka chega, tab tab reverse condition $\pi$ se age Jaega qki reverse bias tab hogi jab Inductor current apne Energy khatam karega qki $\pi$ pe source Reverse Bias hota hai aur Current Inductor Energy loose nai karega isliye $\pi$ ke Bad hi Reverse Bias hoga aur off hoga.

i.e $\boxed{\pi < \beta < 2\pi}$.

→ firing Angle = $\alpha$

→ extinction angle = $\beta$

→ $\boxed{I_o(avg) = \frac{1}{2\pi}\int_{\alpha}^{\beta} \frac{V_m \sin\omega t}{R}\, d\omega t}$

→ $V_o(avg) = I_o(avg) R$

→ Pure Inductor avg voltage always zero.

(b) **uncontrolled :** Put $\alpha = 0$ in all results of controlled.

### ** (3) R-E Load :

**controlled :** (1) ~~R-E load~~ DC motor.

(2) R-E Load corresponds to battery charging like we are charging battery at our home.

→ Sirf 'L' hi aisa hai jab tab hi supply reverse biased hone ke bawajud conduction hota hai but baki load me esa nai hai Thyristor / diode get reverse biased.

→ If E > Vs then ~~supply~~ Thyristor / diode get reverse biased.

→ Exactly at $\alpha$ and $\beta$, current = 0

→ Firing Angle = $\alpha$

→ Extinction Angle = $\beta_2 = \theta_2$ in case of R-E Load.

## Special case :

$\boxed{\int di = \int \frac{V_m \sin\omega t}{L}}$

(1) L - Load (controlled) :-

$\boxed{i_L(t) = \frac{V_m}{\omega L}[\cos\alpha - \cos\omega t]}$

→ maximum value of current occurs at $\omega t = \pi$ in case of Pure Inductor.

→ firing angle = $\alpha$

*** → $\boxed{\text{Extinction Angle} = 2\pi - \alpha}$

** → $\boxed{V_o(avg) = 0 \text{ (for Pure Inductor case)}}$

→ agar Inductor load me laga hai, chahe akele ya phir R-L-E me, then even though supply voltage is Reversed, the device cannot get turned off as Inductor has some Energy.

(2) L - Load (uncontrolled) :- Put $\alpha = 0$

$\boxed{i_L(t) = \frac{V_m}{\omega L}[1 - \cos\omega t]}$ For average value limit integrating 0 to $2\pi$.

→ Here also maximum value of current occurs at $\omega t = \pi$ in case of Pure Inductor.

→ current ($i_L$) becomes zero at $\omega t = 2\pi$.

→ firing angle = $\alpha = 0$

→ $\boxed{\text{Extinction angle} = 2\pi - \alpha = 2\pi}$

→ $\boxed{V_o(avg) = 0 \text{ (for Pure Inductor)}}$

→ $\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$ and $\theta_2 = \pi - \theta_1$

→ $\theta_1 < \alpha \le \theta_2$ (minimum $\alpha$ ; maximum $\alpha$)

→ $I_o(avg) = \frac{1}{2\pi}\int_{\alpha}^{\theta_2 \text{ or } \beta} \left(\frac{V_m \sin\omega t - E}{R}\right) d\omega t$

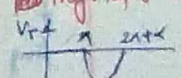
→ PIV = E + $V_m$

**uncontrolled:** Put $\alpha = \theta_1$ in controlled relations to get all relations of uncontrolled.

### Important :

(1) $t_{c}$ / $t_{off}$ : (1) only applicable for controlled rectifier.

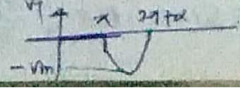
→ ye wo time hai jab Thyristor ke across ka voltage ($V_T$) negative hota hai.




→ $t_{c\text{-}off} = \frac{2\pi + \alpha - \pi}{\omega} = \frac{\pi + \alpha}{\omega}$

(2) PIV :- Maximum negative voltage across thyristor.

Ex




PIV = $V_m$.

# Best approach to get the relations of single phase "Half Wave Rectifier":-

## Formulae for RLE Load (Controlled):

(1) α range:

$\alpha_{min} \le \alpha \le \alpha_{max}$

$\theta_1 \le \alpha \le \theta_2$ ***

$\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$

$\theta_2 = \pi - \theta_1$

(2) Extinction angle:

→ Extinction angle = β

(3)* Conduction Angle:

→ Conduction Angle = $\gamma = \beta - \alpha$

(4) Conduction time ($t_c$):

→ $t_c = \frac{\gamma}{\omega} = \frac{\beta-\alpha}{\omega}$

(7) $V_0$ (avg)

→ $V_0(avg) = I_0(avg)R + E$

(8) PIV **

→ $PIV = V_m + E$

(5) ckt turn off time:

V.Imp $t_{ckt\ off} = \frac{2\pi + \theta_1 - \beta}{\omega}$

(6) $I_0$ (avg):

VVVVV Imp formula ***

$I_0(avg) = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\beta) - E(\beta-\alpha)\right]$

**A

→ In half wave rectifier source current follow o/p current

∴ $I_{rs} = I_{or}$.

** Very Important Note:-

(1) upar likhe hue formulae ko use karte hue hum saare load ke lie formulae derive karenge.

(2) Jis load me 'E' hoga usme 'E' ki value dalenge aur jisme nai hoga usme E = 0 karenge.

(Triggering Angle + Firing Angle)

(3) $t_{ckt\ off}$ ka concept uncontrolled ke lie nai hai.

**(4) For uncontrolled, $\alpha = \theta_1$ (always).

(6) Jab 'L' alag load me tabhi β ko β lenge (β > π) i.e. for R-L and RLE load extinction angle = β.

as in R-Load $\theta_2 = \pi$, ∴ in that case β = π.

*(7) for R and R-E load, $\beta = \theta_2$ (always)

*(8) For pure 'L' Load, $\beta = 2\pi - \alpha$

Upar likhe formulae, half wave rectifier aur discontinous current ke lie hai.

→ $P_{avg}$ (Battery) = $I_0(avg) \cdot E$

→ Power dissipated over resistor = $I_{rms}^2 R$.

→ Continous conduction is only possible with RL or RLE load.

→ R and RE donot Provide Continous Conduction.

→ But R and RE load provide continous conduction in 3φ Rectifier.

## 1-φ Full wave controlled and uncontrolled Rectifier (2 pulse):-

** Assumptions:

(1) The load current is continous and ripple free i.e a constant dc value of $I_0$.

(2) All devices are ideal (Losses = 0)

Note: For continous Ripple free conductions in case of RLE and RL Load, there is no significance of $\theta_1$ and $\theta_2$. Hence operation with R-L and RLE Load will be same.

→ agar question me bole ki load me high 'L' hai ya load current constant hai to samajh jana hai ki continous conduction ka question hai.

→ agar load me L hai aur kuch nai bola hai conduction ke bare me to by default continous ripple free manna hai (Only in full wave rectifier me).

## Controlled single phase mid point (full wave) Rectifier :-

- Firing Angle $= \alpha$
- Extinction Angle $= \beta = \pi + \alpha$ ***
- Conduction time $(t_c) = \frac{\pi}{\omega} = \frac{\beta - \alpha}{\omega} = \frac{\pi}{\omega}$
- $t_{ckt\ off} = \frac{\pi - \alpha}{\omega}$
- $PIV = 2V_m$ — ye jo Vm hai, Vm peak value hai; see here *****
- $V_o(avg) = \frac{2V_m \cos\alpha}{\pi}$

ye bus R-L or RLE load ke lie hai jab full wave rectifier hoga aur $I_0$ constant aur Ripple free hoga.

- $I_0(avg)$ → isko nikalne ke lie $V_0(avg)$ nikal ke load me KVL laga do
  - $V_0(avg) = I_0(avg) R + E$ → RLE load.
- Avg current in each thyristor $= \frac{I_0}{2}$
- RMS current in each thyristor $= I_0/\sqrt{2}$

## Uncontrolled single phase mid point Rectifier :-

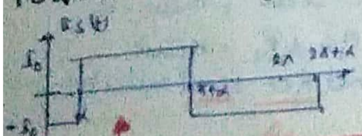
- Firing angle $= \alpha = 0°$
- Put $\alpha$ in all results of controlled.
- $V_0(avg) = \frac{2V_m}{\pi}$

- $I_0(avg) = \frac{1}{\pi}\int_{\alpha}^{\beta}\left(\frac{V_m \sin\omega t - E}{R}\right) d\omega t$

Important

$I_0(avg) = \frac{1}{\pi}\left[V_m(\cos\alpha - \cos\beta) - E(\beta - \alpha)\right]$

## Performance Analysis of 1-ϕ Full wave Rectifier :- (controlled) (only for RL and RLE load)



$$i_s(t) = \sum_{n=1,3,5}^{\infty} \frac{4}{n\pi} \times I_0 \left(\sin\omega t - n\alpha\right)$$ v.imp

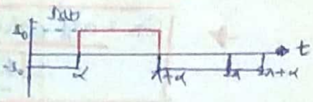
($\frac{4}{n\pi} I_0$ → Peak value)

## Single phase full Bridge Rectifier :-

### Controlled :
(Below Results only applicable for RL or RLE load)

- Firing angle $= \alpha$
- Extinction angle $(\beta) = \pi + \alpha$ *
- Conduction Angle $(\gamma) = \beta - \alpha = \pi$
- Conduction time $= \pi/\omega$
- $t_{ckt} = \frac{\pi - \alpha}{\omega}$
- $V_0(avg) = \frac{2V_m \cos\alpha}{\pi}$ → v.imp
- $PIV = V_m$
- Avg. current in each thyristor $= \frac{I_0}{2}$

Source current :



Time period $= 2\pi$.

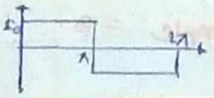
$I_{st}(avg) = 0$ ∵ symmetrical

$I_{st}(rms) = I_0$

### Uncontrolled :

- Firing angle $= \alpha = 0$
- Put $\alpha = 0$ in all results of controlled.
- $V_0(avg) = \frac{2V_m}{\pi}$
- $PIV = V_m$

Source current :



$I_{st}(avg) = 0$

$I_{st}(rms) = I_0$

## Discontinuous conduction of 1-ϕ Full wave Rectifier : (R or R-E load).

- Jab tak RL or RLE load me Full wave rectifier me discontinuous current nai bola hai tab tak iske Results bus R or RE load ke lie use honge.

- Power (Active) me bus fundamental component contribute karta hai, harmonic wasteful power deta hai.

- Fundamental source RMS current $= I_{s r_1} = \frac{Peak}{\sqrt{2}} = \frac{2\sqrt{2} I_0}{\pi}$
- RMS value of source current $I_{sr} = I_0 = \sqrt{(I_{sr_1})^2 + (I_{sr_3})^2 + (I_{sr_5})^2}$
- $C.D.F = \frac{I_{sr_1}}{I_{sr}} = 0.9$ (values ye yad hone chahiye)
- D.F or (Input Fundamental P.F) :- cosine angle of supply voltage and fundamental component of source current = $\cos\alpha$

→ Input Power factor

$= (C.D.F \times D.F)$ ** – अंतराल / [illegible]

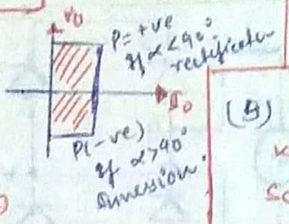
$= 0.9 \cos\alpha$

→ Input Active Power :-

→ It is always contributed by fundamental components.

$P_{active} = V_{S(rms)} I_{Sr_1} \cos\alpha$ ①

$P_{active} = V_0 I_0$ ②




→ Reactive Power :-

$Q_{reactive} = V_0 I_0 \tan\alpha$ ①

$Q_{reactive} = V_{S(rms)} I_{Sr_1} \sin\alpha$ ②

**Special Note :**

(1) Jabbhi SCR ka voltage drop de dia question me to mere formula (jisse baki formula nikalte hai) usme E ko E' se replace karenge aur $E' = E +$ voltage drop across SCR

(2) $\theta_1$ bhi badal jaega i.e $\theta_1 = \sin^{-1}\left(\frac{E'}{V_m}\right)$

(3) agar α nai dia hai to $\alpha_{min}$ lenge i.e $\theta_1$.

(4) $V_{o(avg)} = I_{o(avg)} R + E - V_T$ — But ye tabhi use karna hai jab 'R' known ho, agar R unknown hua to E' wale method se jaenge.

(5) agar question me Braking action likh dia to E ki polarity badalni padegi ya phir power load se source ki taraf jaegi to bhi E ki polarity badlenge qki wo braking / inversion ka case hota hai.

**Special Note :** Agar kabhi question me dedia ki initial current zero hai aur $t = t_0$ pe switch close hora to $t_0$ is firing angle.

**Concept of power factor :**

① Input power factor = C.D.F × D.F

② Input Power factor :

$$\cos\phi = \frac{V_0 I_0}{V_{rs} I_{sr}}$$ **

✓ only applicable for R-L and R-LE load.

③ Input power factor for R load :- **

$$\cos\phi = \frac{I_{or}^2 R}{V_{sr} I_{sr}}$$

④ Input power factor for R-E load :- **

$$\cos\phi = \frac{I_{or}^2 R + E I_0}{V_{sr} I_{sr}}$$

$I_0 \rightarrow$ o/p average current

$I_{or} \rightarrow$ o/p rms current.

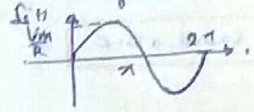
→ $V_{sr} \cdot I_{sr} \cos\phi = V_{rs} I_{rs_1} \cos\alpha$

→ $P = V_0 I_0$ – only for RL and RLE load.

→ For inversion $\alpha > 90°$

for rectification $\alpha < 90°$

→ Agar full wave rectifier hai aur load me sirf 'R' hai to $I_s$ (source current) ka waveform sinusoidal hota hai.




→ Special note :- For R-E load ; ***

$$P_{dc} = I_{o(avg)} E$$

$$P_{ac} = I_{o(rms)}^2 R + I_0 E$$

→ In full wave rectifier, with continuous conduction (RL or RLE load), ***

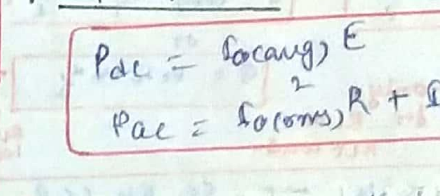
o/p RMS voltage = Source RMS voltage.

→ for R-Load, ***

$$I_{orms} = \left[\frac{V_m^2}{2\pi R^2}\left[\frac{1}{2}(\beta - \alpha) + \frac{\sin 2\alpha}{4}\right]\right]^{1/2}$$

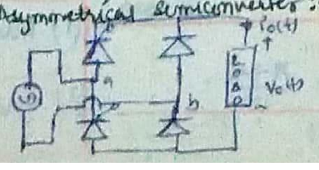
**SINGLE PHASE SEMICONVERTER :-** +ve quadrant operation converter.

(a) Symmetrical semiconverter : (Assumed $I_0$ is ripple free and continuous).




Conduction angle for each Diode and SCR = π, therefore it is called symmetrical configuration.

(b) Asymmetrical semiconverter :-




→ Conduction angle of $T_1$ and $T_2 = \pi - \alpha$

conduction angle of $D_1$ and $D_2 = \pi + \alpha$

∴ Conduction angle of T, D are different ∴ they are called asymmetrical.

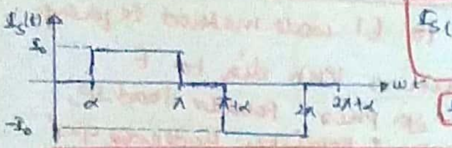
Formulae and performance Analysis of symmetrical and asymmetrical Converter :-

→ $V_{o(avg)} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t$

$V_{o(avg)} = \frac{V_m}{\pi}[1+\cos\alpha]$ — only valid when load is RL or RLE and $I_0$ is Ripple free and continuous. (याद रखना है)

→ $PIV = V_m$ — of semiconverter.

→ Source current:



$I_{s(rms)} = I_0\sqrt{\frac{\pi-\alpha}{\pi}}$

$I_{s(avg)} = 0$ ( ∵ Symmetrical curve).

$I_{sn}(t) = \sum_{n=1,3,5}^{\infty} \frac{4}{n\pi} I_0 \cos\left(\frac{n\alpha}{2}\right)\sin\left(n\omega t - \frac{n\alpha}{2}\right)$ — याद रखना है।

1. Fundamental Rms of source current :

$I_{sr_1} = \frac{4I_0\cos\alpha/2}{\pi\sqrt{2}} = \frac{2\sqrt{2}\,I_0}{\pi}\cos\alpha/2$

2. D.F :

$D.F = \cos\alpha/2$

3. I.P.F :

$IPF = C.D.F \times D.F$

4. Active Power :-

$P = V_{s\,rms} I_{sr_1}\cos\alpha/2$

or

$P = V_0 I_0$ — only for RL or RLE load.

5. Reactive Power

$Q = V_{s\,rms} I_{sr_1}\sin\alpha/2$

or

$Q = V_0 I_0 \tan\alpha/2$ — only for RL or RLE load.

→ ** agar semiconverter me se ek SCR open hogya to semiconverter Half wave rectifier ki tarah behave karega.

→ ** semiconverter me RE load aya tusant full wave rectifier ka discontinous wala case laga do i.e

$I_{o(avg)} = \frac{1}{\pi R}[V_m(\cos\alpha-\cos\beta) - E(\beta-\alpha)]$

In case of Symmetrical semiconverter :

→ Average thyristor current $= \frac{I_0}{2}$

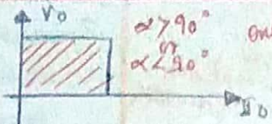
→ Rms thyristor current $= \frac{I_0}{\sqrt{2}}$

** Diode ke liye bhi same hoga

→ conduction time $t_c$ for symmetrical semiconverter $= \pi/\omega$ (Diode and SCR Both)

→ conduction time $t_c$ for asymmetrical S.C (for diode) $= \frac{\pi+\alpha}{\omega}$.

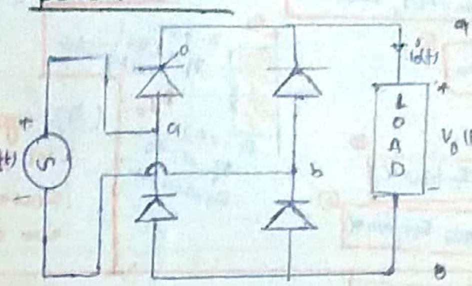
→ $t_c$ for asymmetrical S.C (for thyristor) $= \frac{\pi-\alpha}{\omega}$.



$\alpha > 90°$, $\alpha < 90°$ — only motoring action possible with semiconverter.

→ Free wheeling diode is used in Symmetrical Configuration. In asymmetrical, F.W.D is inbuilt.

Special case :



$V_{o(avg)} = \frac{V_m}{2\pi}[3+\cos\alpha]$ → Only true for R or RL or RLE continuous ripple free conduction

→ Not true for RE load.

→ Special note: agar R aur R-E load aye semiconverter me with discontinous current to semiconverter ka behaviour full wave bridge rectifier ki tarah hoga

i.e we will use $I_{o(avg)} = \frac{1}{\pi R}[V_m(\cos\alpha-\cos\beta) - E(\beta-\alpha)]$

Note: Kisi question me O/P current continous aur constant de dia hai to uska rms value avg value ke Barabar aega.

i.e Rms value average value ke barabar hoga na ki average value Rms value ke.

For symmetrical semiconverter :

$t_{ckt\,off} = \frac{\pi-\alpha}{\omega}$ **

For Asymmetrical semiconverter :

$t_{ckt\,off} = \pi/\omega$ **

In case of Asymmetrical semiconverter :-

For Thyristor :

(1) Average current $= I_0 \times \frac{\pi-\alpha}{2\pi}$ *

(2) Rms current $= I_0 \times \sqrt{\frac{\pi-\alpha}{2\pi}}$

For diode :

(1) Avg. current $= I_0 \times \frac{\pi+\alpha}{2\pi}$ **

(2) Rms current $= I_0 \times \sqrt{\frac{\pi+\alpha}{2\pi}}$

## Effect of Source Inductance :-

→ Same sidha sidha ye karna hai ji's formulae me $\alpha$ hai waha bus $\alpha$ ko $\alpha+\mu$ se replace kardo.

$\mu$ : overlap angle. During overlap period, T and FD both conducts.

### ① 1-φ Half wave rectifier :-

→ $V_{o(avg)}$ with $L_s$ = $\frac{V_m}{2\pi}[1+\cos(\alpha+\mu)]$

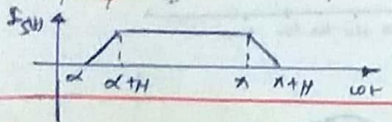
→ Reduction in voltage due to $L_s$ ($\Delta V$) :

$$\Delta V = \frac{V_m}{2\pi}[\cos(\alpha+\mu) - \cos\alpha]$$ – जरूरी है

→ $\Delta V = f L_s I_o$ – जरूरी है

→ Conduction Angle of Thyristor (with $L_s$) = $\pi-\alpha+\mu$

Phle $\pi-\alpha$ tha, ab $\alpha$ ko $\alpha+\mu$ se replace kardiye. Har ek formula jo banega usme $\alpha \to \alpha+\mu$ se replace hota dikhega.



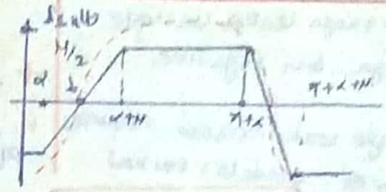

### ② 1-φ Full wave Rectifier :

→ $V_{o(avg)}$ with $L_s$ = $\frac{V_m}{\pi}[\cos(\mu+\alpha) + \cos\alpha]$

→ Conduction Period of Each SCR = $\pi+\mu$

→ $\Delta V = \frac{V_m}{\pi}[\cos\alpha - \cos(\alpha+\mu)]$ – जरूरी है

→ $\Delta V = 4 f L_s I_o$




Note : Fundamental current lags source voltage by $\mu/2$ angle.
∴ Fundamental Power factor = $\cos(\alpha+\mu/2)$

### ③ 3φ full wave rectifier :-

→ $\Delta V = \frac{3V_{mL}}{2\pi}[\cos\alpha - \cos(\alpha+\mu)]$

→ $\Delta V = 6 f L_s I_o$

→ During overlap period '$\mu$' the 3 thyristor are conduct.

→ overlap angle ∝ supply frequency
∝ Load current
∝ Source Inductance
∝ $\frac{1}{\text{supply voltage}}$

---

**Basic :**

PHASE voltages :

$V_{an}(t) = V_{mp}\sin\omega t$

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

$V_{cn}(t) = V_{mp}\sin(\omega t-240°)$ or $V_{mp}\sin(\omega t+120°)$

Line voltages :**

$V_{ab}(t) = \sqrt{3}V_{mp}\cos(\omega t-60°)$

$V_{bc}(t) = \sqrt{3}V_{mp}\cos(\omega t-180°)$

$V_{ca}(t) = \sqrt{3}V_{mp}\cos(\omega t-300°)$ or $\sqrt{3}V_{mp}\cos(\omega t+60°)$

→ $PIV = \sqrt{3}V_{mp} = V_{mL}$ **

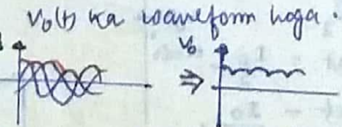
→ conduction time of each diode = 120°

→ $V_{o(avg)} = \frac{3\sqrt{3}V_{mp}}{2\pi} = \frac{3V_{mL}}{2\pi}$ ** – जरूरी है।

## 3-φ Rectifier

**Common Cathode Connection** ** : Sabse phle $V_s$ ka graph bana lo i.e. phase voltages ka waveform aur phir un waveform ka maximum ko trace kardo wahi $V_o(t)$ ka waveform hoga.

for Example :



→ 3 diodes me se phle wo conduct karega jiska Anode potential maximum positive hoga.

→ aur is connection me ek bar me ek hi diode conduct karega, jo diode conduct kia, usi ka phase voltage, o/p voltage me appear hoga. For example, agar phase 'a' wala diode conduct kia, to $v_o(t) = V_{an}(t)$ hoga.

→ aur jo do diode off honge us samay unke across line voltage appear hoga. For example, phase 'a' ka diode conduct kia, to $V_{D_2}$ (Phase b diode) = $V_{ba}$ and $V_{D_3}$ (Phase c diode) = $V_{ca}$.

→ It is a 3 pulse converter.

## Common Anode connection of 3ϕ Rectifier:-

- Its a 3-pulse converter.
- In this connection, the anode potential of all three devices are at same potential. Out of 3 diode, the one will conduct whose cathode potential is at maximum negative.
- Isme bhi supply i.e phase voltages ke teeno phase ka waveform banao aur uswaveform ka minimum lelo aur wahi $V_0(t)$ ka graph hoga.
- Isme bhi jo diode ON rhega uska voltage output me appear hoga but negative sign ke sath.
- Isme jo diodes off rhenge unke across voltages line appear honge. For ex - Diode (a) ON hai to $V_{D_2}$ (b phase diode) = $V_{ab}$

  $V_{D_3}$ (c phase diode) = $V_{ac}$
- $PIV = \sqrt{3} V_{mp} = V_{mL}$
- Each conduction duration of diode = 120°
- 3 pulse converter:-
- $V_{o(avg)} = \frac{3\sqrt{3} V_{mp}}{2\pi} = \frac{3 V_{mL}}{2\pi}$

## 3-ϕ Mid point converter :-

- Isme har ek winding ko 2 tukdo me tod die hai aur $a_1\ a_2\ b_1\ b_2\ c_1\ c_2$ karke six o/p terminals milenge. Har ek phase me ek diode rhega common cathode connection me.
- Phase voltages:

  $v_{a_1n}(t) = V_{mp} \sin \omega t$

  $v_{b_1n}(t) = V_{mp} \sin(\omega t - 120°)$

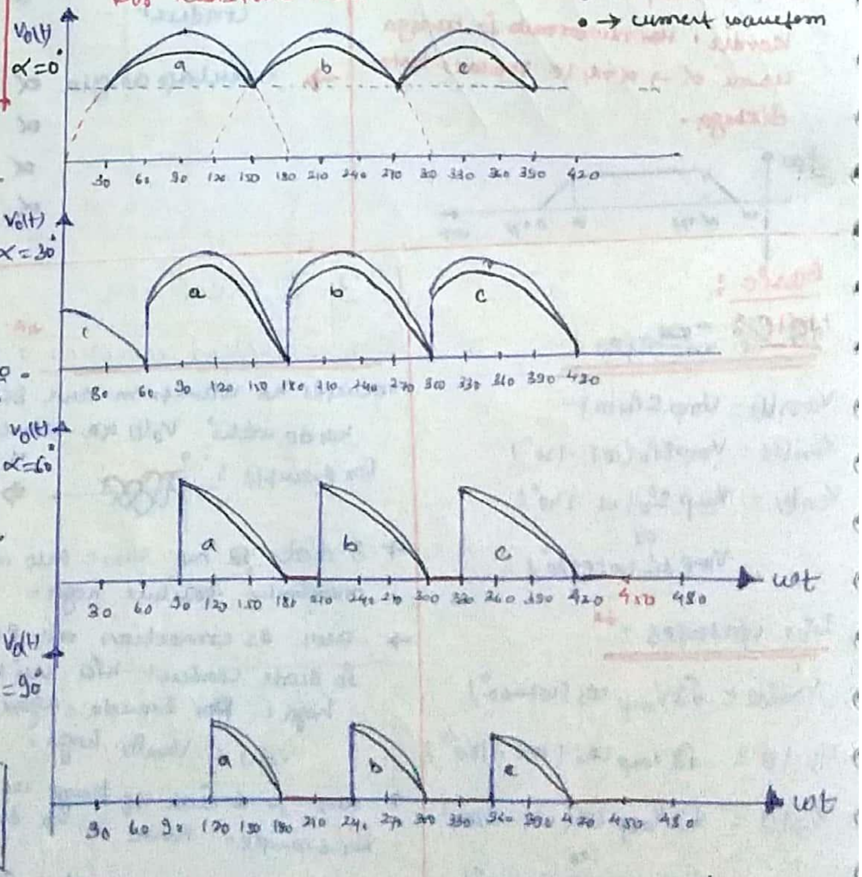
  $v_{c_1n}(t) = V_{mp} \sin(\omega t + 120°)$

  $v_{a_2n}(t) = -v_{a_1n}(t)$ ; $v_{b_2n}(t) = -v_{b_1n}(t)$ ;

  $v_{c_2n}(t) = -v_{c_1n}(t)$.
- Isme har diode 60° ke liye conduct karta hai.
- Isme bhi jo diode conduct karega uska phase voltage us samay o/p me appear hoga.
- PIV nikalne ke liye kisi bhi ek diode ko lelo off state me aur us samay bus ek hi diode conduct karra hoga baaki 5 diode off honge.
- Manlo PIV nikalte same $D_3$ lie aur $a_1$ $c_2$ terminal se juda hai aur uswakt $D_1$ diode conduct karra jo terminal $a_1$ se juda hai to $V_{D_3} = v_{c_2a_1}(t)$ hoga.
- $PIV = +2V_{mp}$ (phase max) $= \frac{2}{\sqrt{3}} V_{mL}$ (line max).

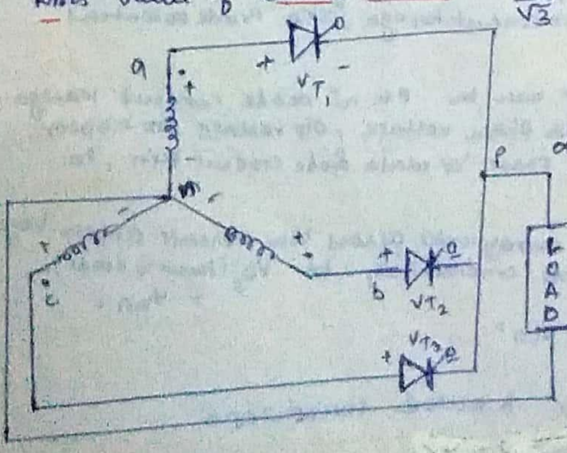
For Resistive load:-

- → voltage waveform
- → current waveform




## 3-ϕ Half wave rectifier (controlled):-

- 3 pulse converter.
- Each thyristor will conduct maximum for 120° (isse kum bhi kar skta hai).
- Each phase will conduct 120°.
- Average value of SCR current $= \frac{I_o}{3}$
- Rms current of SCR $= \frac{I_o}{\sqrt{3}}$
- Avg. value of source current $= \frac{I_o}{3}$
- Rms value of source current $= \frac{I_o}{\sqrt{3}}$




Special Note: (1) $T_1$ will start conducting at $30° + \alpha$

(2) $T_2$ will start conducting at $150° + \alpha$

(3) $T_3$ will start conducting at $270° + \alpha$.

→ In 3ϕ Half wave rectifier, the dead end point is 180° i.e current will become zero at 180°.

→ $PIV = \sqrt{3} V_{mp} = V_{mL}$ **

→ For $\alpha < 60°$, $V_0(t)$ ka Peak $V_s(t)$ ke Peak ke Barabar hoga.

→ But for $\alpha > 60°$, $V_0(t)$ ka Peak less than $V_s(t)$ hoga.

For R Load :-

→ Case 1 : $\alpha < 30°$ → continuous conduction (Load current)

$$\left[V_0(avg) = \frac{1}{\frac{2\pi}{3}} \int_{30+\alpha}^{150+\alpha} (V_{mp} \sin\omega t)\right]$$

$$V_0(avg) = \frac{3\sqrt{3} V_{mp} \cos\alpha}{2\pi}$$ – आता है।

→ Case 2 : $\alpha > 30°$ → discontinuous conduction

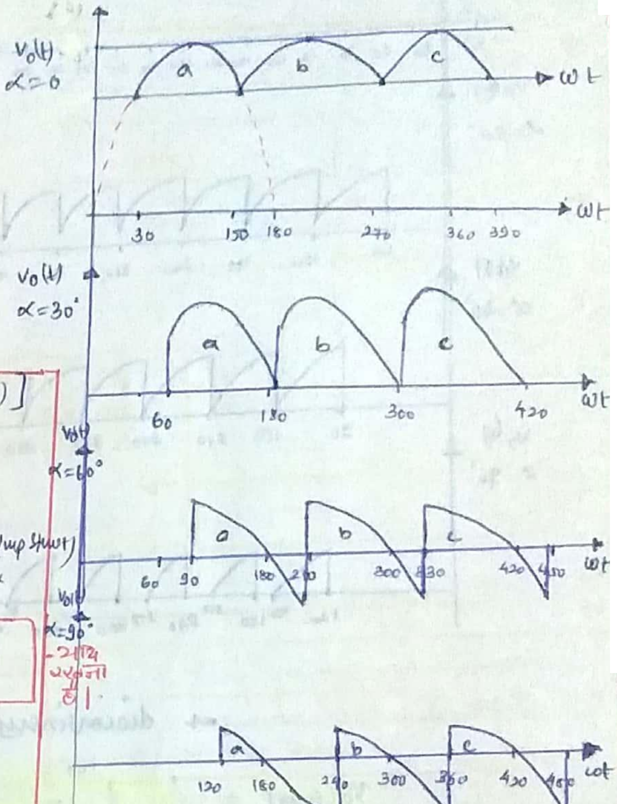
$$V_0(av) = \frac{1}{\frac{2\pi}{3}} \int_{30+\alpha}^{180} (V_{mp} \sin\omega t)$$

$$V_0(avg) = \frac{3 V_{mp}}{2\pi} \left[1 + \cos(30° + \alpha)\right]$$

In case of 3ϕ half wave rectifier, range of $\alpha$ is $0 < \alpha < 150°$

## Half wave Rectifier (3ϕ) with RL and RLE load with continuous ripple free conduction :-

range of $\alpha$ : $0 < \alpha < 150°$




Here for any value of $\alpha$, conduction angle of each SCR will always be 120°.

→ $$V_0(avg) = \frac{3\sqrt{3} V_{mp} \cos\alpha}{2\pi}$$ – $V_0(avg)$ in case of half wave rectifier for R, RL or RLE load is same.

## 3ϕ Full wave rectifier (6 pulse converter).

→ It is a 6 pulse converter.

** → Each SCR will conduct for max^m 120°.

→ Each pair of SCR will conduct Max^m for 60°.

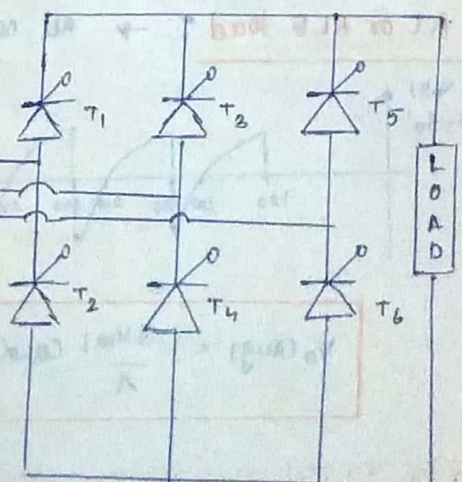
→ Each phase will conduct for 240°.

→ Average value of SCR current $= \frac{I_0}{3}$

→ RMS value of SCR current $= \frac{I_0}{\sqrt{3}}$.

→ ** Avg. value of source current = 0

→ ** RMS value of source current $= I_0 \sqrt{\frac{2}{3}}$

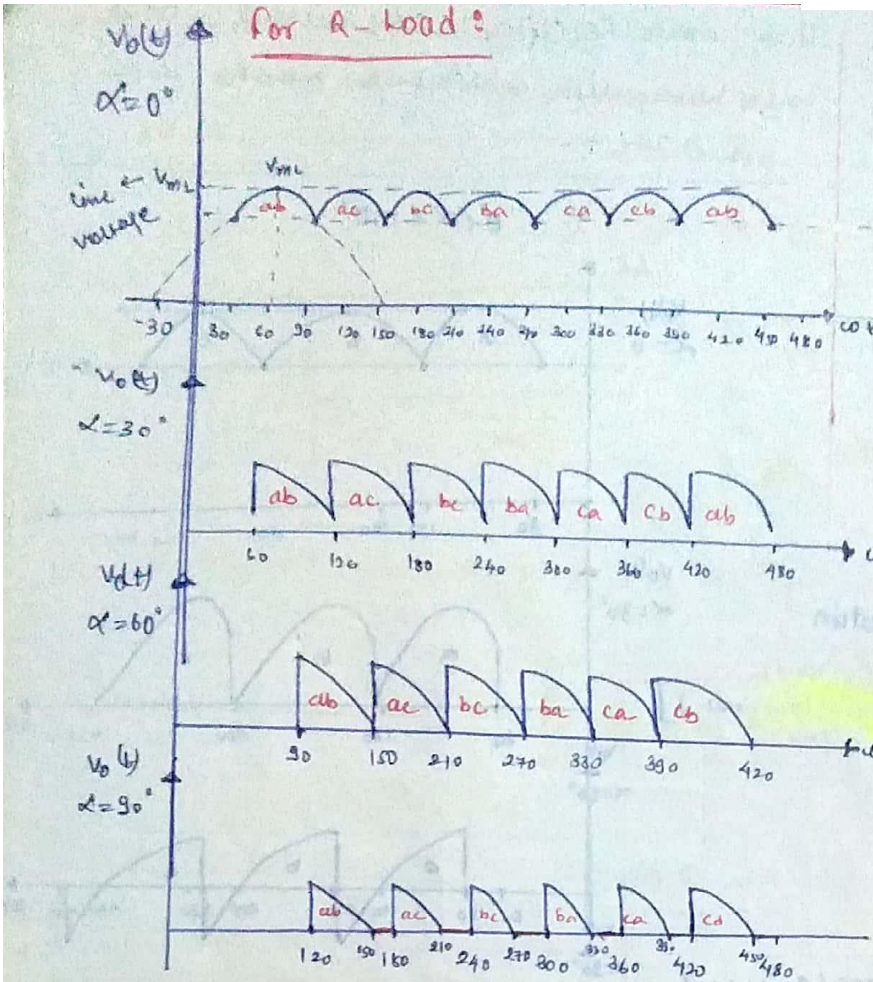



ye fig yad honi chahi, result nikalne ko.

→ $PIV = V_{mL} = \sqrt{3} V_{mp}$ **

range of $\alpha$ : $0° < \alpha < 120°$

## For R-Load:




→ $V_0(t)$ $\alpha = 0$ ka graph yad hona chahi, usi ko reference leke $\alpha = 30, 60, 90$ pe banaenge.

→ ab aur ac phle aenge ye yad rehna chahi phir jo repeat hor wo uske age wale se replace hoga

For Exe
ab ac bc ba
same, change with next, same, change with next.

→ For R Load:

Case I: $\alpha < 60°$ → continuous conduction.

$$V_0(avg) = \frac{1}{\frac{2\pi}{6}} \int_{30+\alpha}^{90+\alpha} V_{mL} \sin(\omega t + 30°)$$

Imp. **

$$V_0(avg) = \frac{3 V_{mL}}{\pi} \cos\alpha = \frac{3\sqrt{3}\, V_{mp} \cos\alpha}{\pi}$$

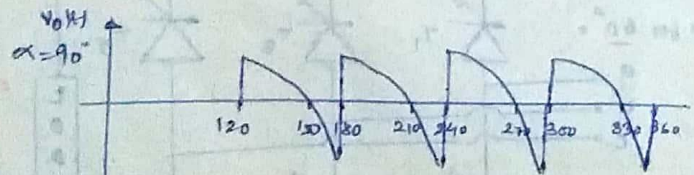
Case II: $\alpha > 60°$ → discontinuous condition

$$V_0(avg) = \frac{1}{\frac{2\pi}{6}} \int_{30+\alpha}^{150} V_{mL} \sin(\omega t + 30°)$$

$$V_0(avg) = \frac{3 V_{mL}}{\pi} [1 + \cos(60° + \alpha)]$$

→ In 3φ full wave rectifier dead point is 150°.

For RL or RLE load: → All waveforms till $\alpha = 60°$ are same as above.



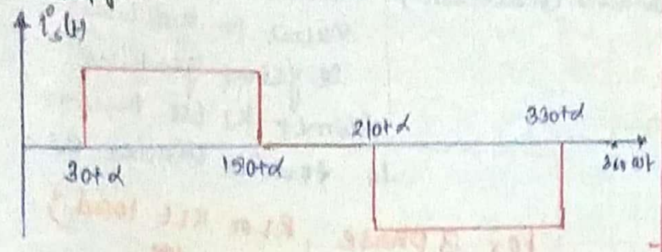

$$V_0(avg) = \frac{3 V_{mL} \cos\alpha}{\pi} = \frac{3\sqrt{3}\, V_{mp} \cos\alpha}{\pi}$$

Note: (1) For 3φ full wave rectifier for pure R load, $\alpha < 60$ me continuous conduction always but ripple free not always that's y $V_0(avg) \neq V_0(rms)$.

(2) Advance angle bola to, $\alpha = 180° -$ advance firing karna hai aur inversion ka case hoga uski formula me E ko −E se replace karenge.

(3) In 3φ full wave rectifier, 2 thyristor conduct karte hai ek time pe to agar unka voltage drop dia to $V_0$ me se $2V_T$ ghataenge aur 3φ half wave dia to $V_0$ me $V_T$ ghataenge kyu ki usme ek thyristor on rehta hai ek baar me.

## Performance Analysis of 3ϕ Full wave rectifier :-




**Instantaneous value of source current :**

$$i_{sn}(t) = \sum_{n=1,3,5} \frac{4}{n\pi} I_0 \sin\left(\frac{n\pi}{3}\right) \cdot \sin(n\omega t - n\alpha)$$ ★★★ ③

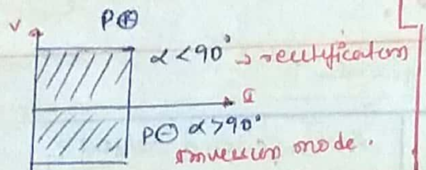
→ $I_{sr_1} = \frac{Peak}{\sqrt{2}} = \frac{\sqrt{6} I_0}{\pi}$ → Input fundamental Power factor or D.F = cos α

→ $I_{sr} = I_0\sqrt{\frac{2}{3}}$ → I.P.F = CDF × cos α

→ $CDF = \frac{3}{\pi} = \frac{I_{sr_1}}{I_{sr}} = 0.955$

→ $P = V_0 I_0$ or $P = \sqrt{3} V_{s\,rms} \cdot I_{s\,rm_1} \cos\phi_1$ (fundamental angle)

→ $Q = V_0 I_0 \tan\alpha$




→ $\cos\phi = \frac{V_0 I_0}{\sqrt{3} I_{sr} V_{sr}}$

I.P.F — line values

→ **Remember :**

| | |
|---|---|
| 1-ϕ Rectifier | 0 < α < π |
| 3-ϕ Half wave | 0 < α < 150° |
| 3-ϕ Full wave | 0 < α < 120° |

**Special Note :**

ckt turn off time :

(1) For α < 60°,

$t_{ckt\,off} = \frac{240° - \alpha}{\omega}$

(2) For α > 60°,

$t_{ckt\,off} = \frac{180° - \alpha}{\omega}$

Note : whenever we are taking the derivation of ckt turn off time, take only the first negative portion of the $V_T$.

**Special Note :** agar 3ϕ me R-E load agya

half wave rectifier ke case me to

$$I_0(avg) = \frac{3}{2\pi R}\left[V_m(\cos\alpha' - \cos\beta) - E(\beta - \alpha')\right]$$

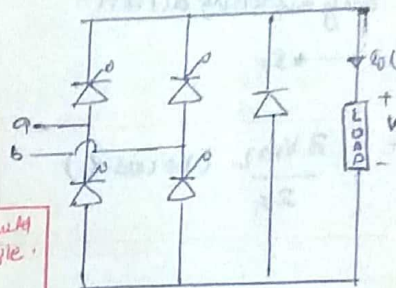
★★ Here $\alpha' = \alpha + 30°$

**Application of free wheeling diode :**

★★ → Free wheeling diode does not come into action if R load is there. (Pure)

→ free wheeling diode only takes place when the o/p voltage is going to be negative.

→ **Case 1 :** 1-ϕ Full wave rectifier.

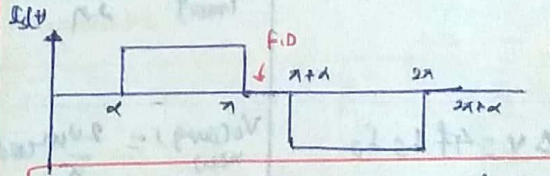



$V_0(avg)$ (without F.D) $= \frac{2V_m\cos\alpha}{\pi}$ ★★

$$V_0(avg) \text{ (with F.D)} = \frac{V_m}{\pi}[1 + \cos\alpha]$$ (Semiconverter ke formula bhi yahi hai.)

→ free wheeling lagane se P.F Increase or Improve.

as $V_0$ ↑, P↑ hence cos ϕ ↑.




$$i_{sn}(t) = \sum_{n=1,3,5}^{\infty} \frac{4}{n\pi} I_0 \cos\left(\frac{n\alpha}{2}\right) \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$ ④ ★★ Same as semiconverter result.

**Note :** There is no need of free wheeling diode in 1-ϕ full wave diode bridge rectifier under continuous ripple free conduction.

**Case 2 :** 3-ϕ Full wave Rectifier :-

→ α ≤ 60°, till this point volt is always +ve, hence F.D will not conduct

→ α > 60°, $V_0(t)$ has negative spikes there for F.D will conduct after α > 60°

Conduction Angle of F.W.D in 3ϕ Full wave rectifier in one cycle of input = α − 60° (α > 60°).

$$V_0(avg) = \frac{3V_{mL}}{\pi}[1 + \cos(60 + \alpha)]$$

Same as Resistive load when α > 60°

**Case 3: 3φ half wave.**

→ for α < 30°, F.W.D will not conduct (∵ continuous conduction)

→ for α > 30°, F.W.D will conduct :

Conduction Angle = α − 30°

α > 30°

→ $V_o(avg)$ (with F.D) $= \frac{3 V_{mL}}{2\pi}\left[1 + \cos(\alpha + 30°)\right]$

**Note:** Kabhi puche Peak instantaneous value to graph se gaana ye phir current ke lie puche to fourier series se.

For 3 phase, RL or RLE load;

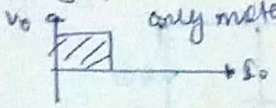
$$\cos\phi = \frac{V_o I_o}{\sqrt{3} V_{rs} I_{rs}}$$

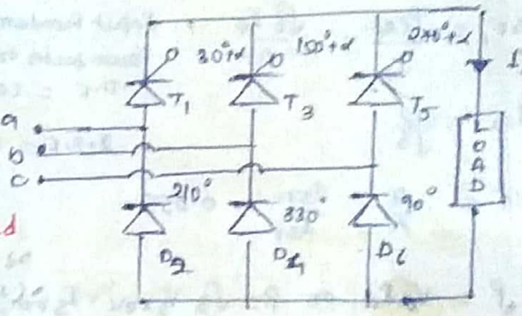
(line value) (jo aksar supply me diye rehta hai)

**3-φ Semi controll converter :-**

→ 3φ Bridge, 3 SCRs and 3 diodes are there.

only motoring action.




→ $V_o(avg) = \frac{3 V_{mL}}{2\pi}(1 + \cos\alpha)$ — for any load (Booklet se likh lena)

→ range of α : $0 \le \alpha \le 180°$.

**Source inductance effect at a glance:**

| Converter | Average volt drop across source inductor | Average load voltage |
|---|---|---|
| 1 pulse converter (1-φ Half wave rectifier) | $\Delta V = f L_s I_o$ | $V_o(avg)_{new} = \frac{V_{mp}}{2\pi}(1+\cos\alpha) - f L_s I_o$ |
| 2 pulse converter (1-φ, full wave) | $\Delta V = 4 f L_s I_o$ | $V_o(avg)_{new} = \frac{2V_m}{\pi}\cos\alpha - 4 f L_s I_o$<br>$V_o(avg)_{new} = \frac{V_{mp}}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]$ |
| 3 pulse converter (3-φ, Half wave) | $\Delta V = 3 f L_s I_o$ | $V_o(avg)_{new} = \frac{3V_{mL}}{2\pi}\cos\alpha - 3 f L_s I_o$<br>$V_o(avg)_{new} = \frac{3V_{mL}}{4\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]$ |
| 6 pulse converter (3φ, full wave) | $\Delta V = 6 f L_s I_o$ | $V_o(avg)_{new} = \frac{3V_{mL}}{\pi}\cos\alpha - 6 f L_s I_o$<br>$V_o(avg)_{new} = \frac{3V_{mL}}{2\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]$ |