# LECTURE NOTES
# ON
# POWER ELECTRONICS & PLC

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**DEPARTMENT OF ELECTRICAL ENGINEERING**

**SEM-5TH**

Chapter-1



# Application of power Electronics

## (1) Aerospace :→

Space shuttle power supplies, satellite power supplies, air craft power systems.

## (2) Commercial :→

Advertising, heating, air conditioning, central refrigeration, computer and office equipments, uninterruptible power supplies, elevators, light dimmers and flashers.

## (3) Industrial :→

Arc and industrial furnaces, blowers and fans, pumps and compressors, Industrial lasers, transformer-tap changers rolling mills, textile mills, excavators, cement mills, welding.

## (4) Residential :→

Air conditioning, cooking, lighting, space heating, dryers refrigerators, electric-doors openers, fans, Personal computers, other entertainments equipments, vacuum cleaners, washing and sewing machines, light dimmers, food mixers, food-warmer trays.

## (5) Telecommunication :→

Battery chargers, power supplies (dc and ups)

## (6) Transportation :→

Battery chargers, traction control of electric vehicles, electric locomotives, street cars, trolley buses, subways, automotive electronics.

(7) Utility systems

High voltage dc transmission (HVDC), excitation systems, VAR compensation, static circuit breakers, fans and boiler-feed pumps, supplementary energy systems (solar, wind)

## Advantages of power Electronic systems

(i) High efficiency due to low loss in power semiconductor devices.

(ii) High reliability of power electronic converter systems.

(iii) Long life and less maintenance due to absence of any moving parts.

(iv) Fast dynamic response compared to electro-mechanical converter systems.

(v) small in size, lesser in weight and lower installation cost etc.

## Disadvantages of power Electronic systems

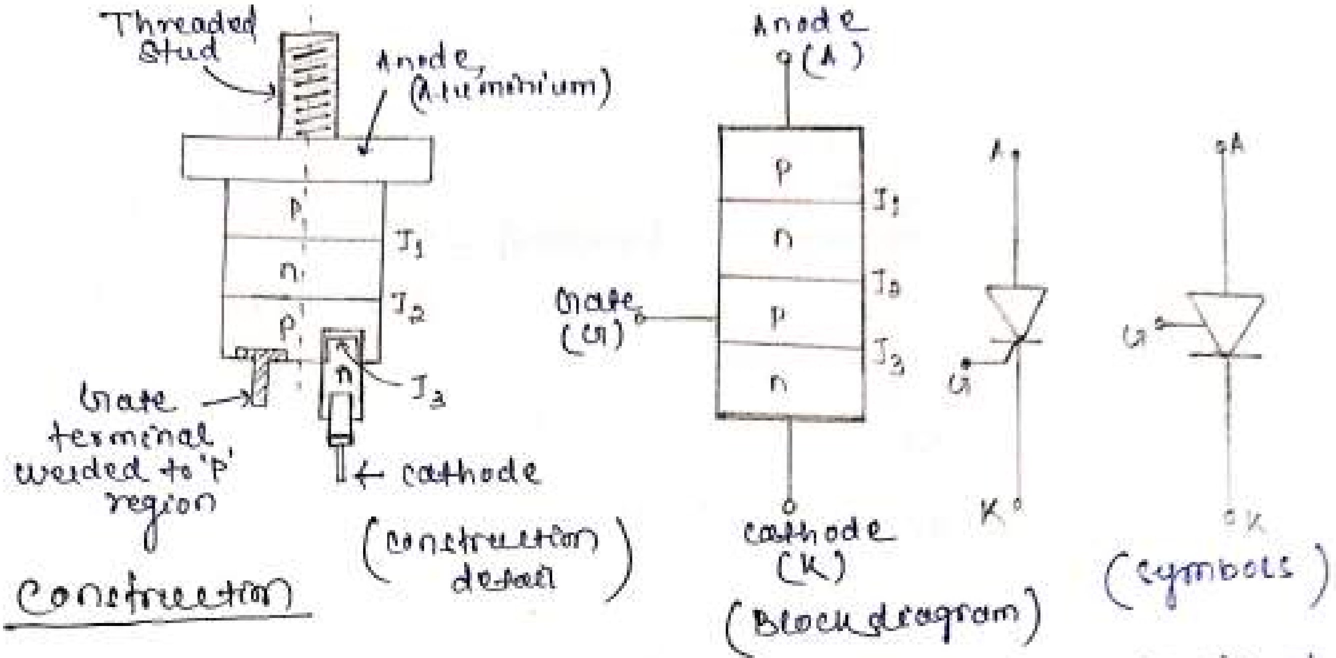
→ circuit in power electronic systems have a tendency to generate harmonics in the supply systems as well as Load circuit.

→ Ac to DC and ac to ac converters operates at a low input power factor under certain operating conditions. In order to avoid a low pf, some special measures have to be adopted.

→ power-electronic controllers have low over-load capacity.

→ Regeneration of power is difficult in power electronic converters systems.

# Thyristor / SCR (Silicon controlled Rectifier)




Construction

→ SCR is a 4 layer, 3-junction, p-n-p-n semiconductor switching device. It has 3 terminals i.e anode, cathode and gate.

→ The terminal connected to outer 'p' layer is called anode 'A'

The terminal connected to outer 'n' layer is called cathode 'K'

The terminal connected to inner 'p' layer is called gate 'G'

→ SCR is a solid-state device, lower in size, high reliable and having higher efficiency.

→ Like the diode, an SCR is an unidirectional device that blocks the current flow from cathode to anode

→ It blocks the current flow from anode to cathode until it is triggered into conduction by a proper gate signal between gate and cathode terminals.

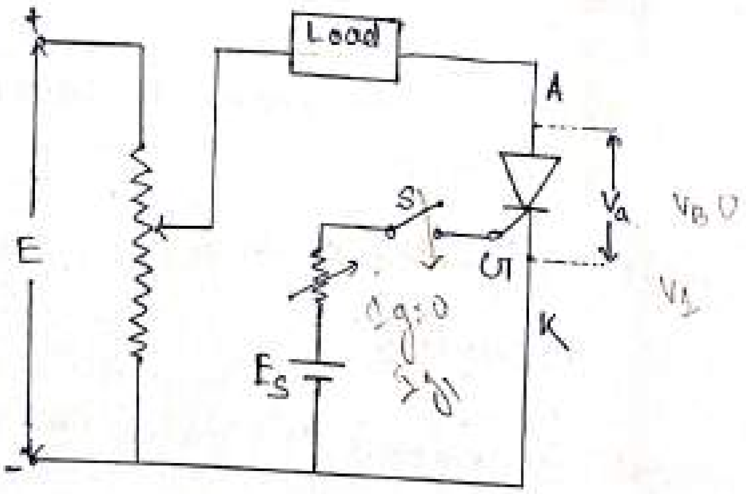
→ An SCR is so called because silicon is used for its construction and its operation as a rectifier can be controlled.

( very low resistance in forward conduction and very high resistance in reverse direction )

Generally SCRs are available in

voltage rating : 10 kV
R.M.S current rating : 3000 Amp
power handling capacity : 30 MW

## Operation




→ Here anode and cathode are connected to main source 'E'

→ The gate and cathode are connected to source $E_s$ which provide positive gate current from gate to cathode.

$V_a$ = anode voltage across thyristor terminal A, K

$I_a$ = anode current

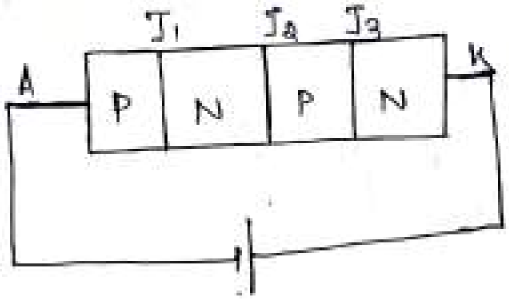
→ A thyristor has '3' basic modes of operation

(a) Reverse blocking Mode

(b) Forward blocking mode (off state)

(c) Forward conduction mode (on state)

(a) Reverse Blocking Mode




→ In this mode of operation, the 'K' is positive with respect to 'A' and switch 'S' is open circuited.

→ under this condition Junction $J_1$ and $J_3$ are reverse biased and $J_2$ is forward biased.

→ A small amount of leakage current (mA) start flowing from 'K' to 'A' due to the existence of charge carrier in junction $J_2$.

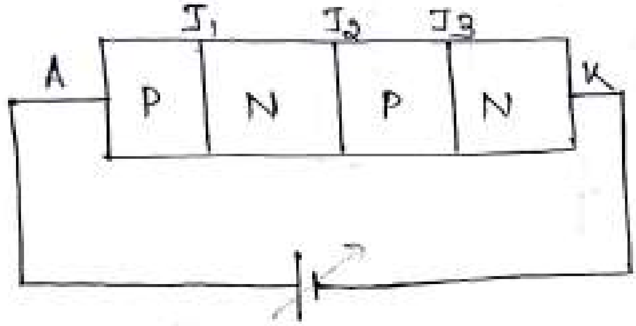
→ This small leakage current is not sufficient to turn on the SCR and this reverse blocking mode, called the off-state of the SCR. This reverse blocking mode is shown by OP.

→ If the reverse voltage is increased, then at reverse breakdown voltage ($V_{BR}$), an avalanche breakdown occurs at Junction $J_1$ and $J_3$ and reverse current increases rapidly.

→ This rapid increase in current may damage the SCR as the junction temperature may exceed it's permissible temperature rise.

→ The reverse avalanche region is shown by PQ.

(b) Forward Blocking Mode (OFF state)




→ When anode is +ve with respect to cathode, with gate circuit open, the thyristor is said to be forward biased.

→ In this case $J_1$ and $J_3$ are forward biased and $J_2$ is reversed biased.

→ Due to junction '$J_2$', there is no flow of current from anode to cathode. However a small amount of leakage current flow from anode to cathode due to the existence of minority charge carrier in the junction $J_2$.

→ Therefore, a thyristor acts as open switch even in forward blocking mode.

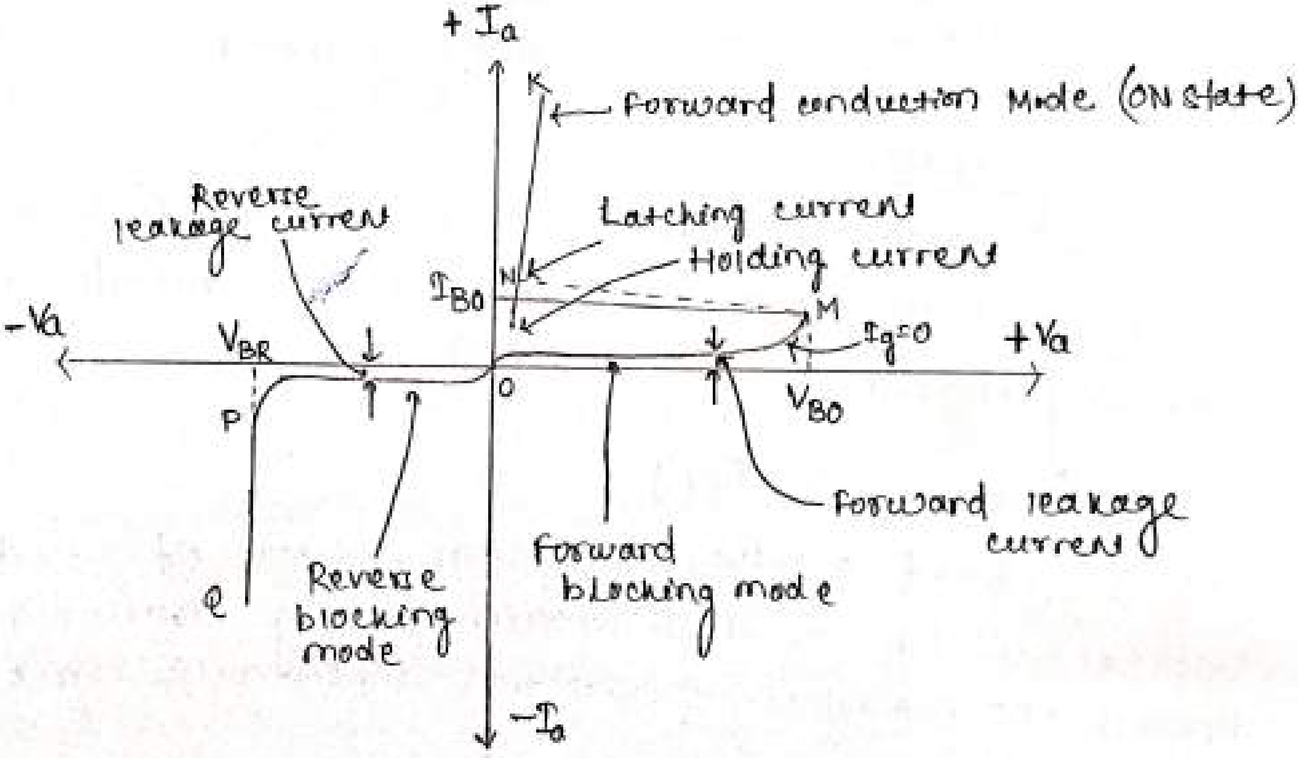
(c) Forward conduction Mode (ON state)

→ When anode to cathode forward voltage is increased with gate circuit open, reverse biased junction $J_2$ will have avalanche breakdown.

→ After this breakdown, thyristor gets turned on and SCR acts like closed switch.

→ The voltage at which the junction $J_2$ breaks down is called as forward breakover voltage or threshold voltage ($V_{BO}$).

## V-I Characteristics of SCR




$V_{BO}$ → forward breakover voltage

$V_{BR}$ → Reverse breakdown voltage

$I_g$ → gate current

→ In VI characteristics, the reverse blocking mode is shown by curve 'op' and high reverse current shown by the region PQ.

→ The curve OM represents the forward blocking mode of SCR. As the forward leakage current is small, SCR offers a high impedance. Therefore, a thyristor can be treated as an open switch even in the forward blocking mode.

→ When the thyristor gets turned on, the point 'M' shifted to 'N' and NK' represent the forward conduction mode.

→ The line NK show that voltage drop across SCR increases slightly with an increase in anode current.

## Latching current

The minimum value of anode current which is required to turn on the thyristor is called as latching current.

(or)

It is defined as the minimum value of anode current which it must attain during turn-on process to maintain conduction when gate signal is removed.

(or)

It may be defined as the minimum amount of anode current required to keep the SCR in the 'ON' state after removing the triggering pulse.

## Holding current

It is defined as the minimum value of anode current below which the device stops conducting and returns to it's off state.

(or) 

**Holding current :→**

The minimum value of anode current below which the thyristor gets turn off is called holding current.

**Application of SCR/Thyristor :→**

Thyristor basically serves two functions
(a) electronic switching
(b) electronic control

Some of the applications of SCR are listed below

1. speed control of 'dc' and 'ac' motors.
2. As rectifier for conversion of 'ac' into 'dc'
3. As inverter for conversion of 'dc' into 'ac'
4. As 'dc' chopper or 'dc to dc' converter for converting 'dc' at one level to 'dc' at another level.
5. As cycloconverter for converting 'ac' of one frequency into 'ac' of another frequency.
6. control of temperature, level, position and illumination
7. power switches ('dc' and 'ac' circuit breakers)
8. HVDC transmission line
9. Improvement of power-factor in transmission lines
10. As static switches
11. control of induction heating.

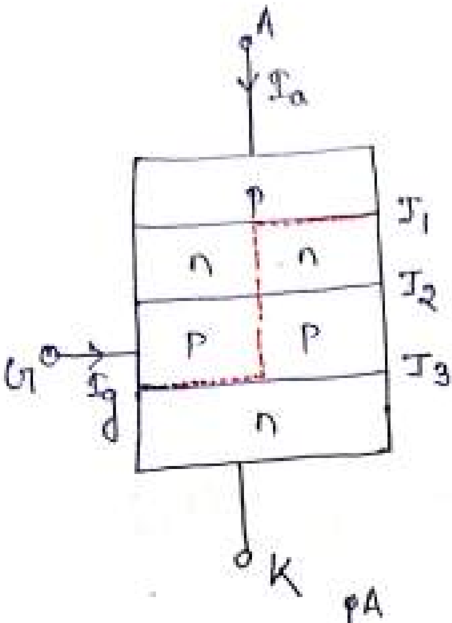
(12) Relay control

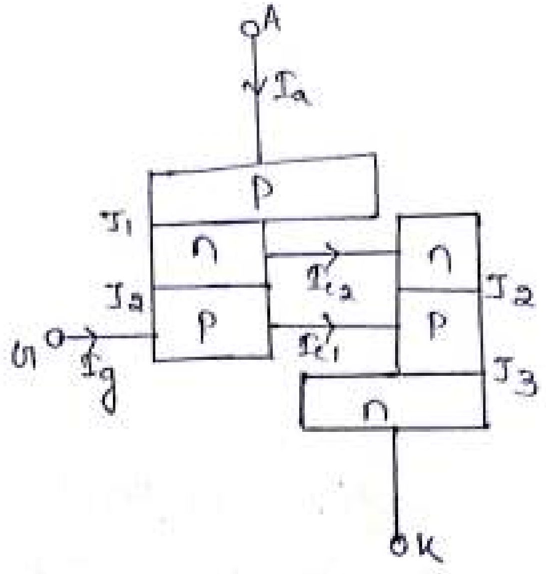
(13) Phase control

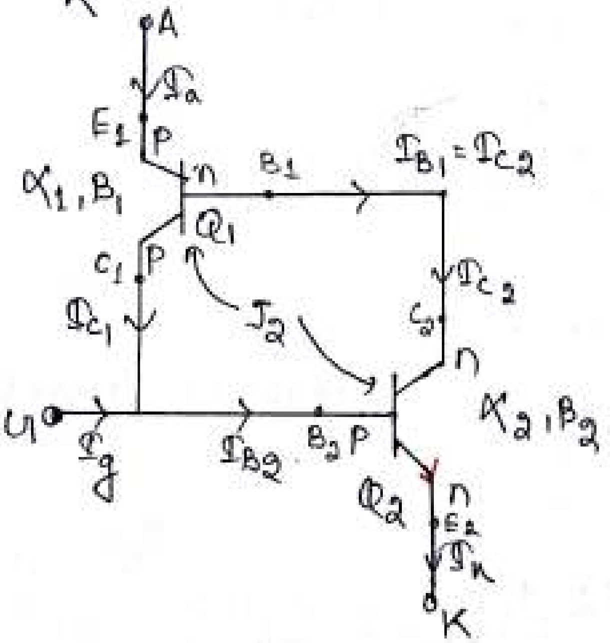
(14) As special power supplies for air-craft and computers etc.

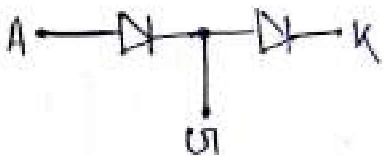
## 1.2 Two transistor analogy of SCR






two diode connected in series

→ The two transistor model can be obtained by bisecting the two middle layers.

→ Junction $J_1$ & $J_2$ and junction $J_2$ & $J_3$ can be considered to constitute pnp and npn transistors separately.

Current gain

$$\alpha = \frac{I_C}{I_E}$$

→ In common base mode of transistor operation

(ii) collector current ($I_C$) can be related to emitter current ($I_E$)

i.e

$$I_C = \alpha I_E + I_{CBO}$$

where, $\alpha$ = common-base current gain

$I_{CBO}$ = common-base leakage current of collector-base junction.

<u>for transistor $Q_1$ (PNP)</u>

Emitter current ($I_E$) = Anode current ($I_a$)

collector current ($I_C$) = $I_{C1}$

Therefore for $Q_1$,

$$I_{C1} = \alpha_1 I_a + I_{CBO1}$$

where, $\alpha_1$ = common-base current gain of $Q_1$

$I_{CBO1}$ = common-base leakage current of $Q_1$

<u>for transistor $Q_2$ (npn)</u>

$$I_{C2} = \alpha_2 I_K + I_{CBO2}$$

where, $\alpha_2$ = common-base current gain of $Q_2$

$I_{CBO2}$ = common-base leakage current of $Q_2$

$I_K$ = emitter current of $Q_2$

→ The sum of two collector current is given by

$I_g = I_{B2}$

$I_E = I_K = I_{C2} + I_B$

$I_a = I_{C1} + I_{C2}$

Now put the value of $I_{C1}$ & $I_{C2}$

$\Rightarrow \quad I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_K + I_{CBO2}$

$\Rightarrow \quad I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$

$\Rightarrow \quad I_a = (\alpha_1 + \alpha_2) I_a + I_{CBO1} + I_{CBO2} + \alpha_2 I_g$

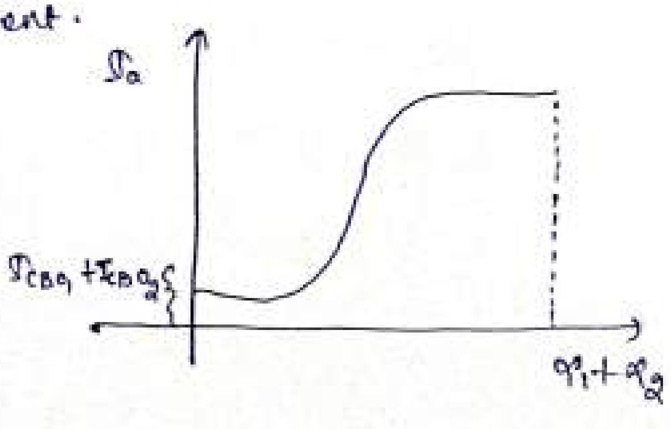
$\Rightarrow \quad I_a - (\alpha_1 + \alpha_2) I_a = I_{CBO1} + I_{CBO2} + \alpha_2 I_g$

$\Rightarrow \quad I_a \left[1 - (\alpha_1 + \alpha_2)\right] = I_{CBO1} + I_{CBO2} + \alpha_2 I_g$

$$\Rightarrow \quad I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{\left[1 - (\alpha_1 + \alpha_2)\right]}$$

* With gate current $I_g = 0$ and with $\alpha_1 + \alpha_2 = 0$ (very low). There is no conduction of SCR as anode current, equal to the forward leakage current, is somewhat more than $I_{CBO1} + I_{CBO2}$

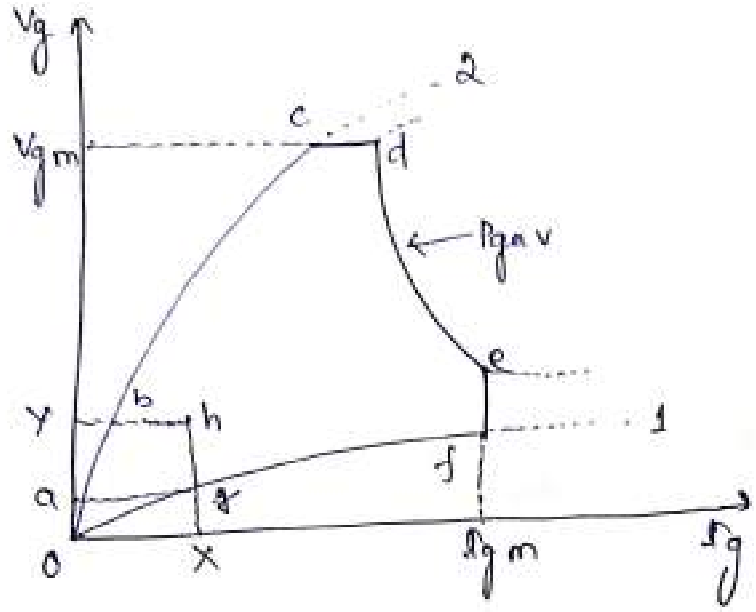
* with $\alpha_1 + \alpha_2 = 1$, $I_a$ would tend to become infinity and the thyristor will turn-on even a small amount of gate current.



1.3

# Gate characteristic of SCR






Pavg = average power dissipation

ox → minimum gate current

oy = minimum gate voltage

Igm = maximum gate current

Vgm = maximum gate voltage

→ Gate characteristic is drawn between gate current ($I_g$) and gate voltage ($V_g$)

→ curve-1 represents the lowest voltage values that must be applied to turn-on the SCR. ($I_{gm}$ = max^m gate current)

→ curve-2 represents the highest possible voltage values that can be safely applied to gate circuit.

→ 'oy', the minimum value of '$V_g$' and 'ox' is the minimum value of '$I_g$' which are reliable to turn-on the SCR.

→ $V_{gm}$ represent maximum value of gate voltage and $I_{gm}$ represent maximum value of gate current.

→ If $V_{gm}$, $I_{gm}$ and $P_{gav}$ are exceeded then the thyristor can be destroyed.

→ bcdefghb is the safe working region or can be represented as gate drive area.

## 1.4 Switching Characteristics of SCR during turn-on and turn-off

(1)

### ① During turn-on process

→ A forward-biased thyristor can be turned on by applying a positive gate voltage between gate and cathode.

→ "The transition of SCR from blocking state to conducting state is called as turn-on time".

→ The total turn-on time can be divided into 3 intervals

(a) Delay time ($t_d$)

(b) Rise time ($t_r$)

(c) spread time ($t_s$)/($t_p$)

### (a) Delay time ($t_d$)

The delay time ($t_d$) is measured from the instant at which gate current reaches 90% $I_g$ ($0.9 I_g$) to the instant at which anode current reaches 10% $I_a$ ($0.1 I_a$)

where $I_g$ = final value of gate current

$I_a$ = final value of anode current

(or)

The delay time can also be defined as the time during which anode voltage falls from $V_a$ to $0.9 V_a$

where $V_a$ = initial value of anode voltage.

(or)

Delay time is the time during which anode current rises from forward leakage current to $0.1 I_a$

where $I_a$ = final value of anode current

## (b) Rise time ($t_r$)

The rise time ($t_r$) is the time taken by the anode current to rise from $0.1 I_a$ to $0.9 I_a$.

(or)

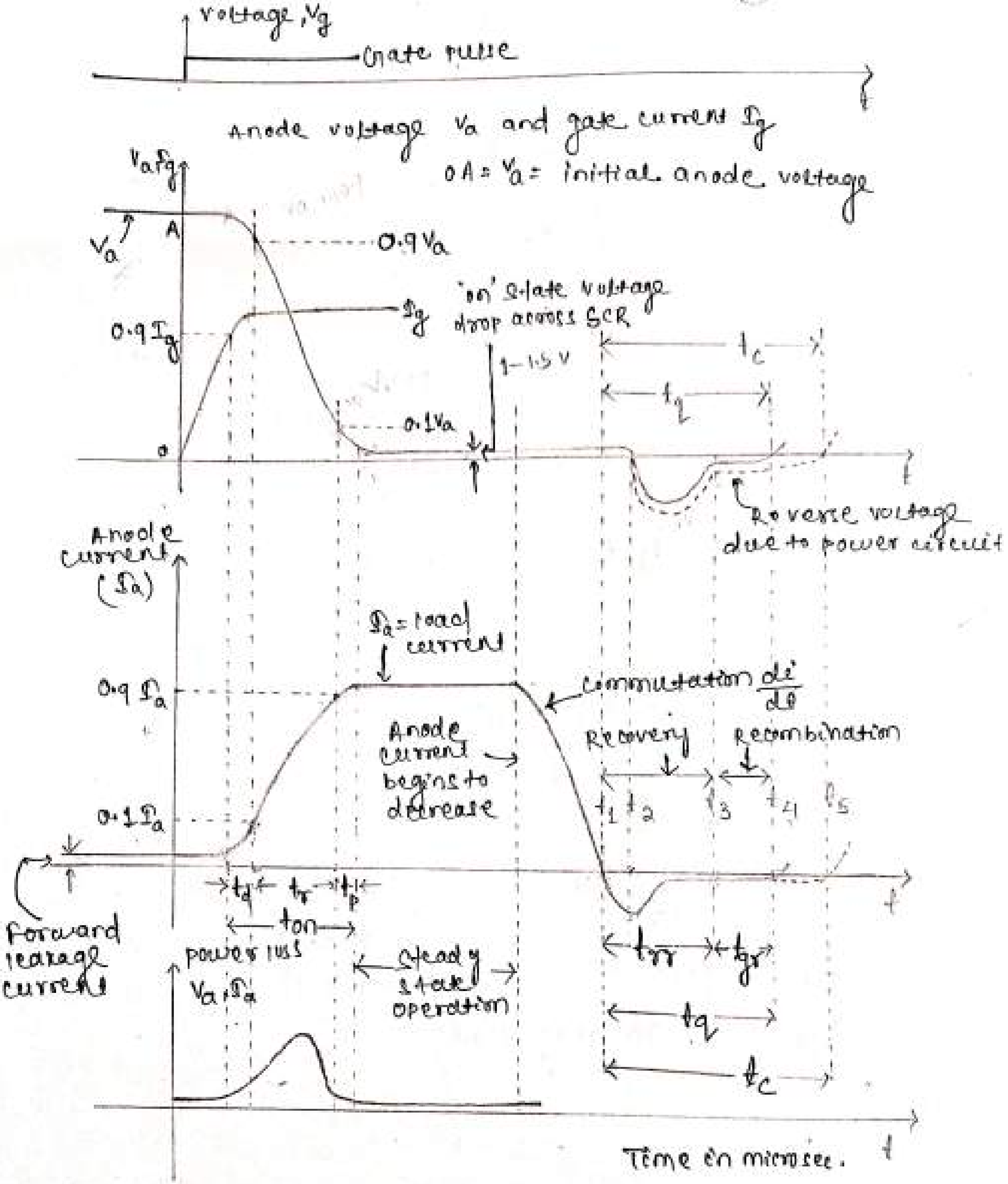
The rise time is also defined as the time required for the forward blocking off-state voltage to fall from 0.9 to 0.1 of its initial value i.e $V_a$.

## (c) Spread time ($t_p$)

The spread time ($t_p$) is defined as the time taken by an anode voltage to drop from 0.1 of it's initial value to the on-state voltage drop (i.e 1-1.5V)

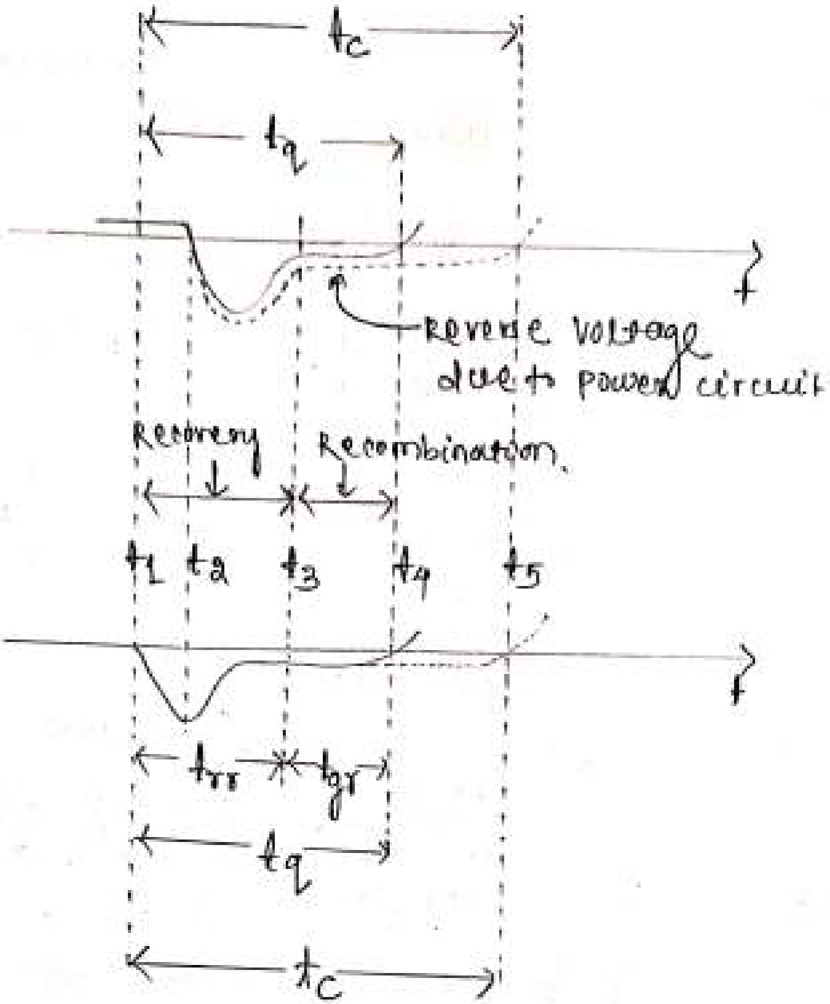
(or)

The spread time is the time taken by the anode current to rise from $0.9 I_a$ to $I_a$.




(Thyristor voltage and current waveforms during turn-on and turn-off process)

## ② During turn-off process




$t_{rr}$ = Reverse Recovery time

$t_{gr}$ = gate recovery time

→ Turn-off process or the commutation process is the dynamic process that is used to bring the SCR from conduction state to forward blocking state.

→ The turn-off time ($t_q$) of a thyristor is defined as the time between the instant anode current becomes zero and the instant SCR regains it's forward blocking capability.

→ During time $t_q$, all the excess carriers from the four layers of SCR must be removed.

→ This turn-off time ($t_q$) is divided into two intervals (a) Reverse recovery time ($t_{rr}$)

(b) gate recovery time ($t_{gr}$)

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

→ The time in which excess carriers are removed from outer 'p' and 'n' layer is called reverse recovery time($t_{rr}$) and this is done by sweeping out of holes from outer p-layer and electrons from outer n-layer.

→ The time in which carriers at junction $J_2$ can be removed by recombination is called the gate recovery time ($t_{gr}$).

→ At instant $t_1$, anode current becomes zero. After $t_1$, anode current builds up in the reverse direction due to presence of charge carriers stored in the four layer.

→ The reverse recovery current removes excess carriers from the end junction $J_1$ and $J_3$ between the instant '$t_1$' and '$t_3$'

→ At instant $t_2$, when about 60% of the stored charges are removed from the outer two layers, carrier density across $J_1$ and $J_3$ begins to decrease and with this reverse recovery current also start decaying.

→ The thyristor is not able to block the forward voltage at $t_3$ due to presence of trapped charges at $J_2$.

→ These trapped charges can be decayed by recombination and this is possible by maintaining a reverse voltage across SCR.

## Circuit turn-off time ($t_c$)

→ circuit turn-off time ($t_c$) is defined as the time between the instant anode current becomes zero ($I_a = 0$) and the instant reverse voltage due to practical circuit reaches zero.

→ time '$t_c$' must be greater than '$t_q$' for reliable turn-off. Otherwise the device may turn-on at an undesired instant, and the process called commutation failure.

## 1.15 Turn on methods of SCR



A thyristor can be turned on by any of the following 5 technique.

(a) Forward voltage triggering
(b) $dv/dt$ triggering
(c) Light triggering
(d) Temperature triggering
(e) Gate triggering

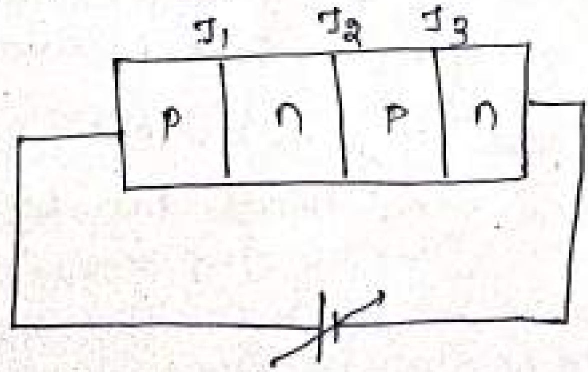
### (a) Forward voltage triggering

1) When forward voltage is applied between anode and cathode with gate circuit open, then $J_1$ & $J_3$ gets forward biased and $J_2$ gets reversed biased.

2) The width of this depletion layer decreases with increase in supply voltage.

3) If the supply voltage is gradually increased, at $V_{BO}$ (Break over voltage), $J_2$ looses it's blocking capability and act as a conductor.

4) Under this condition SCR behaves as a closed switch and is said to be turned on.



(b) dv/dt triggering

→ When forward voltage is applied between anode and cathode of SCR with gate circuit open. The junction $J_1$ and $J_3$ are forward biased and junction $J_2$ is reversed biased.

→ This reversed biased junction '$J_2$' has the characteristics of a capacitor due to charges existing across the junction.

→ If forward voltage is suddenly applied, a charging current through capacitor $C_j$, may turn on the SCR

→ The suddenly applied voltage = $V_a$ appear across the junction $J_2$

The charging current = $i_c = \frac{dq}{dt}$

$$i_c = \frac{dq}{dt}$$

$$= \frac{d}{dt}(C_j . V_a) = C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt}$$

→ As the junction capacitance is almost constant,

$$\frac{dC_j}{dt} = 0$$

therefore $i_c = C_j \frac{dV_a}{dt}$

→ Therefore, if the rate of change of forward voltage $\frac{dV_a}{dt}$ is high, the charging current $i_c$ would be more. This charging current plays the role of gate current and turn on the SCR even though gate signal is zero.

(22)

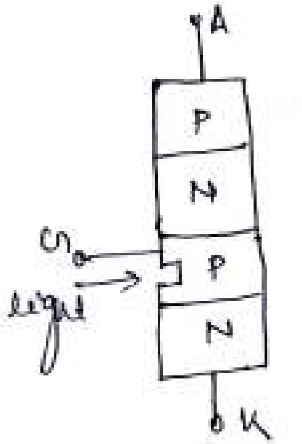
## (c) Light triggering

→ For a light triggering, a recess is made in the inner P-layer.

→ When this recess is irradiated by light wave, free charge carriers (pairs of holes and electrons) are generated, just like when gate signal is applied between gate and cathode.

→ When the intensity of light becomes more than a normal value, SCR starts conducting. This type of SCRs are called as a light activated SCR.

[LASCR]
optical triggering



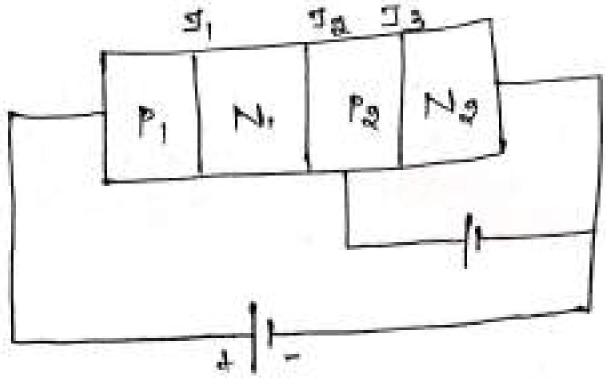

## (d) Temperature triggering

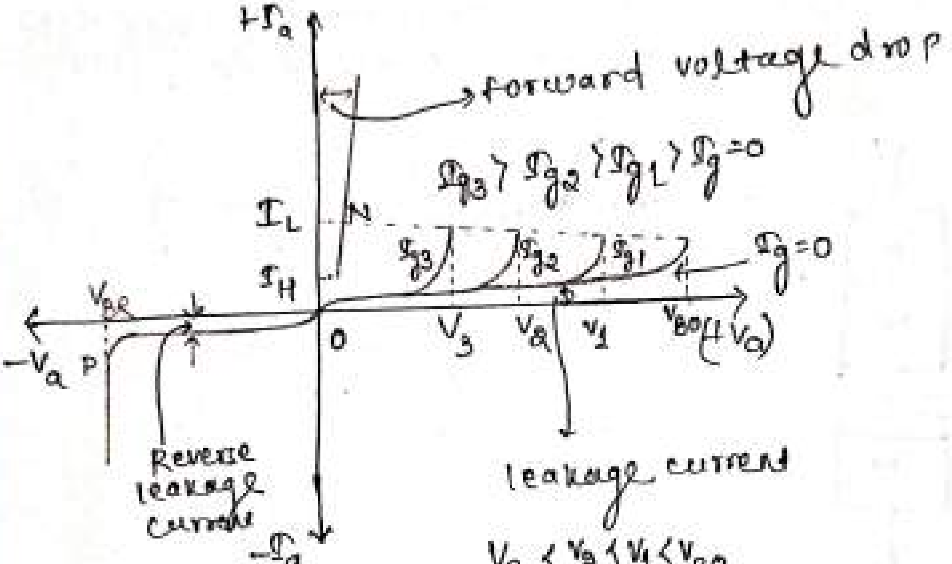
→ During forward blocking mode, most of the applied voltage appears across the reverse bias junction $J_2$.

→ This voltage across $J_2$ is associated with leakage current would raise the temperature of the junction. with increase in temperature, width of depletion layer decreases.

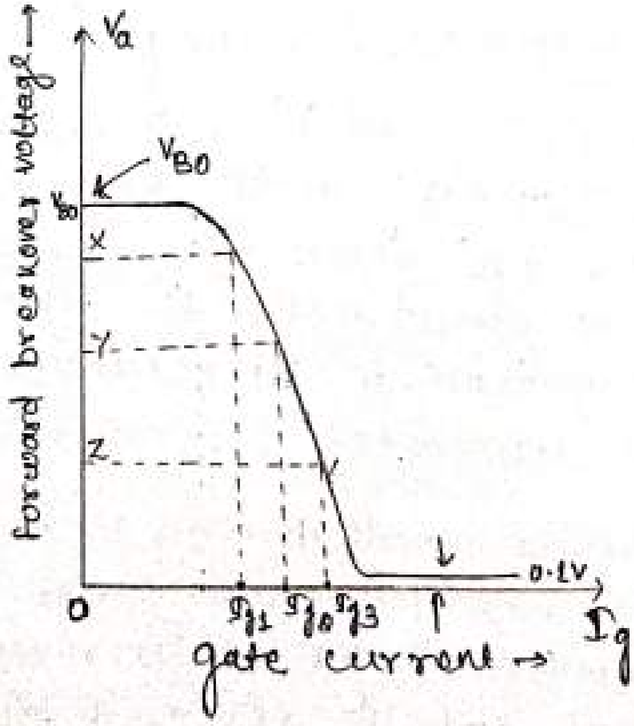
→ This further leads to more leakage current and hence more junction temperature. At some high temperature the depletion layer of the reversed biased junction vanished and the device gets turn on.

(e) Gate triggering




$V_3 < V_2 < V_1 < V_{BO}$




Effect of gate current on forward breakover voltage

→ Turning 'on' of thyristor by gate triggering is simple, reliable and efficient.

→ When a positive gate voltage is applied between gate and cathode, charge carriers are injected into the inner p-layer, there by reducing the depletion layer thickness.

→ As the voltage increases, carrier injection increases and the voltage at which breakover occurs is reduced.

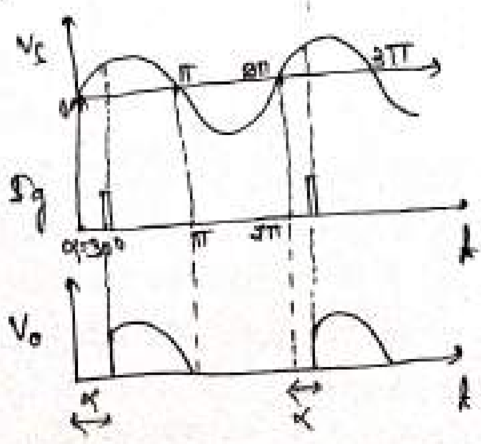
When $I_g = 0$, $V_a = V_{BO}$

$I_g = I_{g1}$, $V_a = 30\%\ V_{BO}$ (x)

$I_g = I_{g2}$, $V_a = 20\%\ V_{BO}$ (Y)

$I_g = I_{g3}$, $V_a = 10\%\ V_{BO}$ (Z)

→ Once the thyristor is conducting, no gate current is required for the device to remain in 'on' state.



## 1.6 Turnoff methods of SCR (line commutation and forced commutation)

→ Thyristor turn off means bringing the device from forward conduction state to forward blocking state.

→ A thyristor can be turned off by reducing the forward current to a level below the holding current ($I_H$).

→ So in order to turn off SCR the condition to be satisfied are given below as :→

(a) $I_a < I_H$

(b) A reverse voltage is applied to SCR for sufficient time to enable it to recover it's blocking state.

### Commutation

→ Commutation is defined as the process of turning off a device.

Commutation

- Line commutation or Natural commutation
- Forced commutation

* Class 'F' commutation (Line commutation)

* Class A commutation → Load commutation
* Class B commutation → Resonant - pulse commutation
* Class C commutation → Complementary commutation
* Class D commutation → Impulse commutation

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| | |
|---|---|
| → It occurs in Ac circuit | → It occurs in DC circuit |
| → SCR turn-off when negative voltage appear across the SCR. | → Forced commutation is achieved by applying reverse voltage across SCR or by reducing SCR current below the holding current |
| → No external commutation circuit is required to turn-off the SCR. | → External commutation circuit is required to turnoff the SCR. |

## Line commutation

→ This can occurs only when the source is 'ac'.

→ when an SCR is energised from 'ac' source current has to pass through it's natural zero at the end of every positive half cycle.

→ when a reverse voltage appear across the SCR, it immediately turn-off the device.

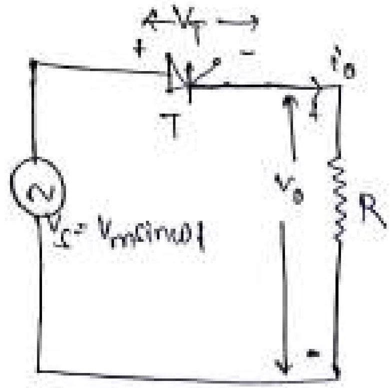
→ This process is called as natural commutation since no external circuit is required for this purpose.

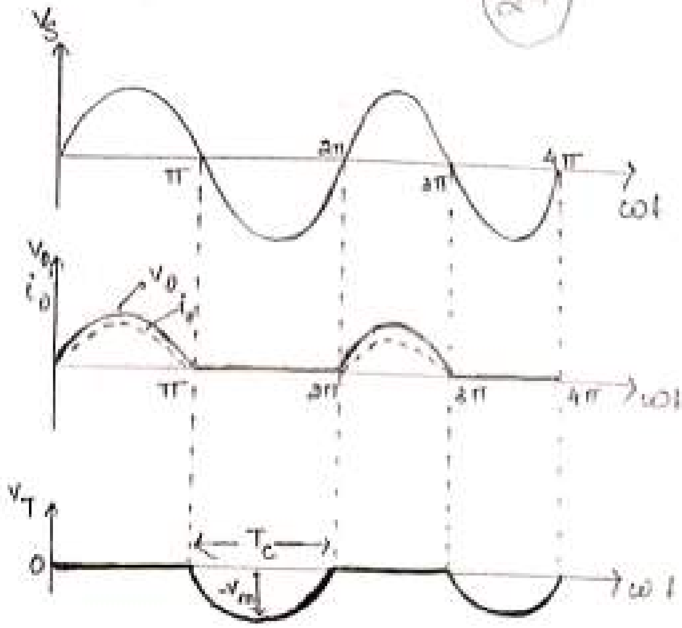
## Application of this types of commutation

① phase controlled rectifier

② Ac voltage controllers

③ cyclo-converter




## Forced commutation

→ This can occurs only when the source is 'dc'.

→ As external circuit is required for commutation process, so it is known as forced commutation.

→ The components (inductor 'L' and capacitor 'c') which constitute the commutating circuits are called as commutating components.

### Application of this type of commutation

→ DC - DC converter (chopper)

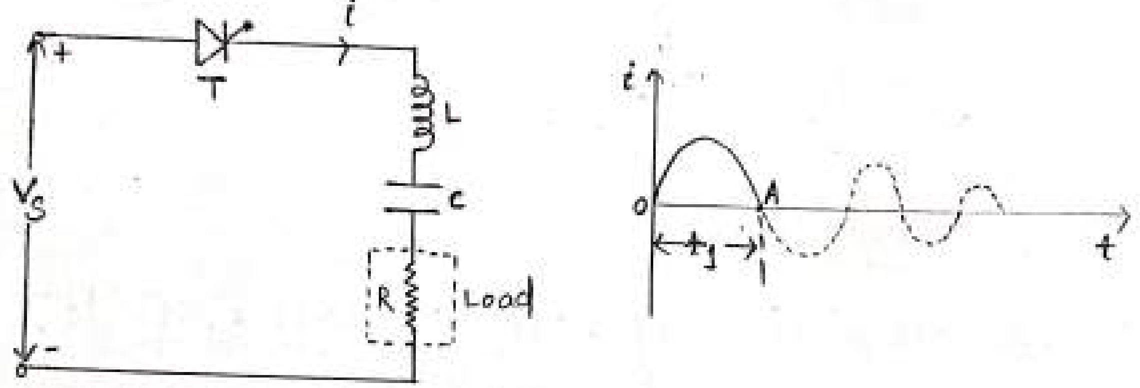
→ DC - AC converter (inverter)

## Class-A Commutation / Resonant commutation / Self-commutation / Load commutation

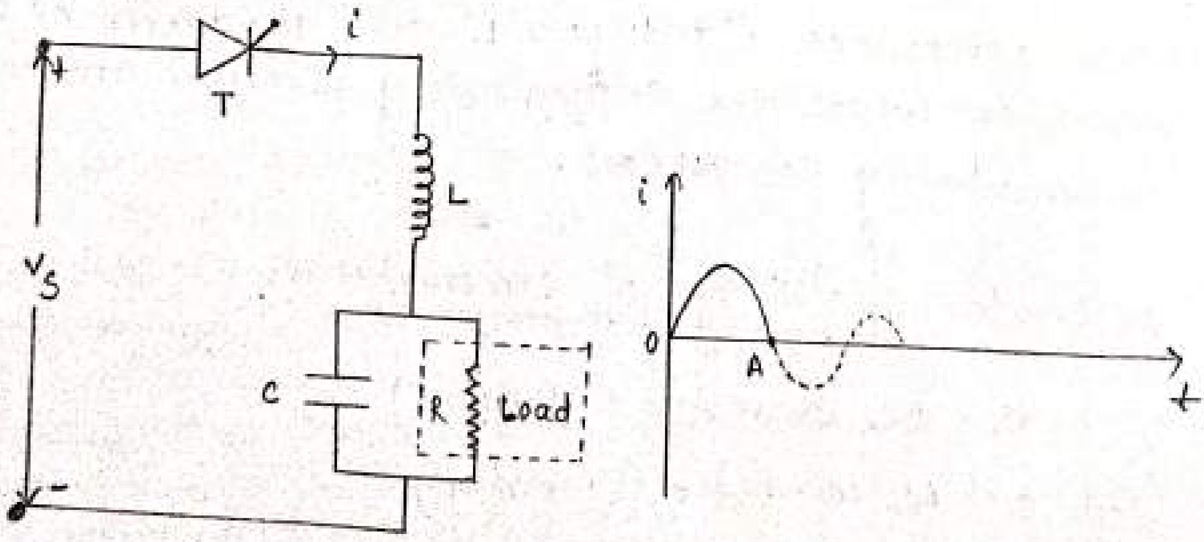


→ For Load commutation, the commutating components 'L' & 'C' are connected with load resistance 'R'.

→ For low value of 'R', 'L' & 'C' are connected in series with 'R'.




→ For high value of 'R', Load 'R' is connected across 'C'.




→ The value of 'L' and 'C' are selected such that with load resistance '$R_L$', the circuit forms an under damped, satisfying the condition

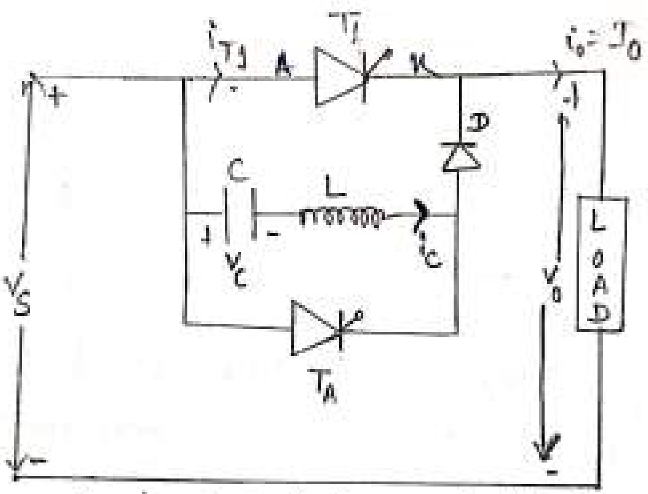
$R_L = 2\sqrt{\frac{L}{C}}$



→ At point '0', when the SCR is triggered, the current is rising initially up to maximum and then begins to fall.

→ At point 'A', current becomes zero through SCR and turn it off.

## Class-B commutation / Resonant-pulse commutation / Current commutation




In this method, SCR is turned off by gradual build-up of resonant current in the reverse direction i.e from 'K' to 'A' of SCR.

In the circuit diagram

$V_S$ = source voltage
$T_1$ = main thyristor
$T_A$ = Auxiliary thyristor
C = commutating capacitor
L = commutating inductor
D = Diode.

and $i_0$ = Load current
$i_{T1}$ = current flowing through main thyristor
$i_C$ = capacitor charging current
$V_C$ = voltage across capacitor

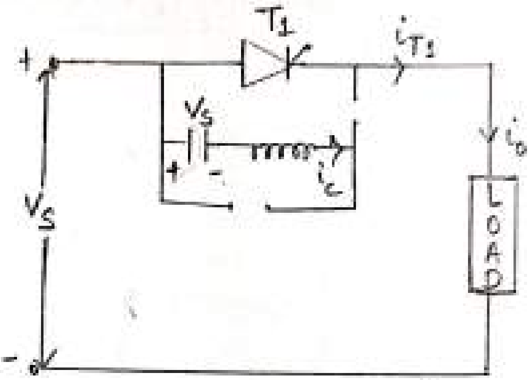
## Assumption

1. Capacitor is fully charged to a voltage '$V_s$'
   $V_C = V_S$
2. Load current is constant i.e $i_0 = I_0$

## Operation

**at $t = 0$** **$T_1$ = ON**

$i_0 = i_{T_1} = I_0$
$V_C = V_S$
$i_C = 0$

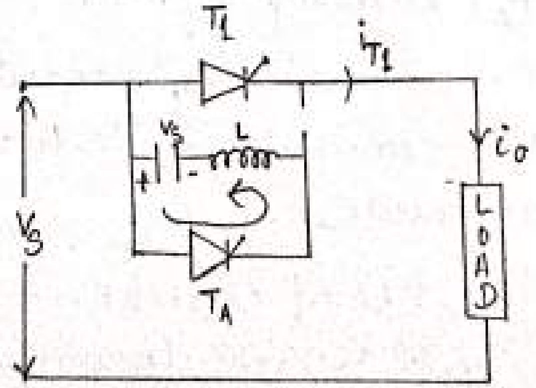



→ when SCR is triggered at $t=0$, then load current '$i_0$' flow through main thyristor '$T_1$' and load.

→ Now to turned-off this main thyristor '$T_1$', we have to triggered the auxiliary thyristor '$T_A$' at $t = t_1$.

**at $t = t_1$** **$T_A$ = ON**

$i_0 = i_{T_1} = I_0$
$V_C = V_S$ = start falling
$i_C$ = start rising in the negative direction



→ when $T_A$ is triggered at $t=t_1$, then a resonant current $i_c$ begins to flow through '$C^+$' - $T_A$ - L - $C^-$.



$$i_c = -V_c\sqrt{\frac{C}{L}}\sin\omega_0 t$$

$$\boxed{i_c = -I_p \sin\omega_0 t}$$

**At $t = t_1^+$**

$i_0 = i_{T_1} = I_0$

$V_c = 0$

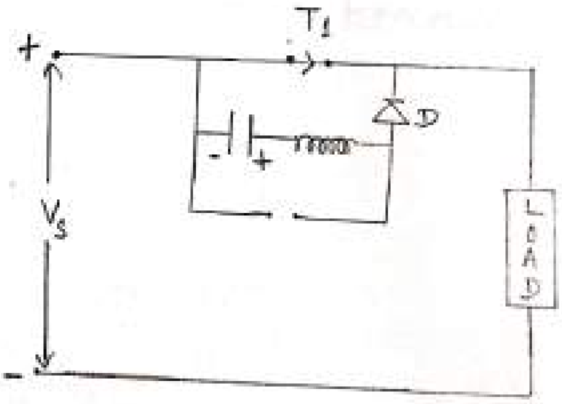
$i_c = -I_p$

→ Now capacitor start charging in the reverse direction and charging current fall from its negative peak value '$I_p$'.

**At $t = t_2$** **$T_A$ = off**

$V_c = -V_s$

$i_c = 0$



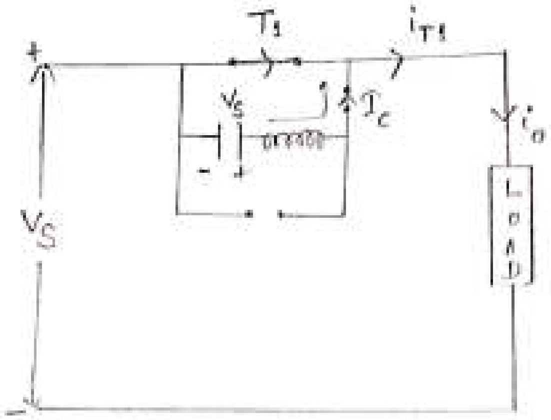

As capacitor is fully charged, it blocks the current flow through $T_A$ i.e $i_c = 0$. Therefore $T_A$ is turn-off and diode 'D' is forward biased.

**At $t = t_2^+$**

$i_0 = i_{T_1} + i_c = I_0$

$V_c$ = start rising from $-V_s$ to zero

$i_c$ = start rising in the positive direction from zero.



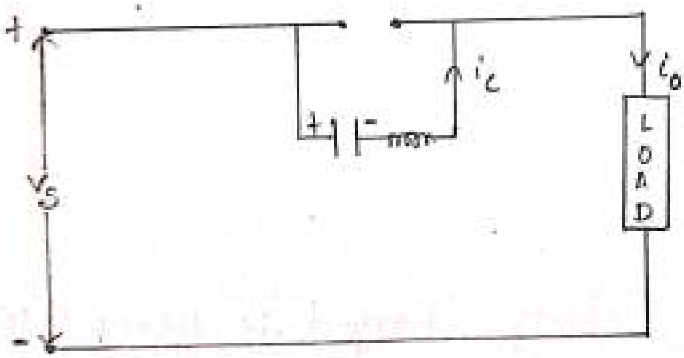

At $t = t_3$

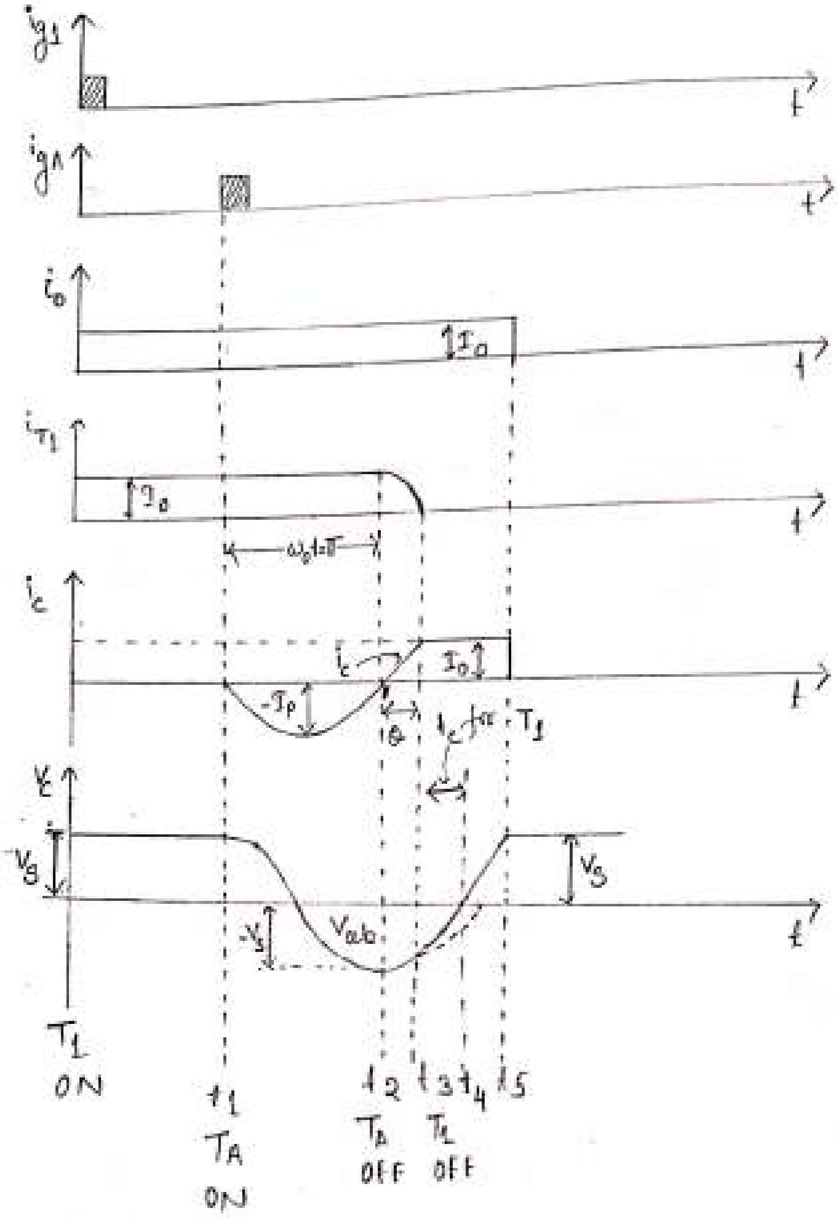
$i_{T_1} = I_0 - i_c$ (when $i_c = I_0$)

$\Rightarrow i_{T_1} = I_0 - I_0$

$\Rightarrow \boxed{i_{T_1} = 0}$

As current through thyristor $T_1$ becomes zero, it will be turned off.





$i_{g1}$
$i_{gA}$
$i_0$
$I_0$
$i_{T1}$
$I_0$
$\omega_0 t = \pi$
$i_c$
$I_0$
$-I_p$
$\theta$
$t_c$
$V_c$
$V_S$
$-V_S$
$V_{ab}$
$V_S$
$t$
$T_1$ ON
$t_1$ $T_A$ ON
$t_2$ $T_A$ OFF
$t_3$ $T_1$ OFF
$t_4$
$t_5$

# 1.7 Voltage & current Ratings of SCR

→ Thyristor ratings indicate voltage, current, power and temperature limits within which a thyristor can be used without damage or malfunction.

→ A thyristor has several ratings such as voltage, current, power, $dv/dt$, $di/dt$, turn-on time, turn-off time etc. For correct application of the device in thyristor circuits, a knowledge of these ratings is desirable.

1st subscript:
- D → forward-blocking region with gate circuit open
- T → on-state
- R → Reverse
- F → forward

2nd subscript:
- W → working value
- R → Repetitive value
- S → surge or non-repetitive value
- T → Trigger

3rd subscript:
- M → Maximum or peak value

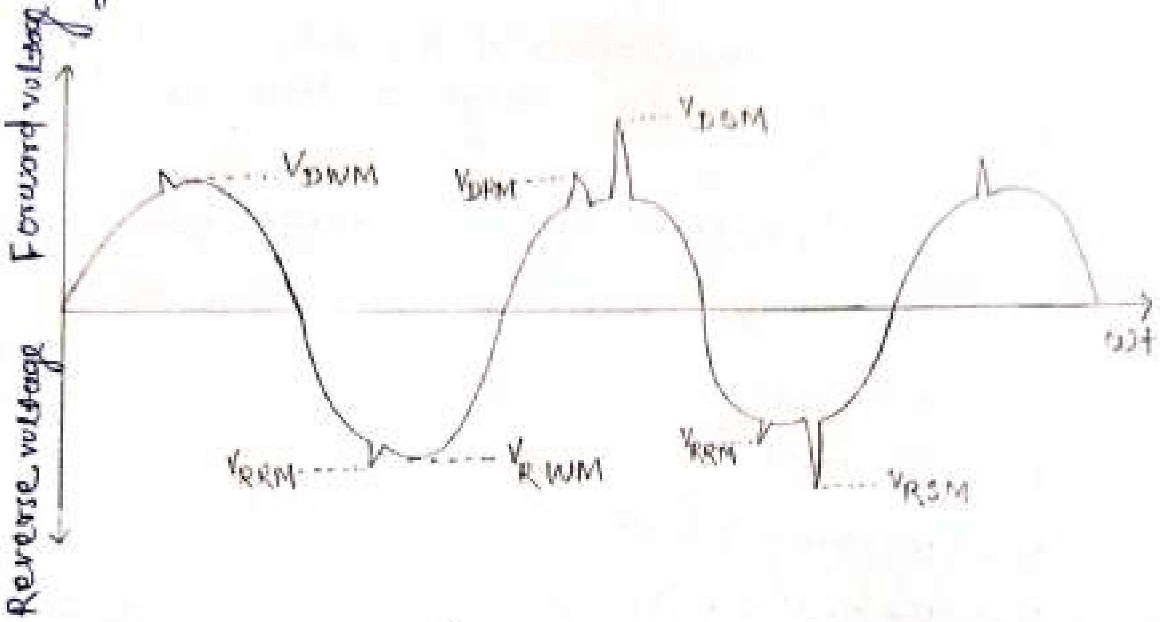
## Anode voltage Rating

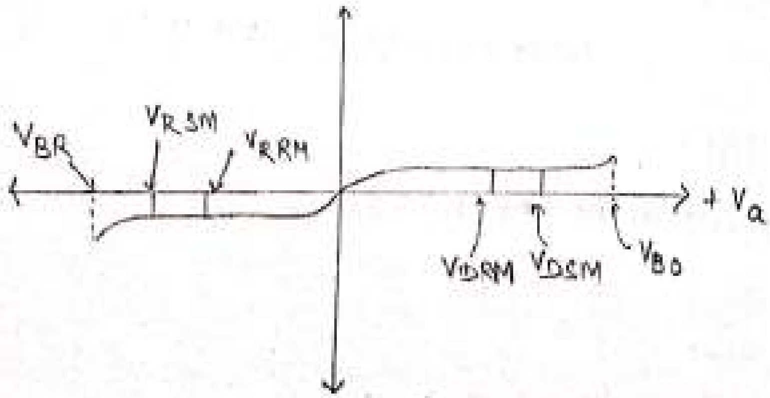
→ The anode voltage rating indicates the values of maximum voltages that a thyristor can withstand without a breakdown of the junction area with gate circuit open.

(i) $V_{DWM}$ → peak working forward-blocking voltage.

→ It specifies the maximum forward-blocking voltage that a thyristor can withstand during it's working.

→ $V_{DWM}$ is equal to the maximum value of sine voltage curve.




(ii) $V_{DRM}$ → peak repetitive forward-blocking voltage

→ It refers to the peak transient voltage that a thyristor can withstand repeatedly or periodically in it's forward blocking mode.

(iii) $V_{DSM}$ → peak surge (or non-repetitive) forward blocking voltage. 

→ It refers to the peak value of the forward surge voltage that does not repeat.

→ Its value is about 150% of $V_{DRM}$, but $V_{DSM}$ is less than forward breakover voltage ($V_{BO}$).

(iv) $V_{RWM}$ → peak working Reverse voltage

→ It is the maximum reverse voltage that a thyristor can withstand repeatedly.

→ It is equal to the peak negative value of a sine voltage wave.

(v) $V_{RRM}$ → peak repetitive reverse voltage

→ It specifies the peak reverse transient voltage that may occurs repeatedly in the reverse direction.

(vi) $V_{RSM}$ → peak surge (non-repetitive) reverse voltage

→ It represents the peak value of the reverse surge voltage that does not repeat.

→ Its value is about 150% of $V_{RRM}$. But $V_{RSM}$ is less than reverse breakdown voltage $V_{BR}$.

(vii) $V_T$ → on state voltage drop

→ It is the voltage drop between anode and cathode with specified forward on-state current and junction temperature.

→ Its value is of the order of 1 to 1.5 volt.

## (viii) forward dv/dt rating.

→ If the rate of rise of forward anode-to-cathode voltage is high, thyristor may turn-on even when

(a) There is no gate signal and

(b) anode-to-cathode voltage is less than forward breakover voltage.

→ A high value of $dv/dt$, at which a thyristor just gets turned on is called critical rate of rise of anode voltage or forward $dv/dt$ rating of the device.

→ The forward $dv/dt$ rating depends on the junction temperature. Higher the junction temperature, lower the forward $dv/dt$ rating of device.

## (ix) voltage safety factor ($V_{SF}$)

→ It is defined as the ratio of peak repetitive reverse voltage ($V_{RRM}$) to the maximum value of input voltage

$$V_{SF} = \frac{\text{peak repetitive reverse voltage } (V_{RRM})}{\sqrt{2} \times \text{rms value of input voltage}}$$

→ voltage safety factor is usually taken between 2 to 3.

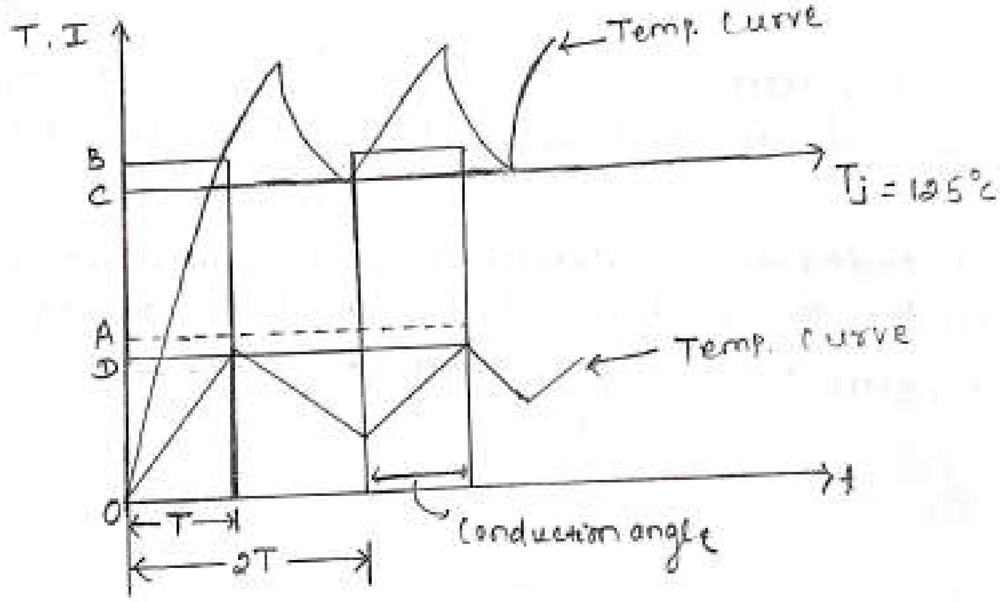
## (X) finger voltage

→ It is the minimum value of forward bias voltage between anode and cathode for turning-on the device by gate triggering.

## Anode current ratings

SCR is made up of semiconductor material which has quite small thermal capacity. Even for short currents, the junction temperature may exceed the rated value and the device may be damaged. Therefore a correct choice of current rating is essential for a long working of the device.

## Average on-state current ($I_{TAV}$)

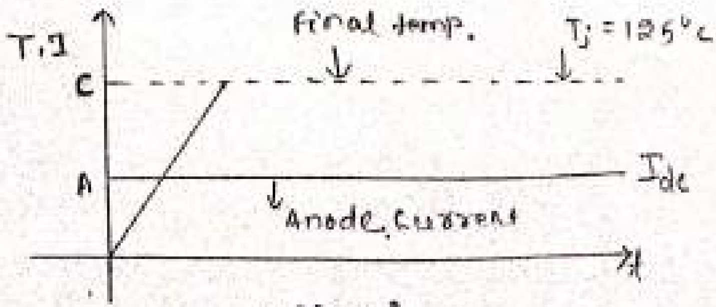



(Fig. 2)

Fig. 1

→ Consider a continuous 'dc' current 'OA' flowing through the SCR.

At $t=0$, the junction temperature starts rising and reach to its rated value within the less time, because SCR has low temp. co-efficient.




(Fig. 1)

Fig. 2

Consider, a rectangular pulse current flowing through the SCR, with magnitude OB = 2 [OA]

OA = average value of Rectangular wave

In this case also, as SCR has short time constant the junction temperature goes on increasing more than its normal value and than decrease slighly below it and so. But it is not desirable to have $T_j$ more than its normal value, so it should be reduced.

→ The above desire can be achieved by reducing the amplitude of anode current wave from OA to OD.

→ Thus inorder to maintain the junction temperature with in the specified limits, SCR must be rated at a lower value of average anode current ($I_{TAV}$)

## ② RMS current Rating :→

→ Generation of heat in the device present where resistive elements are present in the device.

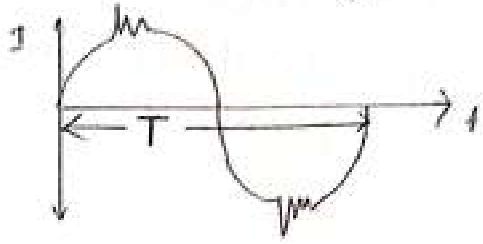
→ Resistive elements such as metallic joints are totally dependent upon RMS current as power loss is $I_{RMS}^2 \cdot R$ which convert to heat.

→ Hence, $I_{RMS}$ rating of a thyristor must be a suitable value so that maximum heat capability of SCR can not exceed.

## ③ Surge current Rating

→ Surge current rating indicates the maximum possible voltage or current that the device can withstand without any damage.

→ To overcome this problem a maximum allowable surge current rating is also specified by the manufacturer.




## ④ $I^2t$ rating of SCR

→ $I^2t$ rating is useful for selecting a fuse or any other protective equipment for the SCR.

$$I^2t \text{ rating} = \left[\text{RMS value of one cycle surge current}\right]^2 \times \left(\text{time for one cycle}\right)$$

## 5.8.1 Overvoltage protection



### (a) Internal overvoltage :→

→ Large voltage may be generated internally during the commutation of a thyristor. After the anode current reduces to zero, anode current reverses due to stored charges.

→ When the reverse current reaches to a peak value, then it decays with large $\frac{di}{dt}$.

→ Because of the series inductance (L) of the SCR circuit, large transient voltage $L\frac{di}{dt}$ is produced.

→ This internal over voltage may destroy the thyristor permanently.

### (b) External overvoltage :→

→ External over voltages are caused due to the interruption of current flow in an inductive circuit and also due to lightning strokes on the lines feeding the thyristor systems.

→ When a thyristor is fed through a transformer, voltage transients are occurs when the T/F primary is energised or de-energised.

→ For reliable operation, the over voltages must be suppressed.

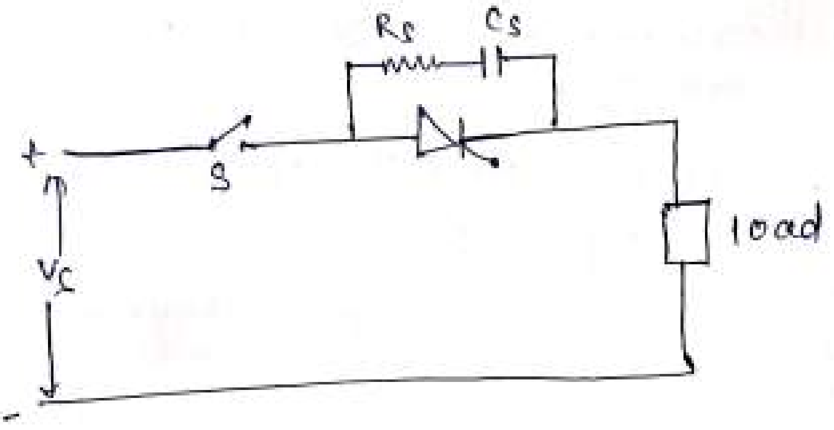
* Such over-voltages may cause random turn-on of a thyristor. As a result, the over voltage may appear across the load causing the flow of large fault current. over voltage may also damage the thyristor by an inverse breakdown.

1.8 Protection of SCR

## 1.8.1 Suppression of over voltage of SCR

The effect of over voltage is usually minimized by using snubber's circuit (RC circuit) and non-linear resistors called voltage clamping devices.

### ① Snubber circuit (RC circuit)




* If rate of rise of applied voltage across thyristor is high, the device may get turned on, by $\frac{dv}{dt}$ turn-on methods and it leads a false operation. This false operation may be controlled by a snubber ckt.

* $\uparrow I_c = \frac{c\,dv}{dt} \uparrow$

when $I_c \uparrow$, then, a false or unwanted operation occurred through the SCR.

* When SCR is turned-on, the capacitor discharges through the SCR and send a current equal to

$$\uparrow I = \frac{V_s}{\left(\text{Resistance of local path formed by } c_s \text{ and SCR}\right)}$$

(44)

→ A series combination of resistor ($R_s$) and capacitor ($C_s$) is called as snubber ckt. They are connected across the SCR to protect it from high $\frac{dv}{dt}$ value.

→ capacitor ($C_s$) is used to limit the $\frac{dv}{dt}$ across SCR.

→ The resistor ($R_s$) is used to limit high discharging current through the SCR.

→ when switch (S) is closed, the capacitor ($C_s$) behaves like a short circuit, and the voltage across SCR is zero. with the increase in time the voltage across '$C_s$' increases at a slow rate, and $C_s$ charges to full voltage $V_s$.

→ when the SCR is turn-on, capacitor discharges through the SCR and send a current which is very high due to low resistance.

→ In order to limit the magnitude of discharge current, a resistance ($R_s$) is inserted in series with $C_s$.

* Function of snubber :→

→ It provides a local path for internal over voltages caused by reverse recovery current.

→ snubber ckt is also helping in damping over voltage transient spikes and for limiting $\frac{dv}{dt}$ across the thyristor.

→ snubber ckts are also connected across T/F secondary terminals to supress overvoltage transient caused by switching on or switching off of the primary winding.

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## Voltage clamping device

→ It is a non linear register called varistor (variable + resistor) connected across the SCR.

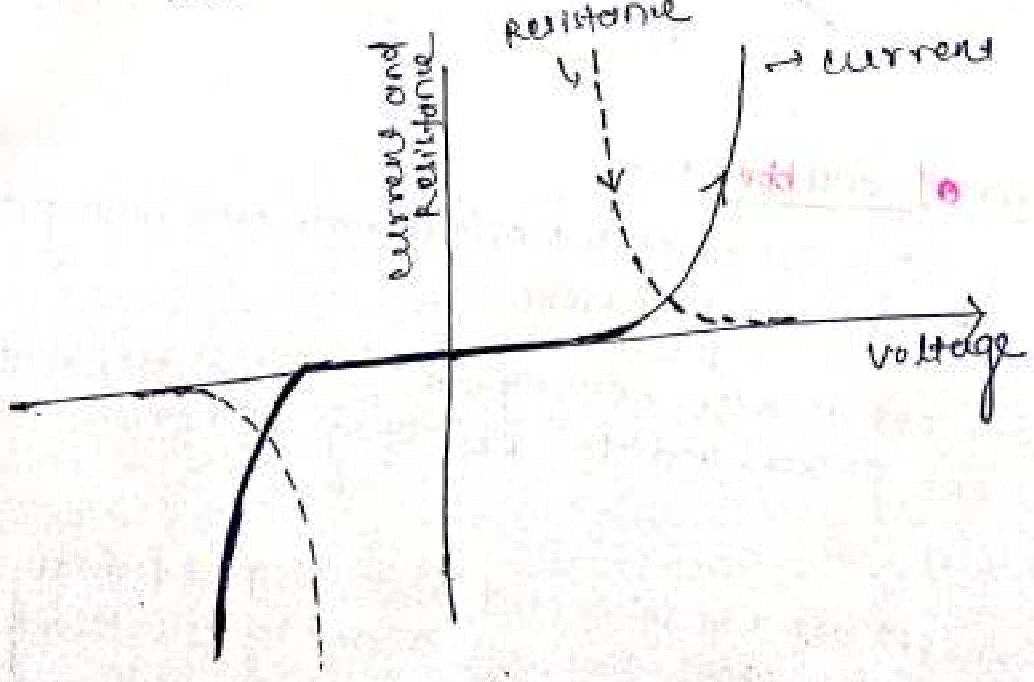
→ The resistance of varistor will decreases with increase in voltage.

→ During normal operation it has high resistance and draws only a small leakage current.

→ When high voltage appears across SCR, it operates in low resistance region and the surge energy is dissipated across the resistance by producing a virtual short circuit across the SCR.

→ After the surge energy is dissipated in the non linear resistor, the operation of the V.C device returns to its high resistance region.

Ex:→ selenium thyrector diodes metal oxide varistor (MOV) and avalanche diode suppressors.




* RC snubber ckt is not enough for overvoltage protection of SCR. therefore, a combined protection consisting of RC snubber and V.C device is provided to thyristor.

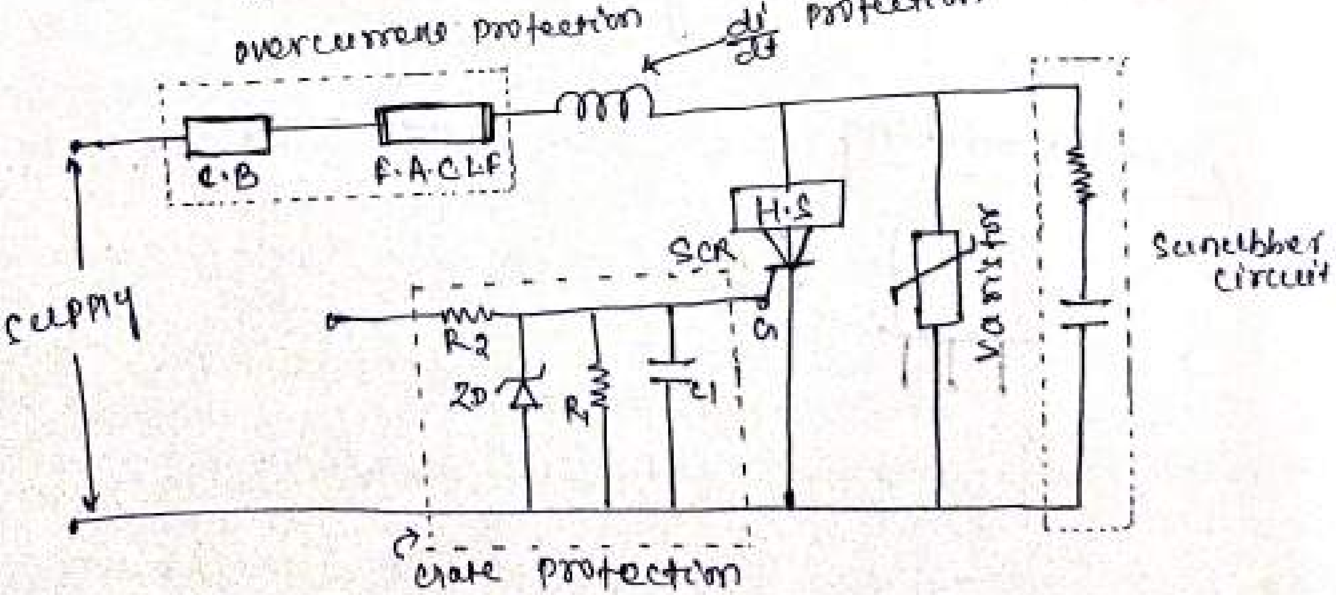
## Overcurrent protection

→ If a thyristor is subjected to overcurrent due to faults, short circuits or surge current. if the junction temperature may exceed the rated value, then the device may damage.

* over current occurs due to different types of fault in the circuit.
* Due to overcurrent. $I^2R$ loss will increase and high generation of heat may take place that may exceed the permissible limit and burn the device.

### Protection

* SCR can be protected from over current by using circuit breaker and fast acting current limiting fuses (FACLF). are used for the protection of thyristor from overload or surge current.
* circuit breakers are used from surge current of long duration as circuit breaker has long tripping time.
* But the fast acting fuses is used for protection of SCR from large surge currents of short duration.




(Circuit components showing the thyristor protection)

# Thermal protection

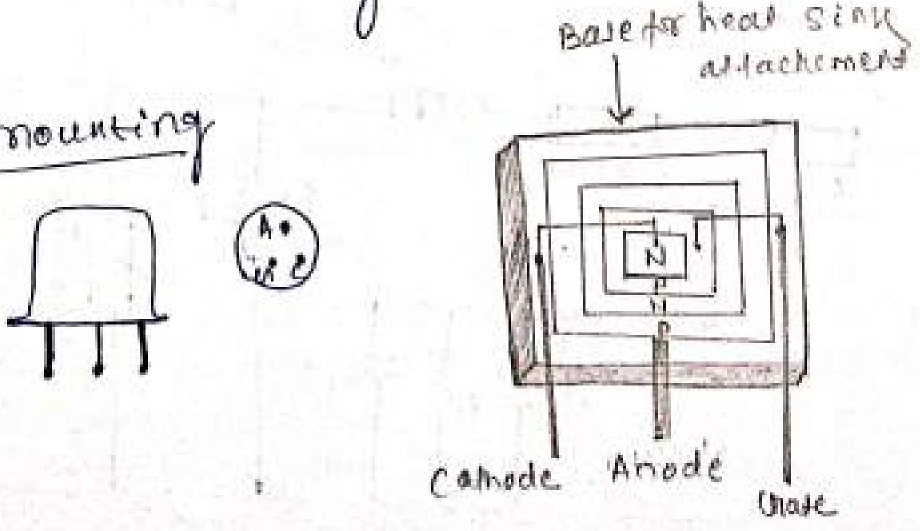
With the increase in the temperature of the junction, insulation may get failed and SCR may damaged. So thermal protection achieve by mounting heat sink over SCR.

* It is basically a heat exchanger that radiate heat by conduction or convection method to the surrounding parts or liquid or air and reduce heat.

* This heat sink which is mounting over SCR is basically a high thermal conductivity metals like Aluminium (Al), copper (Cu) etc. mainly Aluminium is used due to it's low rate.

* There are several types of mounting techniques for SCR such as
  - i) Lead mounting
  - ii) Stud mounting
  - iii) Bolt-down mounting,
  - iv) press-fit mounting
  - v) press-pack mounting

i) Lead mounting



## Gate protection

* **over voltage!** →

→ over voltage across the gate circuit can cause false triggering of the SCR.

→ protection against over-voltages is achieved by connecting a zener diode (ZD) across the gate circuit.

* **over current!** →

→ over current may raise junction temperature beyond specified limit leading to it's damage

→ A resistor $R_2$ connected in series with the gate circuit provides protection against overcurrents.

* Noise signal in gate circuit can also cause false triggering which can be avoided by using a resistor and a capacitor in parallel.

→ Noise is unwanted electrical or electromagnetic energy that degrades the quality of signals and data.

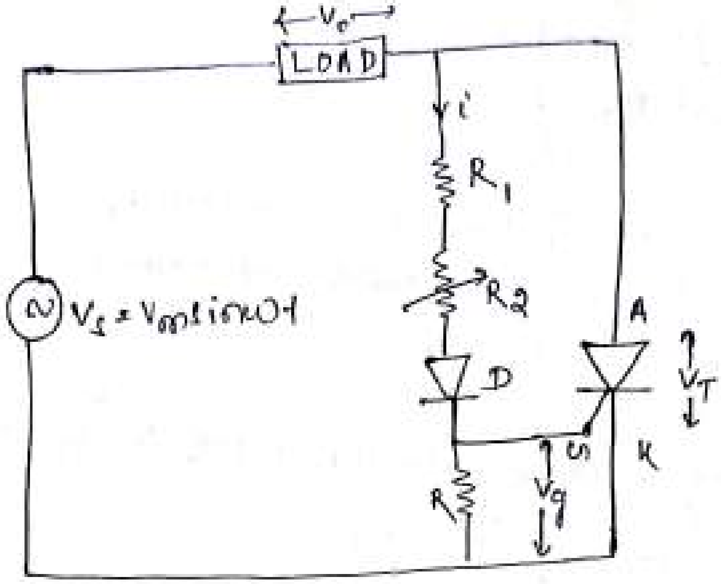
→ Noise occurs in digital and analog systems, and can affect files and communications of all types, including text, programs, images, audio and telemetry.

* Gate protection against such spurious firing is obtained by using shield cables or twisted gate leads.

* Radio interference phenomenon → electromagnetic interference.

## 1.9.2 Resistance firing circuit (R-firing circuit)

* R-firing circuit is the simplest and most economical method of firing.
* Limit Range of firing angle control is '0' to '90' degree.




(R-firing ckt)

$R_1$ = Basic resistance
$R_2$ = variable resistance
R = stabilizing resistance
D = (diode) = allow the flow of current during the half cycle only
(i.e. gate voltage $V_g$ is half-wave dc pulse)

→ when $R_2$ is zero, gate current may flow from source to $R_1$, D and gate to cathode.

→ This current should not exceed maximum permissible gate current ($I_{gm}$).

$$\frac{V_m}{R_1} \leq I_{gm}$$

So $$\boxed{R_1 \geq \frac{V_m}{I_{gm}}}$$

where $V_m$ = maximum value of source voltage

$I_{gm}$ = maximum value of gate current.

→ Resistance '$R_1$' is used to limit the gate current to a safe value as $R_2$ is varied

→ Resistance 'R' should have such a value that voltage drop across this resistance should not exceed the maximum possible gate voltage ($V_{gm}$).

By putting voltage divider rule, the voltage across 'R' is given by ($R_2 = 0$)

$$\frac{V_m R}{R_1 + R} \leq V_{gm}$$

$$\Rightarrow V_m R \leq V_{gm} R_1 + V_{gm} R$$

$$\Rightarrow R(V_m - V_{gm}) \leq V_{gm} R_1$$

$$\Rightarrow \boxed{R \leq \frac{V_{gm} R_1}{V_m - V_{gm}}}$$

→ As resistance $R_1$ and $R_2$ are large, gate triggering circuit draws a small current.

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The potentiometer setting $R_2$ determines the gate voltage amplitude. When $R_2$ is large, current 'i' is small and the voltage across R, i.e. $v_g = iR$ is also small.

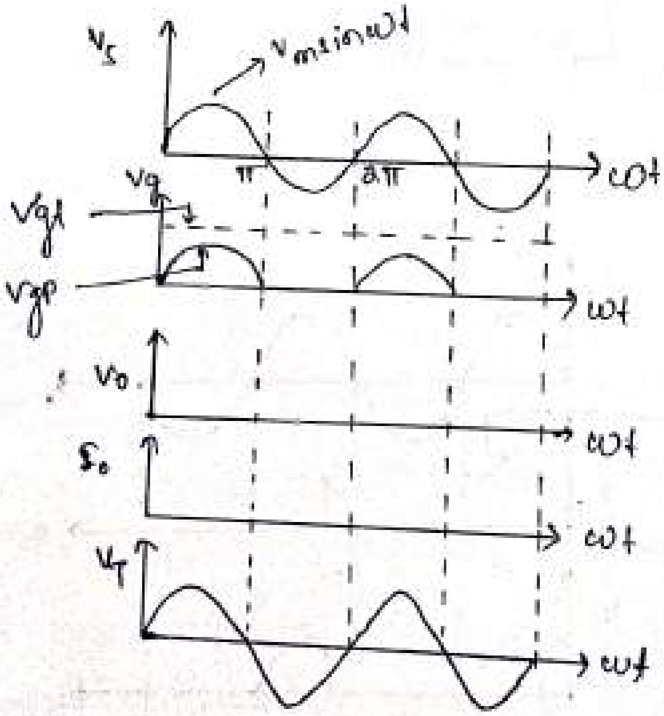
Case-1 ($v_{gp} < v_{gt}$)

where $v_{gp}$ = (peak value of gate voltage $v_g$)

$v_{gt}$ = (gate triggering voltage)

→ As $v_{gp}$ is less than $v_{gt}$, SCR will not turn on. Therefore load voltage $v_0 = 0$, $i_0 = 0$ and supply voltage $v_s$ appear as $V_T$ across SCR.

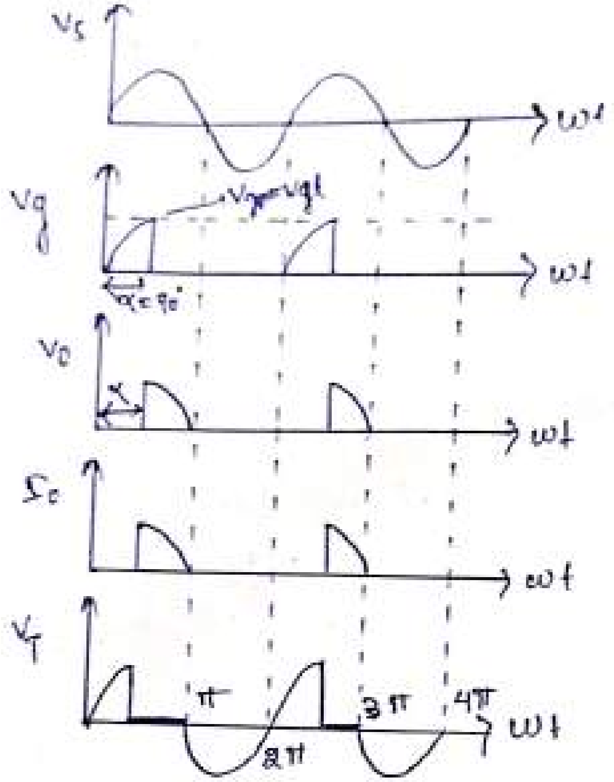
* As triggering circuit consist of resistance only, so $v_g$ is in-phase with the source voltage $v_s$.



(case-1)

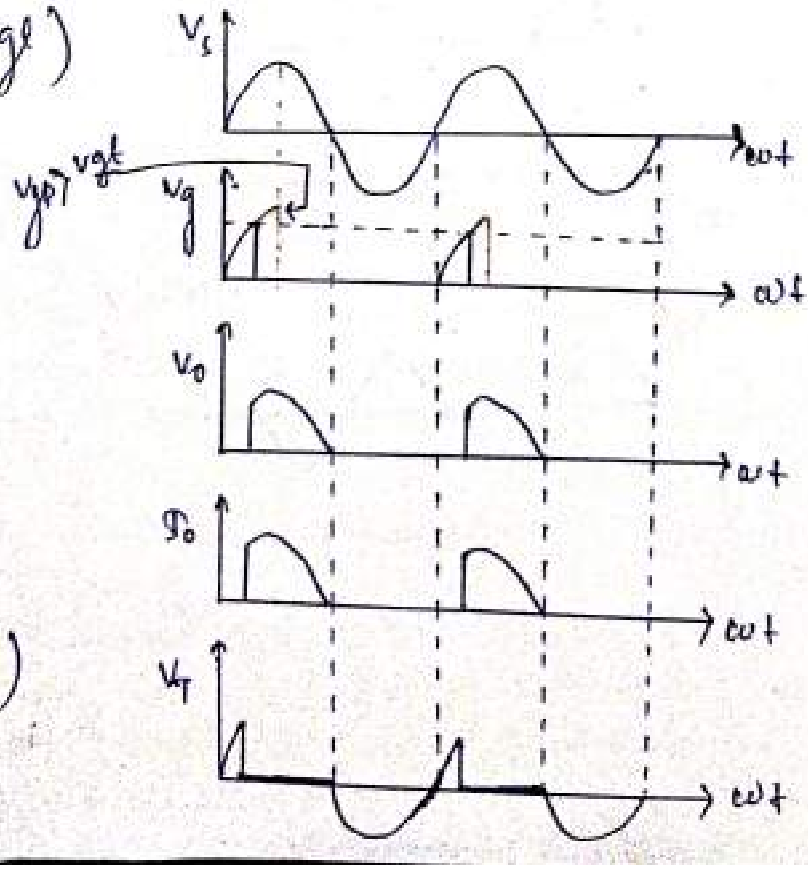
## Case-2 ($V_{gp} = V_{gt}$)

→ Resistance $R_2$ is adjusted such that $V_{gp} = V_{gt}$. This gives the firing angle at 90°.




($\alpha = 90°$)

## Case-3 ($V_{gp} > V_{gt}$)




($\alpha' < 90°$)

→ as soon as $v_g$ becomes equal to $V_{gt}$ for first time SCR is turned on at a firing angle less than 90°.

* when $v_g$ reaches $V_{gt}$ for the first time, SCR fires, gate loses control and $v_g$ is reduced to almost zero (about 1V).

* It may also be seen that firing angle can never be equal to zero degree.

<u>Relation between $V_{gp}$, $V_{gt}$ and 'α'</u>

The relation between these three is given by

$$V_{gp} \sin\alpha = V_{gt}$$

$$\Rightarrow \sin\alpha = \frac{V_{gt}}{V_{gp}}$$

Now, $V_{gp} = \frac{V_m R}{R_1 + R_2 + R}$

$$\Rightarrow \alpha = \sin^{-1}\left(\frac{V_{gt}}{V_{gp}}\right)$$

$$\Rightarrow \alpha = \sin^{-1}\left(\frac{V_{gt}}{\frac{V_m R}{R_1 + R_2 + R}}\right)$$

$$\Rightarrow \alpha = \sin^{-1}\left[\frac{V_{gt}(R_1 + R_2 + R)}{V_m R}\right]$$

In the above equation the value of $R_1, R, V_m$ and $V_{gt}$ are constant.

so $\alpha = \sin^{-1}(R_2)$

$$\boxed{\alpha \propto R_2}$$

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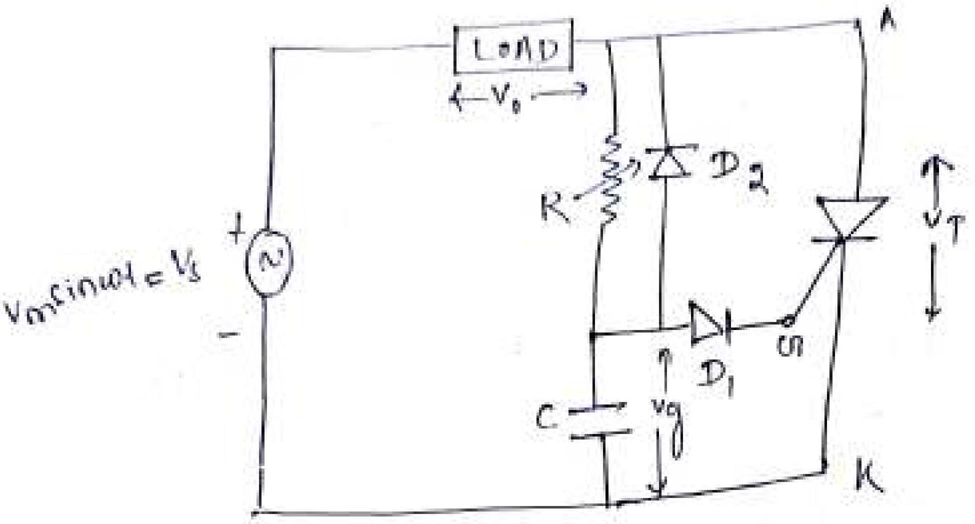
1.9.3

## RC-firing circuit

* The limited range of firing angle control by resistance firing circuit can be overcome by RC firing ckt.

### (a) RC half-wave trigger circuit




→ By varying the value of 'R' firing angle can be controlled from zero to 180°.

→ In the negative half cycle, capacitor 'C' charges through $D_2$ with lower plate '+ve' to the peak supply voltage $V_m$ at $\omega t = -90°$

→ After $\omega t = -90°$ the source voltage decreases from $-V_m$ at $\omega t = -90°$ to zero at $\omega t = 0$

→ During this period capacitor voltage '$V_c$' may fall from $-V_m$ at $\omega t = -90°$ to some lower value 'oa' at $\omega t = 0°$

→ As the SCR anode voltage passes through zero to positive half cycle, the capacitor charges through variable resistance 'R' from the initial voltage '-oa' to gate trigger voltage '$V_{gt}$'.

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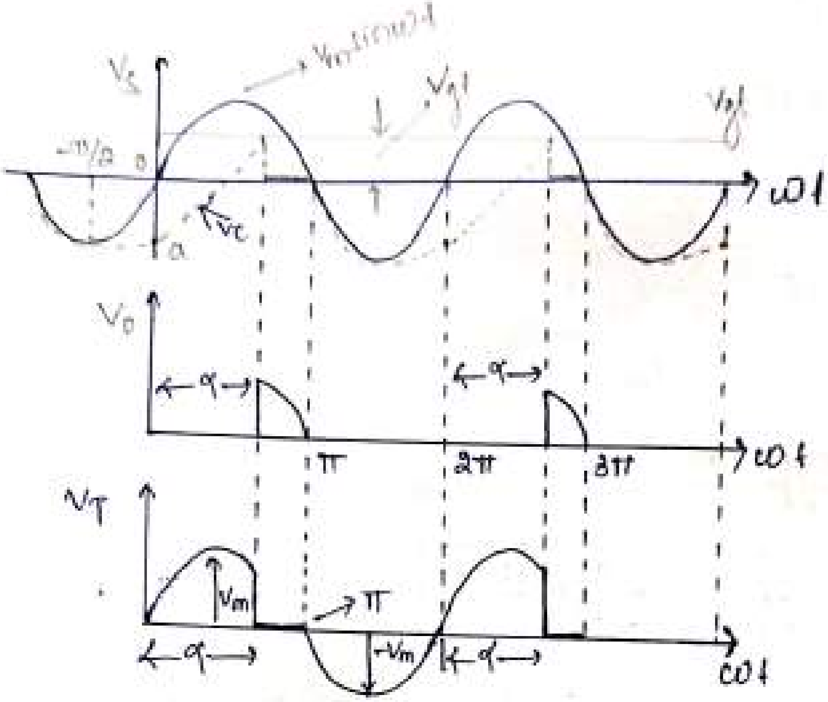
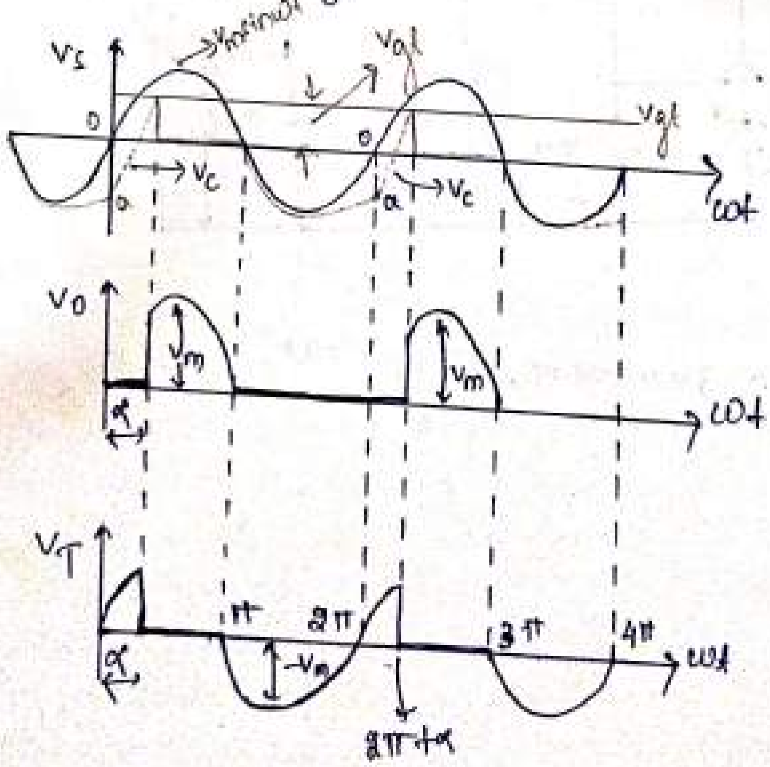
→ when capacitor voltage is equal to '$V_{gt}$', SCR is fired and start conducting.

→ During the half cycle, the diode $D_1$ prevent the breakdown of the gate to cathode junction.




(For high value of R)




(For low value of R)

SCR will trigger when

$$V_C = V_{gt} + V_d$$

where $V_C$ : voltage across capacitor

$V_{gt}$ : gate triggering voltage

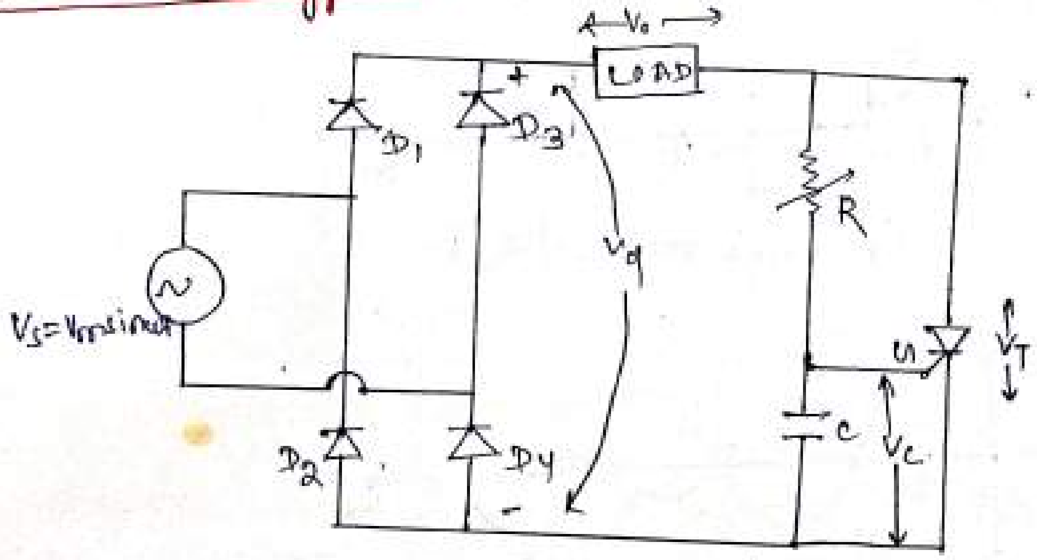
$V_d$ : voltage across diode

$$V_s \geq R I_{gt} + V_C$$

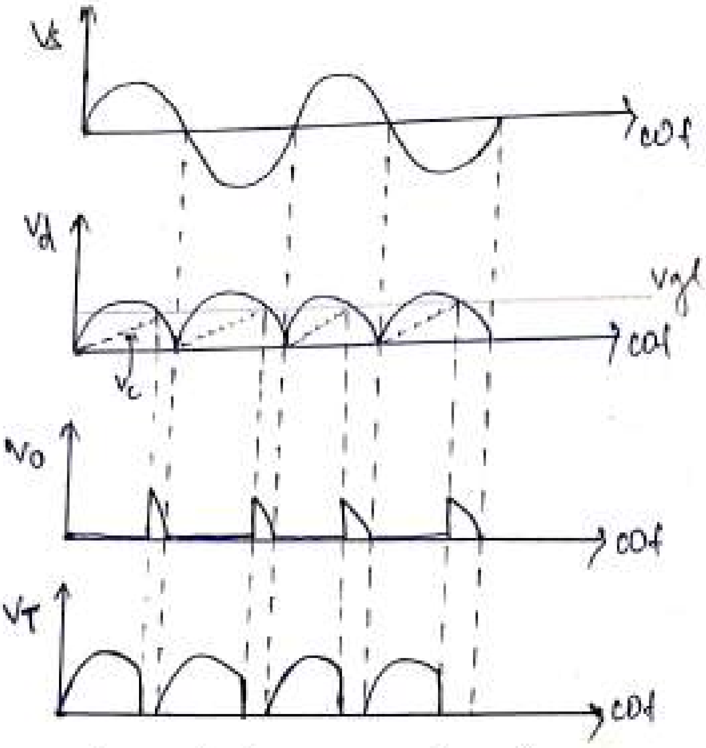
$$V_s \geq R I_{gt} + V_{gt} + V_d$$

$$R \leq \frac{V_s - V_{gt} - V_d}{I_{gt}}$$

## RC Full-wave trigger ckt




RC - full wave trigger ckt



(for high value of R)

→ In the positive half cycle the capacitor charges through $D_1$ and $D_4$ when the capacitor voltage $V_c$ reaches $V_{gt}$, the SCR is fired.

→ During the negative half cycle the capacitor charges through $D_3$ & $D_3$.

$$R \leq \frac{V_s - V_{gt}}{I_{gt}}$$

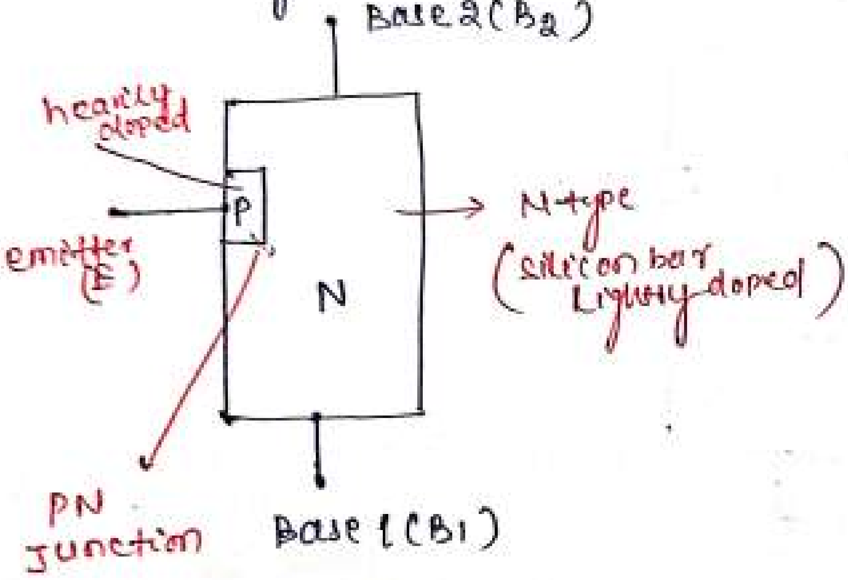
## UJT (Unijunction Transistor)

→ An UJT is made up of an N-type silicon bared to which P-type emitter is embedded.

→ The N-type base is lightly doped where as P-type is heavily doped.

→ The two ohmic contacts are provided at each end are called base-one ($B_1$) and base-two ($B_2$). So UJT has 3 terminals emitter (E), $B_1$ and $B_2$

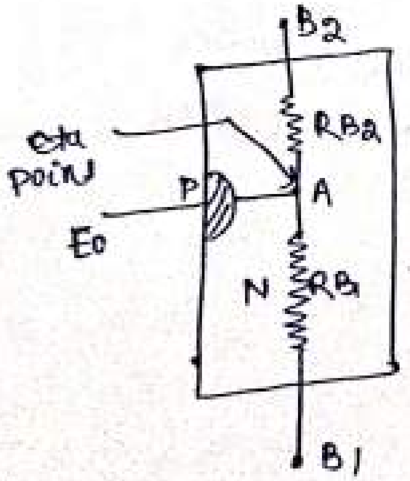
→ $R_{B1}$ and $R_{B2}$ are the internal resistances from $B_1$ and $B_2$ to the point 'A' respectively and they behaves like an ordinary resistance.



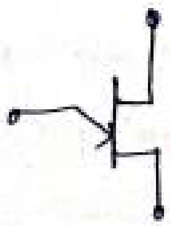

'p' is near to base '2' so $R_{B2}$ is less than $R_{B1}$

$$R_{B2} << R_{B1}$$

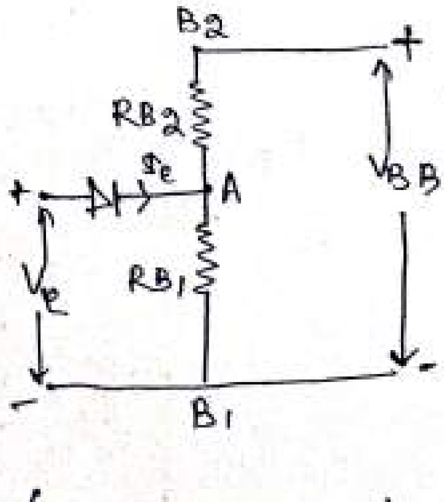
$$R_{BB} = R_{B1} + R_{B2}$$




(Basic structure)



(symbol)




(equivalent ckt)

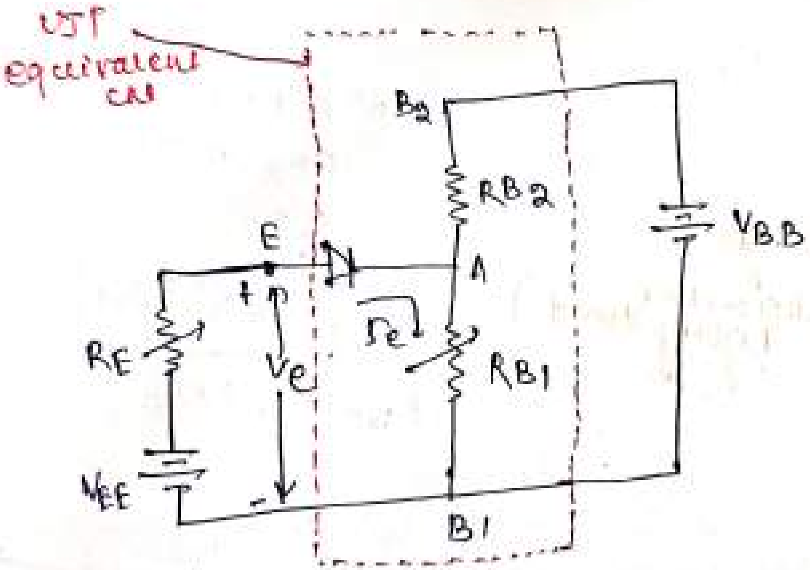
$$V_{RB1} = \frac{V_{BB} R_{B1}}{R_{B1}+R_{B2}}$$

$$\Rightarrow V_{RB1} = \frac{R_{B1}}{R_{B1}+R_{B2}} V_{BB}$$

$$\Rightarrow \boxed{V_{RB1} = \eta V_{BB}}$$

$\eta$ = Intrinsic stand-off ratio (0.51 to 0.82)

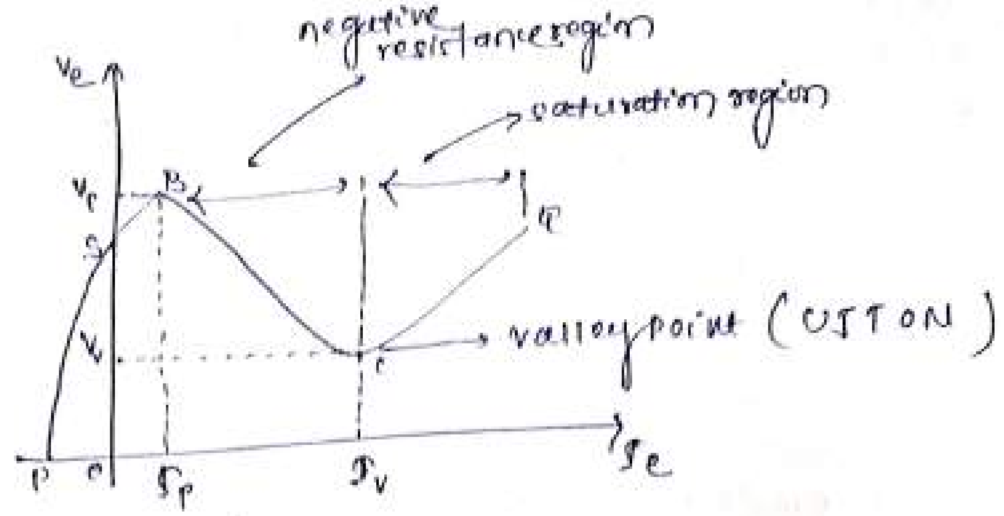
## V-I characteristics of UJT




$R_{BB} = R_{B1} + R_{B2}$

if Diode low Resistance F.B → closed switch
High Resistance R.B → open switch

$$\boxed{I_e = \frac{V_{EE} - V_D}{R_{B1} + R_E}}$$




→ A constant 'DC' voltage source '$V_{BB}$' is applied b/w $B_1$ and $B_2$ and a 'dc' source $V_{EE}$ is in series with '$R_E$' is applied in b/w 'E' and B1.

$$\text{so} \quad V_{RB1} = \frac{V_{BB} \cdot RB1}{RB1 + RB2} = \eta V_{BB}$$

→ The magnitude of voltage '$V_E$' can be varied by regulating external resistance $R_E$.

→ A region 'PS' is obtained when the voltage '$V_E$' < $\eta V_{BB}$ & the emitter current $I_e$ is -ve as the E-B1 junction is reverse biased.

→ The region 'PS' of very low current is treated as 'off' state of UJT & the resistance b/w E-$B_1$ ($R_1$) junction is very high.

→ At peak point 'B', the emitter voltage $V_e = \eta V_{BB} + V_D$. and the diode becomes F.B and $I_e$ is positive.

Scanned with OKEN Scanner

→ At this point, the resistance $R_{B1}$ begins to decrease as more no. of holes are injected from heavily doped emitter 'E' into the lower base B1. With this, the potential of $\eta V_{BB}$ will decrease.

$$\downarrow V_{RB1} = \downarrow \eta V_{BB} = \frac{\downarrow R_{B1}}{(R_{B1}+R_{B2})} V_{BB}$$

→ The emitter voltage ($V_e$) decrease as emitter current ($I_e$) increase till the point 'C' is reached, and the region 'BC' is called as the negative resistance region.

→ The point 'C' is called valley point and $V_V$ and $I_V$ are valley point voltage and valley point current respectively.

→ At this point diode is completely saturated with carriers and the $R_1$ is remains constant.

→ When the valley point is reached the UJT is 'ON' and with increase in '$I_e$' cause an increase in '$V_e$' and is indicated by the point 'CQ' which is known as saturation region.

* At valley point, the current $(I_V) = \frac{V_V}{R_{B1}}$
* valley point current is also called as holding current. and keep UJT ON.
* when emitter current ($I_e$) falls below $I_V$, UJT off.

(1)

# Phase controlled Rectifier

Silicon Controlled Rectifier (SCR)

As we know that the silicon controlled rectifier is so named because silicon material is used for it's construction and it's operation as a rectifier can be controlled.

## Rectifier :→

A Rectifier is a circuit, which converts 'ac' power into 'Dc' power.

## converters :→

A converter is a circuit which converts the nature of energy namely from 'ac' to 'dc' or from 'dc' to 'ac'.

Thus, a converter has 2 mode of operation namely

1) 'ac' to 'dc' i.e as a rectifier
2) 'dc' to 'ac' i.e as a inverter

so every rectifier is a converter but every converter need not be a rectifier so based on the convenience, rectifiers are classified into 3 types namely.

1) uncontrolled Rectifier
2) Fully controlled Rectifiers
3) half-controlled Rectifiers / semi-controlled.

## Uncontrolled Rectifier

In case of uncontrolled rectifier there is no possibility to change the conduction as well as the magnitude of output voltage.

* The ckt contain only diode
* The o/p voltage amplitude is fixed by the amplitude of the dc supply.

Eg - diode 

## Fully-controlled Rectifier

In case of controlled rectifier there is a possibility to change the conduction as well as the magnitude of output voltage.

* The ckt consist of only SCR

Eg - SCR 

## Semicontrolled / half-controlled Rectifier

The half-controlled rectifier contain a mixture of diode and thyristors.

eg → diode + SCR

* Allowing a more limit control over the d.c output voltage level than the fully-controlled rectifier.
* The half-controlled Rectifier is cheaper than a fully-controlled rectifier of the same rating.

## Application

1) Aerospace application
2) For battery driven vehicles
3) Electric traction system
4) Textile mills
5) Rolling mills
6) paper industry
7) printing press
8) High voltage dc transmission
9) portable hand tool drives

(3–7) } Many industries application make use of controllable dc power.

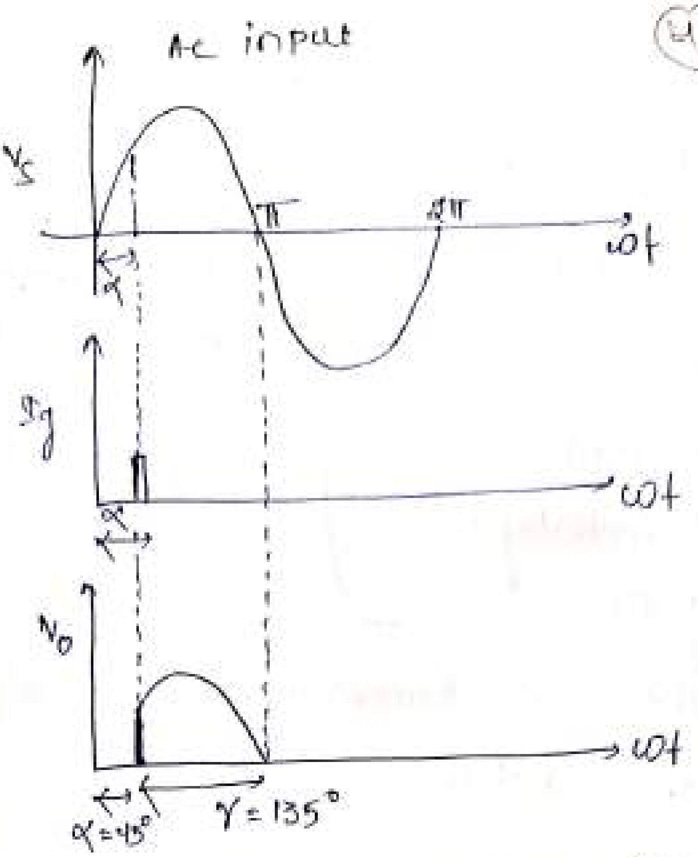
* Earlier, dc power was obtained from Motor-generator (MG) sets or ac power was converted to dc power by means of mercury-arc rectifier or thyratrons.

## Firing angles ($\alpha$) / duty angles

It is define as the angle measured from the instant SCR gets forward biased to the instant it is triggered.

OR

Firing angle is the angular time after the input voltage start to go positive until the thyristor is fired at $\omega t = \alpha$.




α = firing angle or delay angle

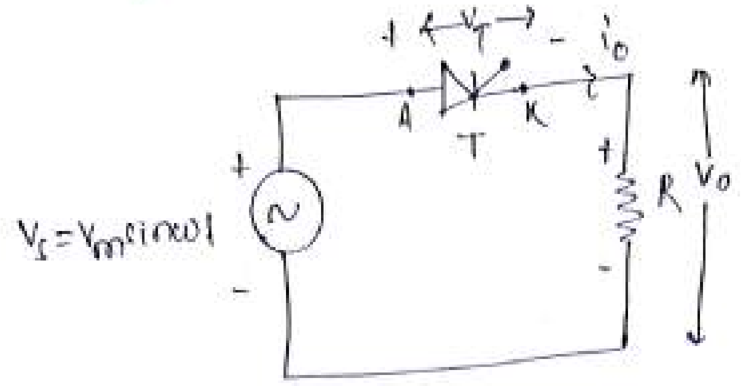
γ = conduction angle.

## Conduction angle

conduction angle is defined as the angle between the instant the SCR is triggered and the instant at which the SCR is turned off.

## 2.2 Single-phase half-wave controlled Rectifier with R-Load

(3)




→ The ckt is energised by a 'ac' source voltage i.e $V_s = V_m \sin \omega t$

→ During the positive half-cycle of the supply voltage the anode of thyristor is +ve w.r.to it's cathode and it block the flow of load current ($I_0$) until the thyristor is triggered by a gate pulse

→ when the thyristor is fired at angle 'α', then SCR will turn 'on' and a 'DC' output voltage ($V_0$) is applied to the load (R)

→ The load current will flow until it's commutated by reversal of supply voltage at $\omega t = \pi$

→ The angle $\pi - \alpha = \gamma$ during which the thyristor conducts is called as conduction angle.

### Equation for average load voltage

$$V_0 = E_{dc}(avg) = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t)$$

$$= \frac{V_m}{2\pi}\left[-\cos \omega t\right]_{\alpha}^{\pi}$$

(6)

$$\Rightarrow V_0 = \frac{V_m}{2\pi}\left[-\cos\pi + \cos\alpha\right]$$

$$\Rightarrow V_0 = \frac{V_m}{2\pi}\left[-(-1) + \cos\alpha\right]$$

$$\Rightarrow \boxed{V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)}$$

average load current $\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R}(1+\cos\alpha)}$

when $\alpha = 0$

$$V_0 = \frac{V_m}{2\pi}(1+\cos 0)$$

$$V_0 = \frac{V_m}{2\pi} 2 = \frac{V_m}{\pi}$$

$$I_0 = \frac{V_0}{R}$$

$$I_0 = \frac{V_m}{R\pi}$$

## Equation for Rms value of load voltage

$$V_{0(rms)} = \frac{1}{\sqrt{2\pi}}\left[\int_\alpha^\pi (V_m \sin\omega t)^2 \, d(\omega t)\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{2\pi}}\sqrt{\int_\alpha^\pi \sin^2\omega t \, d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2\pi}}\sqrt{\int_\alpha^\pi \frac{1-\cos 2\omega t}{2} \, d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2\pi}} \frac{1}{\sqrt{2}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_\alpha^\pi}$$

$$= \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[(\pi-\alpha) - \left(\frac{\sin 2\pi - \sin 2\alpha}{2}\right)\right]}$$

$$\Rightarrow V_{0(rms)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

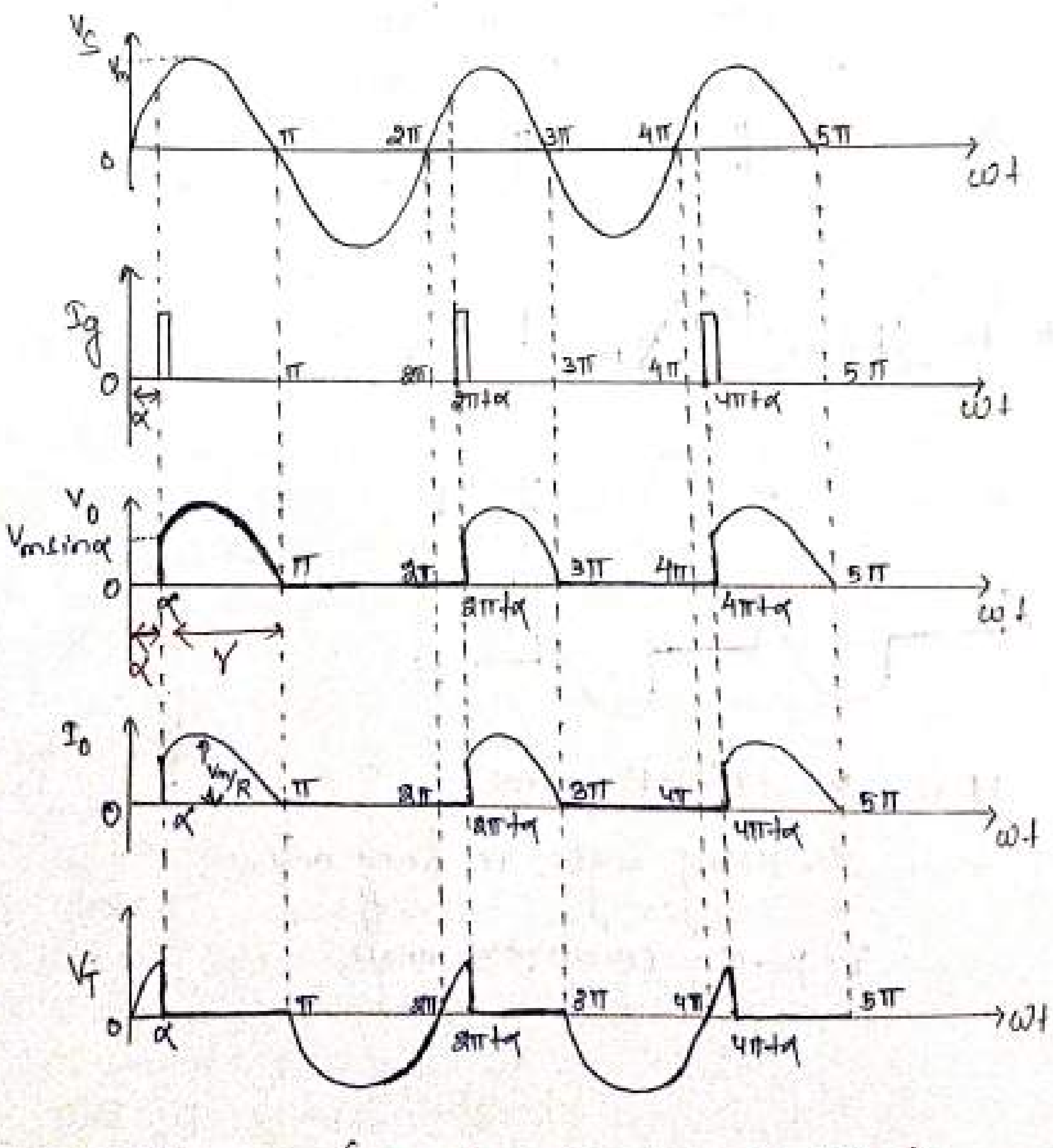
Value of Rms current $I_{o(rms)} = \frac{V_{o(rms)}}{R}$

Power delivered to resistive load $= I_{o(rms)} \times V_{o(rms)}$

$$= \frac{V^2_{o(rms)}}{R} = I^2_{o(rms)} \times R$$

input power factor $= \frac{\text{power delivered to load}}{\text{input VA}}$

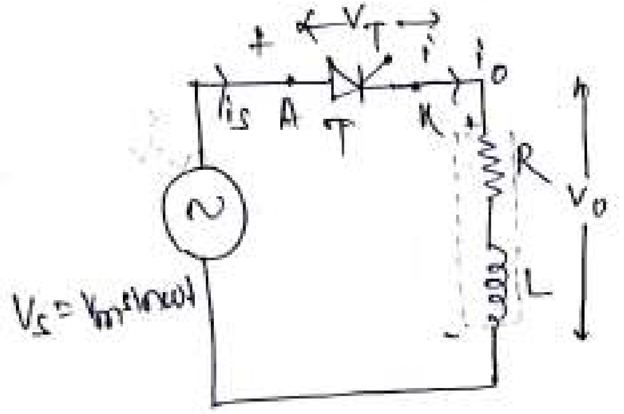
$$= \frac{V_{o(rms)} \, I_{o(rms)}}{V_s \, I_{o(rms)}} = \frac{V_{o(rms)}}{V_s}$$

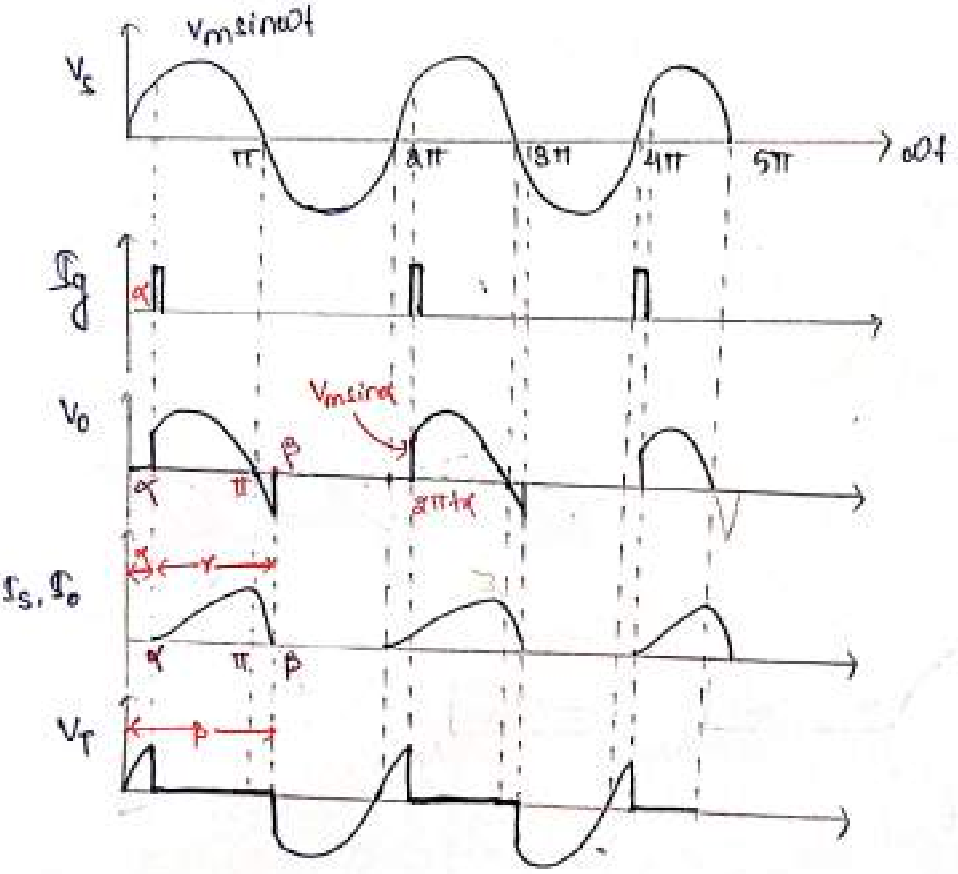



(Wave form for 1φ · half wave Controlled Rectifier)

# Single phase half-wave controlled Rectifier with R-L Load

8




Here β = extinction angle

α = delay angle or firing angle

γ = β − α = conduction angle

1) at $\omega t = \alpha$, thyristor is turned on by gating triggering signal and output voltage ($V_0$) is equal to source voltage ($V_s$)

2) Due to inductive load (L), the output current ($I_0$) increase gradually and energy is stored in inductor during time, $\alpha$ to $\pi$

3) At $\pi$, the output voltage ($V_0$) is at zero where the load current ($I_0$) is at it's maximum value.

4) After $\pi$, SCR is subjected to reverse biased, but it will not be turned off as load current ($I_0$) is greater than the holding current ($I_h$) [$I_0 > I_h$]

5) During $\pi$ to $\beta$, the inductor discharge it's stored energy and $I_0$ becomes zero at $\beta$, & T gets turned off.

at $\beta$: $V_0 = 0$
$I_0 = 0$
SCR = off

6) at $\omega t = 2\pi + \alpha$, SCR is triggered again, $V_0$ is applied to the load and load current ($I_0$) develops as before.

7) The half-wave ckt is not normally used since it produces a large output voltage ripple and is incapable of providing continuous load current.

## Equation for average load voltage

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\beta} = \frac{V_m}{2\pi}\left[-\cos\beta + \cos\alpha\right]$$

$$= \frac{V_m}{2\pi}\left[\cos\alpha - \cos\beta\right]$$

$$I_0 = \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$$

average load current

## Rms Load voltage

$$V_{or} = \left[\frac{1}{2\pi}\int_{\alpha}^{\beta} V_m^2 \sin^2\omega t \cdot d(\omega t)\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{2}\sqrt{\pi}}\sqrt{\int_{\alpha}^{\beta}\left(\frac{1-\cos 2\omega t}{2}\right) d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2}\sqrt{2}\sqrt{\pi}}\sqrt{\int_{\alpha}^{\beta}(1-\cos 2\omega t)\, d(\omega t)}$$

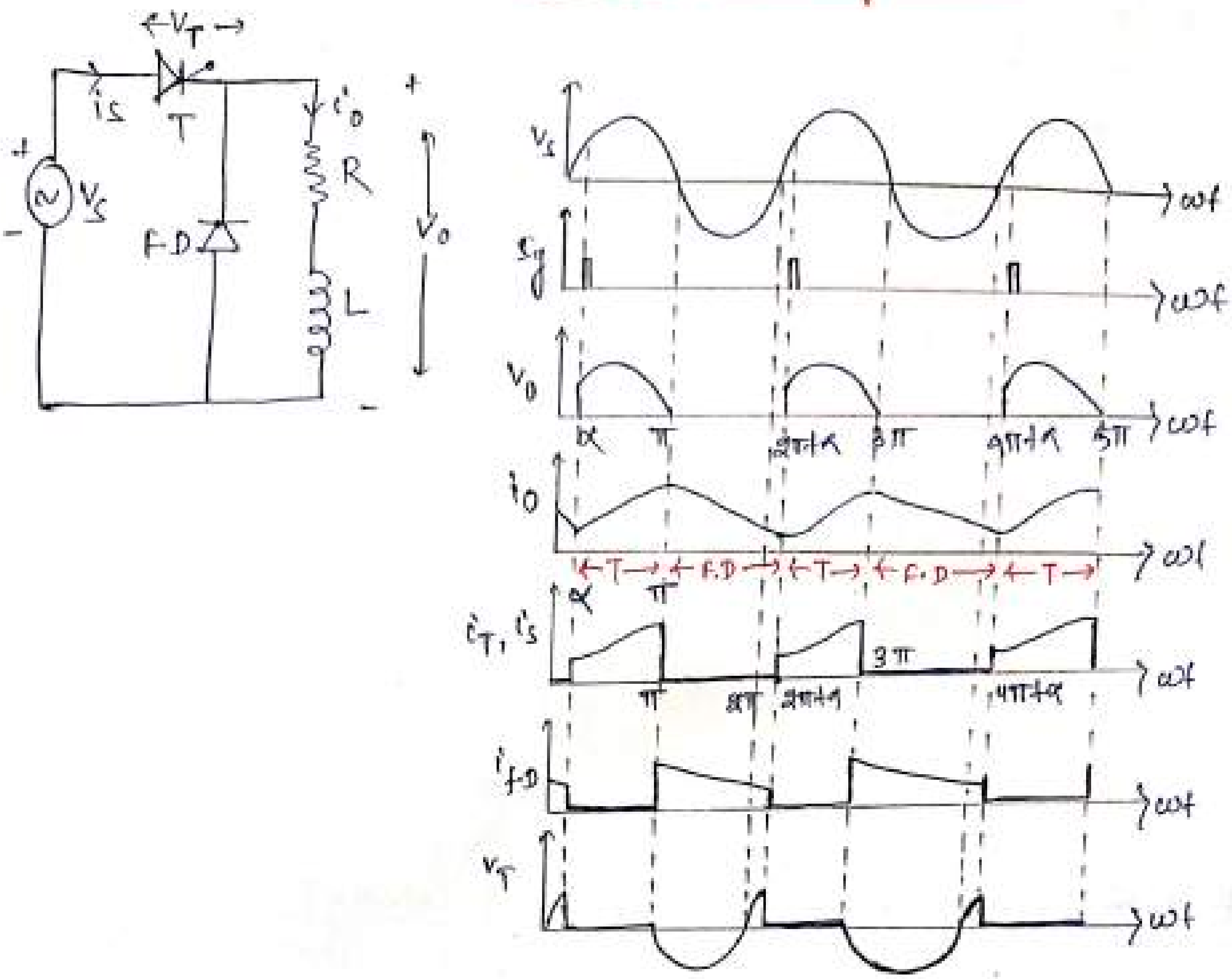
$$= \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\beta}}$$

$$\Rightarrow V_{or} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[(\beta-\alpha) - \frac{1}{2}(\sin 2\beta - \sin 2\alpha)\right]}$$

2.3

## Single phase half-wave converter with R-L Load and free wheeling diode

(11)




→ when thyristor (T) is triggered at angle 'α' then load current ($I_0$) flow through $V_s^+$ - T - R - L - $V_s^-$ & the output voltage ($V_0$) is equal to source voltage ($V_s$).

→ Due to inductive load (L), the output current ($I_0$) increase gradually and energy is stored in inductor during time α to π.

→ At ωt = π, the SCR is subjected to Reversed biased and freewheeling diode becomes forward biased and the inductor discharge it's energy through F.D. so ($I_0$) flows through $L^+$ - F.D - R - $L^-$.

→ under this mode, F D conduct from $\pi$ to $2\pi+\alpha$.

(12)

## Equation for average load voltage

$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$\Rightarrow V_0 = \frac{V_m}{2\pi}\int_{\alpha}^{\pi} \sin\omega t \, d(\omega t)$$

$$\Rightarrow V_0 = \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_m}{2\pi}\left(-\cos\pi + \cos\alpha\right)$$

$$\Rightarrow \boxed{V_0 = \frac{V_m}{2\pi}\left(1+\cos\alpha\right)}$$

## average load current

$$\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R}\left(1+\cos\alpha\right)}$$

## Equation for Rms value of load voltage

$$V_{0(rms)} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(V_m^2 \sin\omega t^2\right) d(\omega t)\right]^{\frac{1}{2}}$$

$$= \left[\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi}\left(\sin^2\omega t\right) d(\omega t)\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{2\pi}}\left\{\int_{\alpha}^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d(\omega t)\right\}^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{2\pi}}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}$$

$$= \frac{V_m}{2\sqrt{\pi}}\left[(\pi-\alpha) - \left(\frac{\cancel{\sin 2\pi}^{\,0} - \sin 2\alpha}{2}\right)\right]$$

$$\Rightarrow V_{0(rms)} = \frac{V_m}{2\sqrt{\pi}}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]$$

## Understanding need of freewheeling diode

→ It is also called as flywheel diode or commutating diode.

→ It is connected across the inductor to remove flyback voltage

(or)

freewheeling diode prevents the load voltage $V_0$ from becoming negative.

→ It transferred the load current ($I_0$) from main thyristor to F.D, by allowing the thyristor to regain its blocking state.

## Advantages

→ Improve the input power factor.

→ It improves the load current wave form.

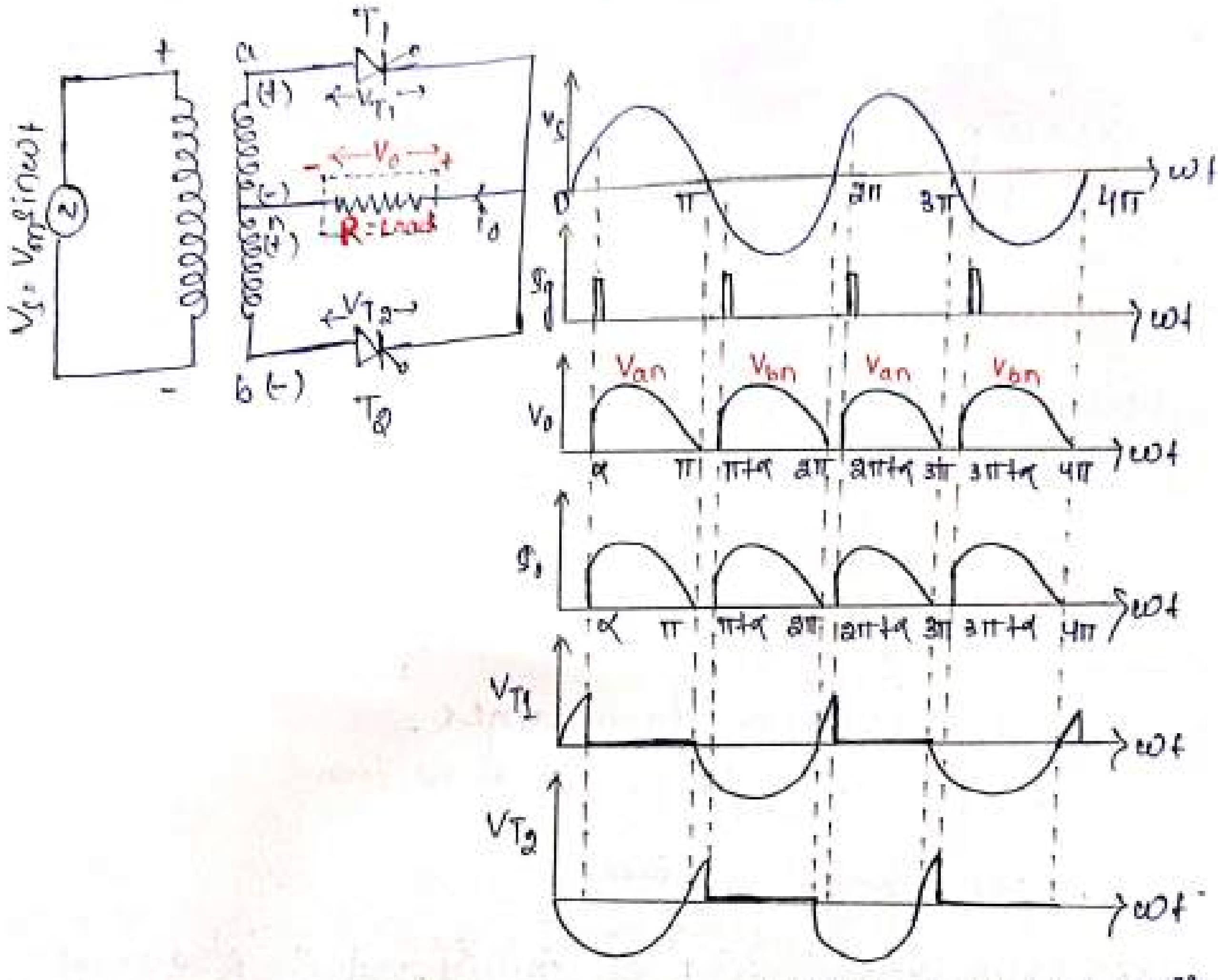
→ load performance is better

→ As energy stored in 'L' is transferred to 'R' during the freewheeling period, overall converter efficiency improves.

**Q.4** Full-wave Rectifier

1. Mid point type (2-SCR) R, R-L
2. Bridge type (4-SCR) R, R-L, R-L with F.D

## Single phase full-wave converter with R-Load (Mid point-type)




→ In this type of full wave rectifier, two SCRs are connected to centre tapped secondary of a Transformer.

→ During the +ve half cycle, when terminal 'a' of the transformer is +ve w.r.to terminal 'n', the SCR-1 is forward biased.

→ When SCR-1 is triggered at angle 'α', so flow through "a+ - T1 - R - n". The load current ($I_0$) continues to flow upto an angle π.

→ when line voltage change it's polarity then SCR-1 is turned off. (13)

→ During -ve half cycle of AC supply, the terminal 'b' is '+ve' w.r.to the terminal 'n' and SCR-2 is forward biased.

→ when SCR-2 is triggered at angle $\pi+\alpha$, then load current ($I_0$) flow through $b^+ - T_2 - R - n^-$. This current continues to flow upto $2\pi$ and then SCR-2 is turned off.

## Equation for average load voltage

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\int_{\alpha}^{\pi}\sin\omega t \, d(\omega t) = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos\pi + \cos\alpha\right] = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$\Rightarrow \boxed{V_0 = \frac{V_m}{\pi}(1+\cos\alpha)}$$

## average load current

$$\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R}(1+\cos\alpha)}$$

## Equation for Rms value of load voltage

$$V_{0(rms)} = \frac{1}{\sqrt{\pi}}\left[\int_{\alpha}^{\pi}(V_m \sin\omega t)^2 \, d(\omega t)\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{\pi}}\sqrt{\int_{\alpha}^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}}$$

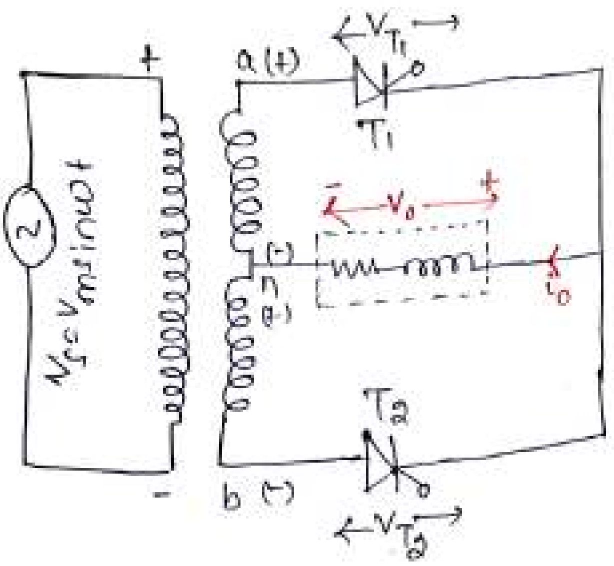
$$\Rightarrow V_{o(rms)} = \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{(\pi-\alpha) - \frac{(\sin 2\pi^{0} - \sin 2\alpha)}{2}}$$ (16)

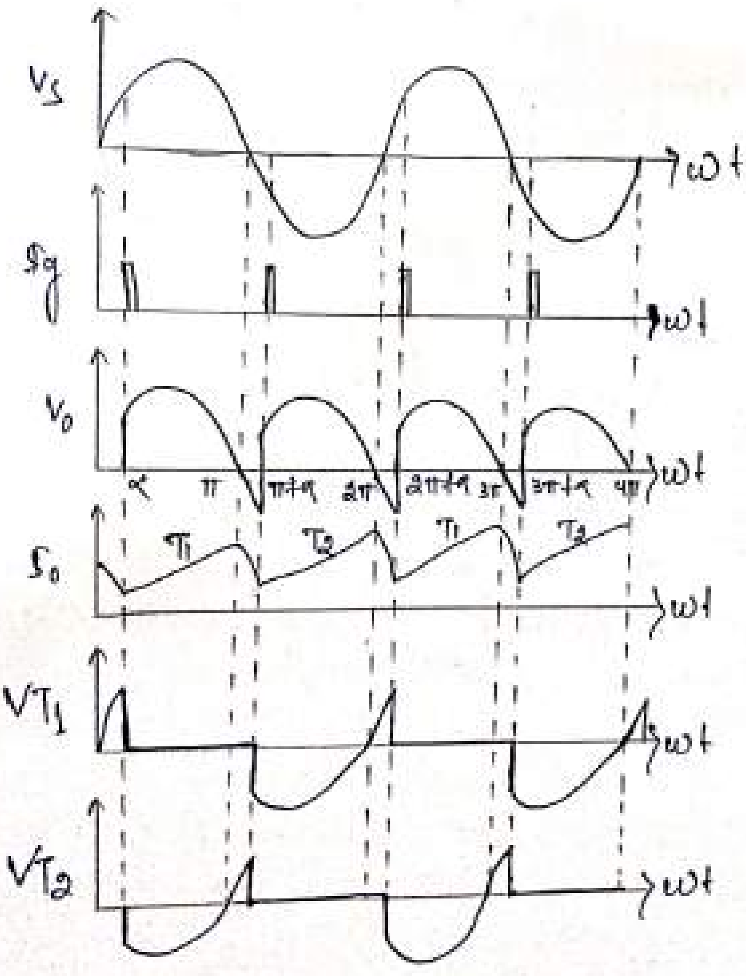
$$\Rightarrow V_{o(rms)} = \frac{V_m}{\sqrt{2}\,\sqrt{\pi}}\sqrt{\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$I_{o(rms)} = \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}\cdot R}\sqrt{(\pi-\alpha) + \left(\frac{\sin 2\alpha}{2}\right)}$$

# Single Phase Full-wave converter with R-L Load (Mid Point-type)





(12)

→ During the +ve half cycle of supply voltage, terminal 'a' is +ve w.r.to 'n'. The SCR-1 is forward biased.

→ When SCR-1 is triggered at angle 'α', the load current ($I_0$) flow through $a^+ - T_1 - R - L - n^-$. The ($I_0$) flow upto an angle $\pi + \alpha$.

→ During -ve half cycle of supply voltage, terminal 'b' is +ve w.r.to 'n'. The SCR-1 is turned off at $\pi + \alpha$. and SCR-2 is forward biased.

→ When SCR-2 is triggered at angle $\pi + \alpha$, then load current ($I_0$) flow through $b^+ - T_2 - R - L - n^-$. The $I_0$ continue to flow upto an angle $2\pi + \alpha$.

Eqn of average load voltage

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

$$\Rightarrow V_0 = \frac{V_m}{\pi} \int_{\alpha}^{\pi+\alpha} \sin \omega t \, d(\omega t)$$

$$\Rightarrow V_0 = \frac{V_m}{\pi} \left[ -\cos \omega t \right]_{\alpha}^{\pi+\alpha} = \frac{V_m}{\pi} \left[ -\cos(\pi + \alpha) + \cos \alpha \right]$$

$$\Rightarrow \boxed{V_0 = \frac{2V_m}{\pi} \cos \alpha}$$

average load current

$$\boxed{I_0 = \frac{V_0}{R} = \frac{2V_m}{R\pi} \cos \alpha}$$

Equation for rms value of load voltage

$$V_{o(rms)} = \frac{1}{\sqrt{\pi}}\left[\int_{\alpha}^{\pi+\alpha} \left[V_m^2 \sin^2 \omega t\right] d(\omega t)\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{\pi}}\left[\int_{\alpha}^{\pi+\alpha}\left(\frac{1-\cos 2\omega t}{2}\right) d\,\omega t\right]^{\frac{1}{2}}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}}$$

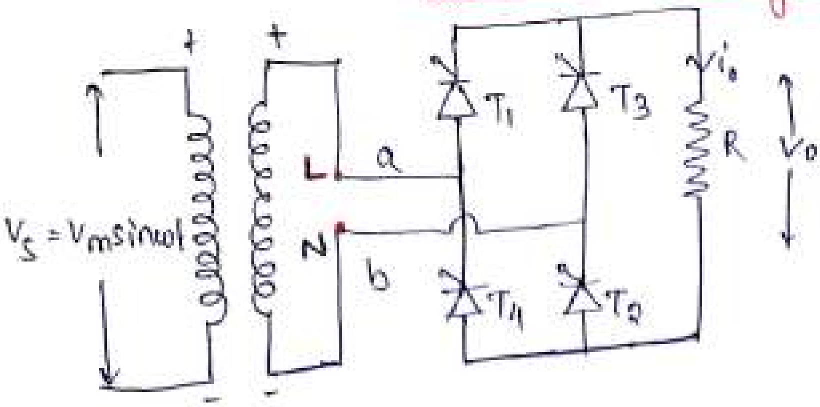
$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{(\pi+\alpha-\alpha) - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

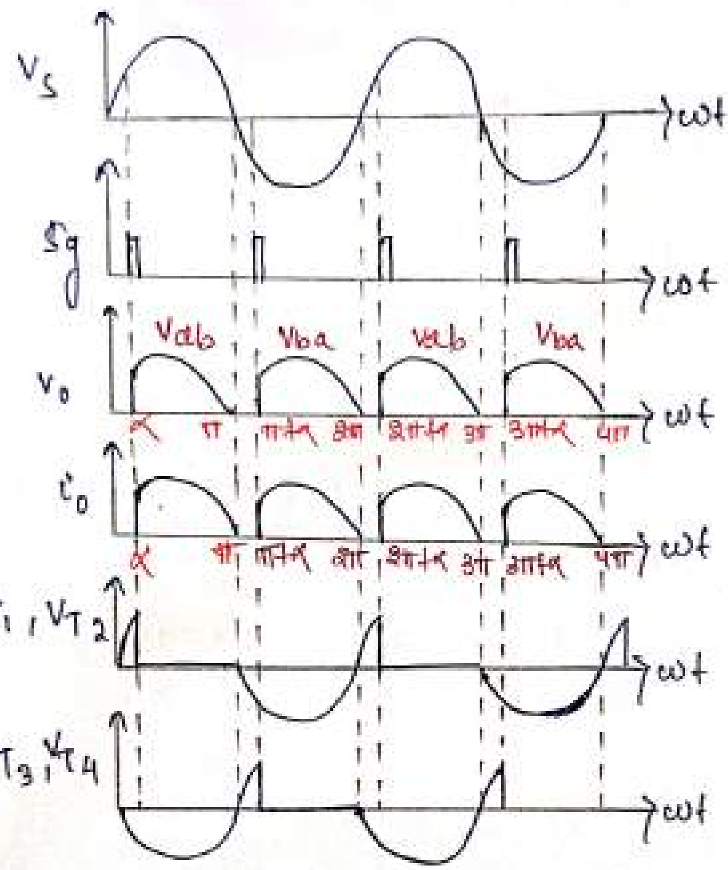
$$\Rightarrow V_{o(rms)} = \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{\pi - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

$$I_{o(rms)} = \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}\cdot R}\sqrt{\pi - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

## Single Phase Full-wave controlled Rectifier with R-Load (Bridge type)






→ During +ve half cycle, the thyristor $T_1$ and $T_2$ are forward biased. When they are triggered simultaneously at angle '$\alpha$'. Then current flows through the path $L - T_1 - R - T_2 - N$.

→ During -ve half cycle of the ac input, the thyristor $T_3$ and $T_4$ are forward biased. When they are triggered simultaneously at angle $\pi+\alpha$

then current will flows through the path N-$T_3$-R-$T_4$-L.

→ When the supply voltage falls to zero, the current also goes to zero. Hence thyristors $T_1$ & $T_2$ in positive half cycle and $T_3$ & $T_4$ in negative half cycle turn off by natural commutation. (21)

## average output voltage ($V_0$)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{V_m}{\pi}\left[-\cos\pi + \cos\alpha\right]$$

$$\Rightarrow \boxed{V_0 = \frac{V_m}{\pi}(1+\cos\alpha)}$$

## average load current ($I_0$)

$$\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R}(1+\cos\alpha)}$$

## Equation for rms value of Load voltage

$$V_{0(rms)} = \frac{1}{\sqrt{\pi}}\sqrt{\int_{\alpha}^{\pi}\left[V_m^2\sin^2\omega t \; d\omega t\right]}$$

$$= \frac{V_m}{\sqrt{\pi}}\sqrt{\int_{\alpha}^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right] d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{(\pi-\alpha) - \left(\frac{\sin 2\pi - \sin 2\alpha}{2}\right)}$$

$$V_{0(rms)} = \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}}\sqrt{(\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$\Rightarrow I_{0(rms)} = \frac{V_m}{R\sqrt{2}\cdot\sqrt{\pi}}\sqrt{(\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

# Single Phase Full-wave controlled Rectifier with R-L Load (Bridge-type)

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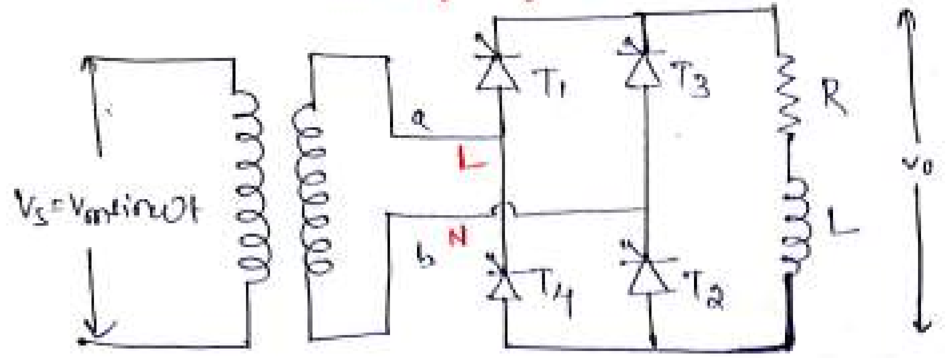
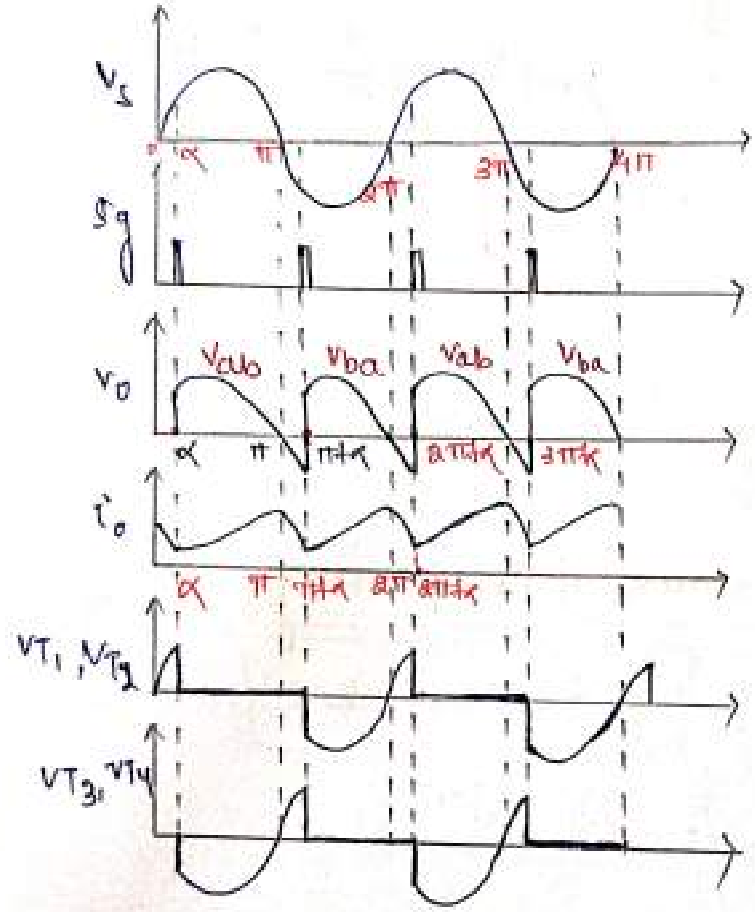



→ During positive half-cycle, the thyristor $T_1$ & $T_2$ are forward biased. When they are triggered simultaneously at angle $\omega t = \alpha$, then the load current will flow through the path $L - T_1 - R - L - T_2 - N$.
The thyristor $T_1$ & $T_2$ conduct from $\alpha$ to $\pi + \alpha$.

(23)

→ Due to presence of inductive load, the load current ($I_0$) is maximum at '0' voltage and it keeps the thyristor $T_1$ and $T_2$ in conducting state and hence, the negative supply voltage appears across output terminals.

→ During the -ive half cycle, thyristor $T_3$ & $T_4$ are forward biased, when they are triggered at angle $\omega t = \pi + \alpha$, then the current will flow through the path N - $T_3$ - R - L - $T_4$ - L. The thyristor $T_3$ & $T_4$ conduct from $\pi + \alpha$ to $2\pi + \alpha$.

→ During the positive half-cycle, there will be a reverse voltage drop across $T_3$ and $T_4$. Similarly during the -ive half cycle, there will be a reverse voltage drop across $T_1$ and $T_2$.

**$V_0$ (average output voltage) ⇒**

$$\begin{cases} \cos(\pi+\alpha) = -\cos\alpha \\ \cos(\pi+\alpha) = -\cos\alpha \end{cases}$$

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

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi+\alpha} = \frac{V_m}{\pi}\left[-\cos(\pi+\alpha) + \cos\alpha\right]$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}(\cos\alpha + \cos\alpha)$$

$$\Rightarrow \boxed{V_0 = \frac{2V_m}{\pi}\cos\alpha}$$

**average load current ($I_0$)**

$$\boxed{I_0 = \frac{V_0}{R} = \frac{2V_m}{\pi R}\cos\alpha}$$

Equation for rms value of load voltage

(21)

$$V_{o(rms)} = \frac{1}{\sqrt{\pi}} \sqrt{\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2 \omega t \; d(\omega t)}$$

$$= \frac{V_m}{\sqrt{\pi}} \sqrt{\int_{\alpha}^{\pi+\alpha} \left[\frac{1-\cos 2\omega t}{2}\right] d(\omega t)}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}} \sqrt{\int_{\alpha}^{\pi+\alpha} (1-\cos 2\omega t) \; d(\omega t)}$$

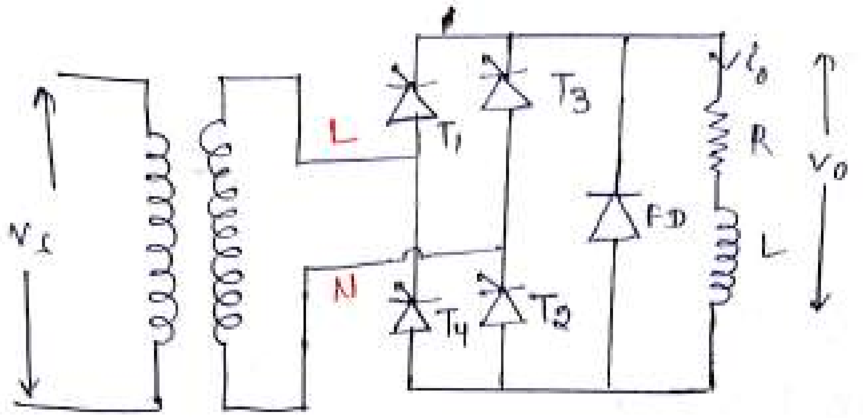
$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}} \sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi+\alpha}}$$

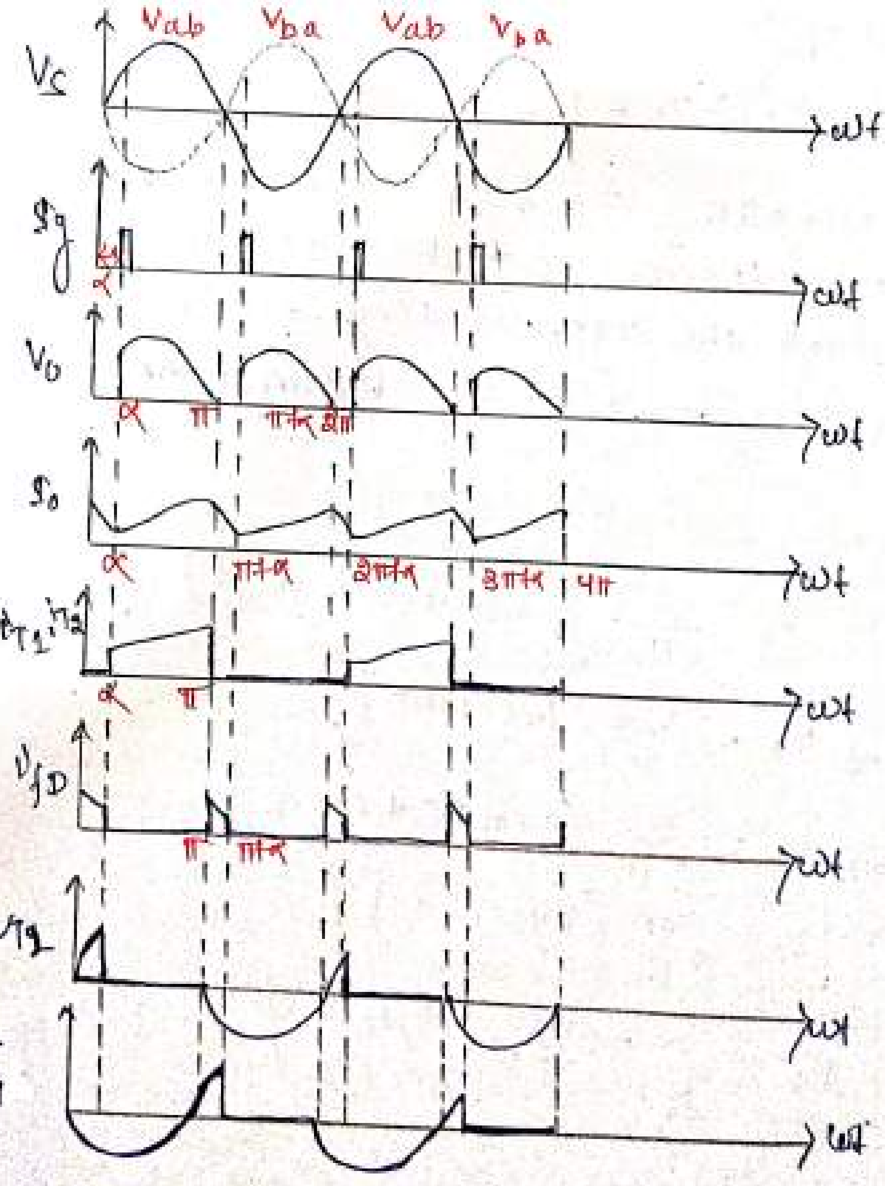
$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}} \sqrt{(\pi + \alpha - \alpha) - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

$$= \frac{V_m}{\sqrt{2}\cdot\sqrt{\pi}} \sqrt{\pi - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

$$I_{o(rms)} = \frac{V_m}{R\cdot\sqrt{2}\cdot\sqrt{\pi}} \sqrt{\pi - \left(\frac{\sin 2(\pi+\alpha) - \sin 2\alpha}{2}\right)}$$

## 3.8 Single phase full-wave controlled converter with R-L load and freewheeling diode (Bridge type)



→ During positive half-cycle of a.c supply, $T_1$ & $T_2$ are forward biased. When $T_1$ and $T_2$ are triggered at angle 'α', then the load current ($I_0$) flow through the path $L - T_1 - (R-L) - T_2 - N$.

→ At $\omega t = \pi$, $T_1$ & $T_2$ turn off and load current ($I_0$) flow through the free-wheeling diode, from π to π+α.

→ In this way ($I_0$) continuously flow from α to π+α.

→ During negative half-cycle, $T_3$ and $T_4$ are forward biased. When $T_3$ and $T_4$ are triggered at angle π+α, then the load current ($I_0$) flow through the path $N - T_3 - (R-L) - T_4 - L$.

→ At $\omega t = 2\pi$, $T_3$ & $T_4$ are turned-off by natural commutation. so that load current ($I_0$) flow through the free-wheeling diode. In this way ($I_0$) continue to flow from 2π to 2π+α.

average output voltage ($V_0$)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

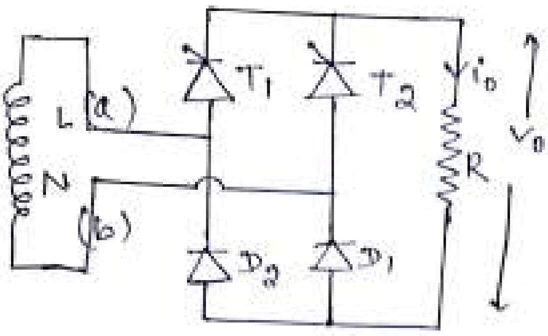
$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left(-\cos\pi + \cos\alpha\right)$$

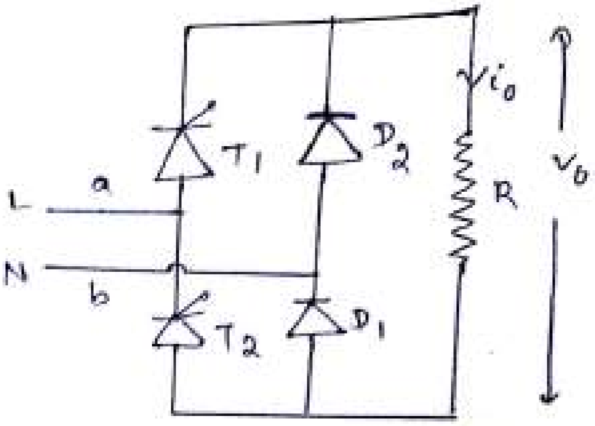
$$\Rightarrow \boxed{V_0 = \frac{V_m}{\pi}\left(1+\cos\alpha\right)}$$

$$\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{\pi R}\left(1+\cos\alpha\right)}$$

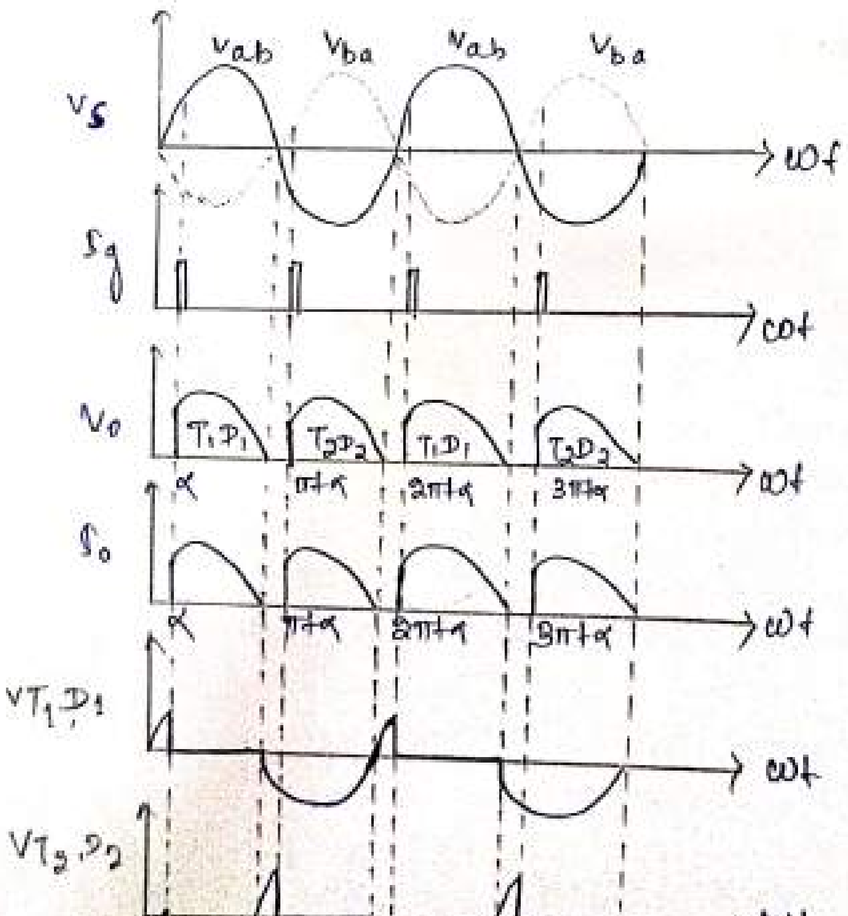
## 3.9 Single Phase half controlled bridge converter with R-Load (semi-converter)




(Symmetrical configuration)




(A-symmetrical configuration)




* for symmetrical configuration, single triggering ckt is used & for Asymmetrical configuration separate triggering circuits are to be used.

## Average output voltage ($V_0$)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left(-\cos\pi + \cos\alpha\right)$$

$$\Rightarrow \boxed{V_0 = \frac{V_m}{\pi}\left(1+\cos\alpha\right)}$$

$$\boxed{I_0 = \frac{V_0}{R} = \frac{V_m}{R\pi}\left(1+\cos\alpha\right)}$$

### Consider the symmetrical configuration

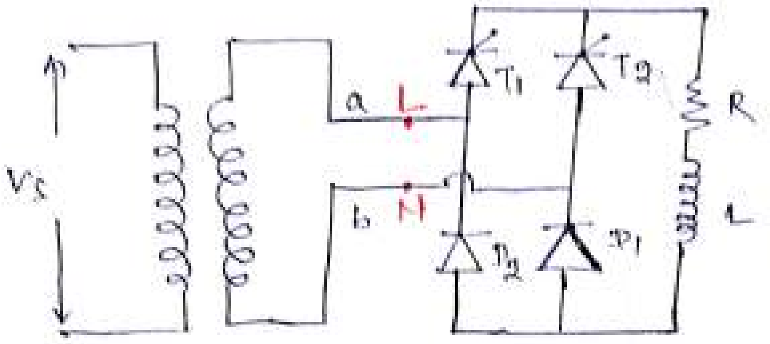
→ During the '+ve' half-cycle of the a.c supply, Thyristor $T_1$ & $D_1$ are forward biased. when the SCR $T_1$ is triggered, at a firing-angle '$\alpha$', the current will flow through the path $L - T_1 - R - D_1 - N$.

→ The load current ($I_0$) will flow from $\alpha$ to $\pi$, and $T_1$ & $D_1$ will turned-off at $\omega t = \pi$ by natural commutation.

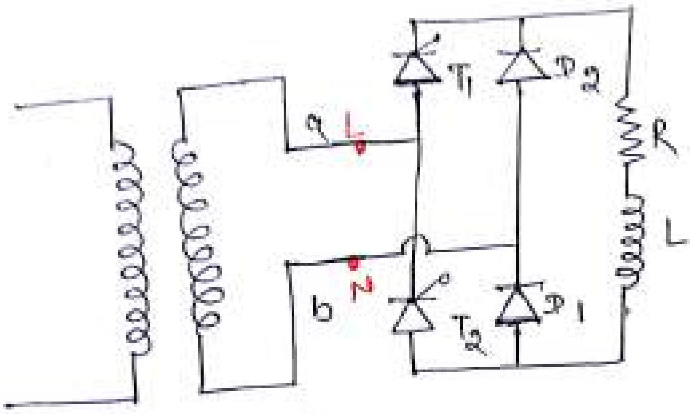
→ During the negative half-cycle of the a.c supply, Thyristor $T_2$ and $D_2$ are forward biased. when SCR $T_2$ is triggered at angle $\pi+\alpha$, the current flow through the path $N - T_2 - R - D_2 - L$.

→ The thyristor $T_2$ and $D_2$ conduct from $\pi+\alpha$ to $2\pi$. and $T_2$ & $D_2$ will turned-off at $\omega t = 2\pi$ by natural commutation.

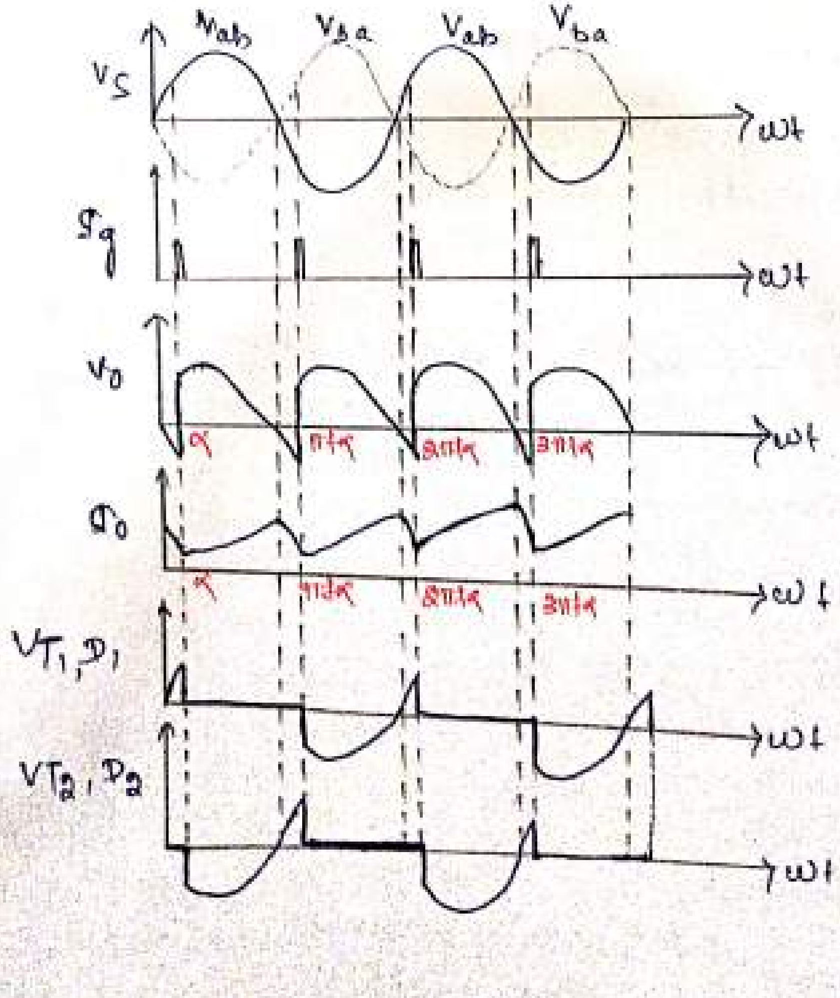
Single Phase half controlled converter with R-L load
(semi converter, bridge type)




(Symmetrical configuration)




(Asymmetrical configuration)



## Consider a symmetrical circuit configuration.

→ During the positive half-cycle of the a.c supply, the SCR $T_1$ and diode $D_1$ are forward biased.

→ When the SCR $T_1$ is triggered at angle 'α', the current ($I_0$) flow through the path $L - T_1 - R - L - D_1 - N$. Through $T_1$ and $D_1$, the conduction occurs from α to π.

→ At $\omega t = \pi$, the $D_1$ will turn-off due to reverse voltage and load current ($I_0$) flow through the path $L - D_2 - T_1 - R$. Through $T_1$ & $D_2$, the conduction occurs from π to π+α.

→ During the negative half-cycle of the ac supply, the SCR-$T_2$ and diode $D_2$ are forward biased.

→ When SCR $T_2$ is triggered at angle π+α, the current ($I_0$) flow through the path $N - T_2 - R - L - D_2 - L$. Through $T_2$ and $D_2$, the current flow from π+α to 2π.

→ At $\omega t = 2\pi$, the $D_2$ will turn-off due to reverse voltage and load current ($I_0$) flow through the path $L - D_1 - T_2 - R$. Through $T_2$ and $D_1$, the current ($I_0$) flow from 2π to 2π+α.

## average output voltage ($V_0$)

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t) = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi+\alpha}$$

$$\Rightarrow V_0 = \frac{V_m}{\pi}\left[-\cos(\pi+\alpha) + \cos\alpha\right] = \frac{V_m}{\pi}(\cos\alpha + \cos\alpha)$$

$$\Rightarrow \boxed{V_0 = \frac{2V_m}{\pi}\cos\alpha}$$

$$\boxed{I_0 = \frac{V_0}{R} = \frac{2V_m}{\pi R}\cos\alpha}$$