LECTURE NOTES

ON

POWER ELECTRONICS & PLC (TH-5)

DIPLOMA COURSES

5TH SEMESTER

ELECTRICAL ENGINNERING

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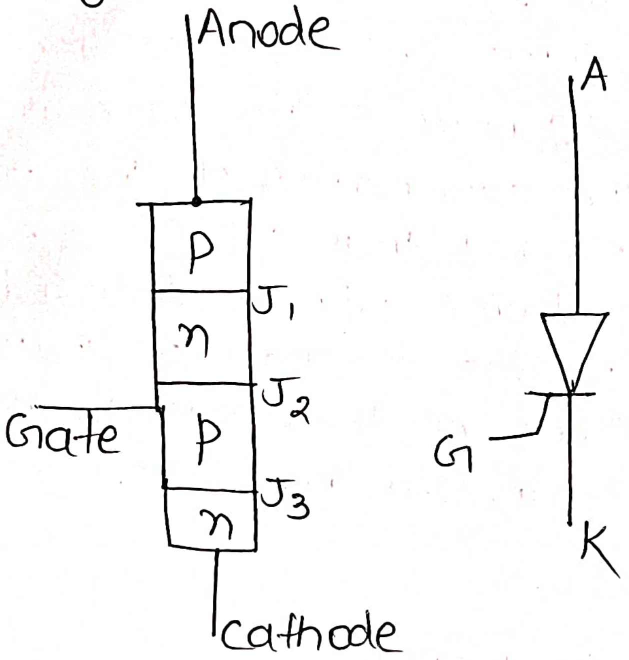
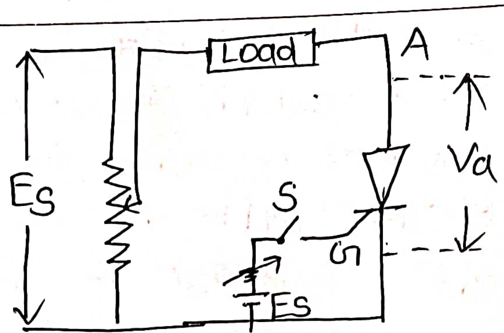
Objectives of the Lecture	Construction, Operation, V-I characteristics & Application of power diode, SCR.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	Thyristor is a family of power semiconductor switching devices. The thyristor has four or more layer and 3 or more Junctions. The name of the thyristor is derived by the combination of the capital letters from THYRatron and transISTOR i.e Thyristor is a solid state device like a transistor and has characteristics similar to that of thyratron tube. Members of thyristor family are → SCR - Silicon controlled Rectifier. → Diac → Triac → GTO (Gate Turned OFF) → SUS - (Silicon unilateral switch) → SBS → LASIR - Light activated SCR **Principle of Operation of SCR:-** Thyristor is a Four layers, three Junction, p-n-p-n semiconductor switching device. It has 3 terminals, Anode, cathode & gate. It consists of four alternate p-type & n-type semiconductor forming 3 Junctions J_1, J_2 and J_3. An SCR is so called because silicon is used for its construction and its operation as a rectifier can be controlled.

→ Thyristor is a unidirectional device.
→ Normally gate terminal is provided at the p-layer near the cathode.



* Silicon provides good Gate ~~terminal~~ thermal conductivity · high voltage and current capability.
* Cathode is must heavily doped · Gate and anode are next heavily doped, lowest doping is switch central n layer.
→ When Anode is made positive w.r.t cathode, J_1 & J_3 are forward biased but J_2 is reverse biased. Thus junction J_2 due to presence of depletion layer doesn't allow any current to flow through the device · Only leakage current of small magnitude flows due to drift of mobile charges · which is insufficient to make the device conduct · This is called Forward blocking state or OFF state for the device.

→ Anode & Cathode are connected to main Source through the load. The gate and Cathode are fed from



a Source E_S which provides positive gate to current.

Generally thyristor has three basic modes of operation.

→ Reverse blocking mode
→ forward blocking mode
→ forward conduction mode.

Reverse blocking Mode :-

When cathode is made positive but anode with switch 'S' open, thyristor is reverse biased Junction J_1, J_3 are reverse biased and J_2 is forward biased. Therefore a small leakage current flows (mA).

→ The reverse blocking mode is called the OFF state and shown by 'op'.

→ If the reverse voltage is increased then at a critical level, called reverse breakdown voltage (V_{BR}), an avalanche occurs at J_1 & J_3 & reverse current increases rapidly.

→ If the current isn't limited to a safe value power dissipation will increase to a dangerous level that may destroy the device. PQ is the reverse avalanche region.

→ When the Cathode is made positive wrt anode, J_2 is forward biased whereas J_1 and J_3 is reverse biased. Only a small leakage current flows where which is insufficient to make the device conduct or OFF state.

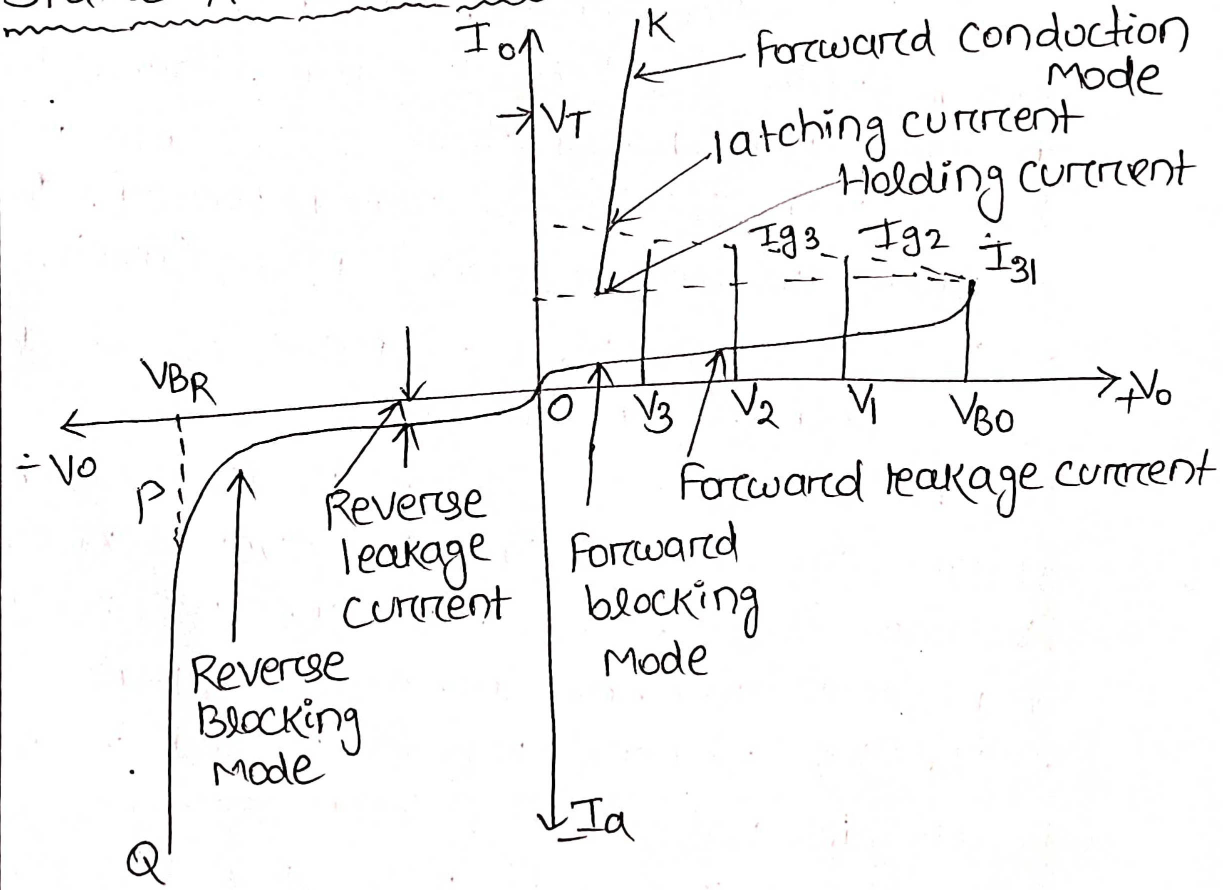
→ The width of depletion layer at J_2 decreases with increase in anode to cathode voltage and at a stage depletion layer of J_2 vanishes.

→ The reverse biased Junction J_2 breakdown due to large voltage gradient across it & the phenomenon called as Avalanche breakdown.

→ Now J_1 J_2 & J_3 are forward biased; so, large amount of current flows through the device.

→ The device starts conducting and called as conducting state or ON state.

Static Anode - cathode characteristics of SCR



→ If the reverse voltage applied across the device is below V_{BR}, the device will behave as a high impedance device in the reverse region.

* **Forward Blocking region:-**

When anode is positive w.r.t cathode, with gate open, thyristor is said to be forward biased.

→ Therefore, J_1, J_3 are forward biased while J_2 is reverse biased and a small leakage current called forward leakage current flows through the device.

→ As forward leakage current is small, SCR offers a high impedance.

→ Thyristor can be treated as an open switch in forward blocking mode.

Forward Conduction Region:-

When anode to cathode forward voltage is increased with gate ckt open, reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward Breakover voltage V_{BO}.

→ V_{BO} is corresponding to 'M', when the device latches on to conduction state.

→ As the device latches on to its ON state, the voltage across the device drops from several volt to 1-2 volts, depending on rating of SCR and suddenly a large amount of current starts flowing.

→ This characteristic is called forward conduction State and Thyristor treated as a open Switch.

→ When gate signal is applied, thyristor turns on before V_{BO} reached. The forward voltage at which the device turns on depends upon the magnitude of gate current.

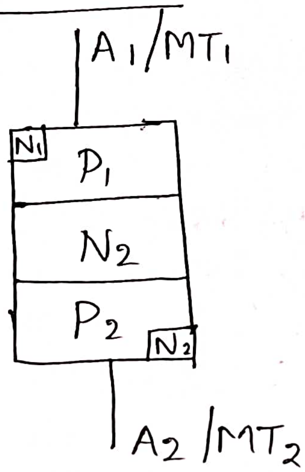
→ As the magnitude of gate signal increases, the voltage at which the thyristor turns on decreases.

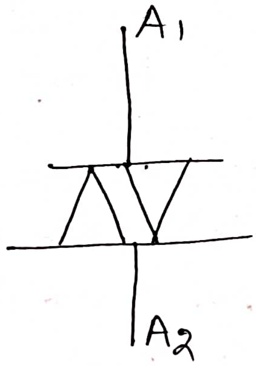
$$I_{g3} > I_{g2} > I_{g1}$$

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

Objectives of the Lecture	
Learning Outcomes	Construction, Operation, V-I characteristics & application of DIAC, TRIAC.
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	Diac is the bidirectional device. It is the Diode for alternating current. Combination of two diode in Anti parallel.

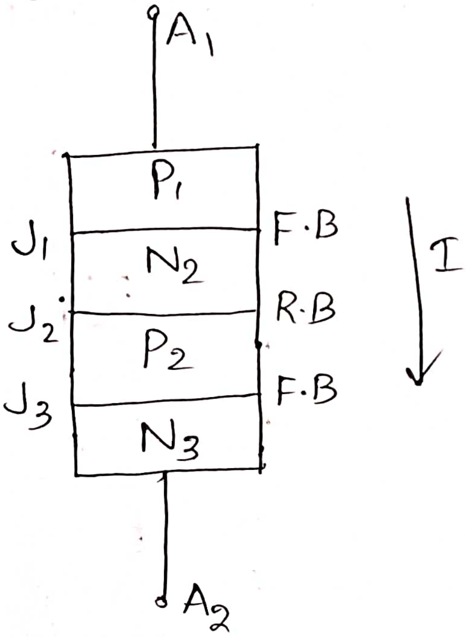
Construction :-



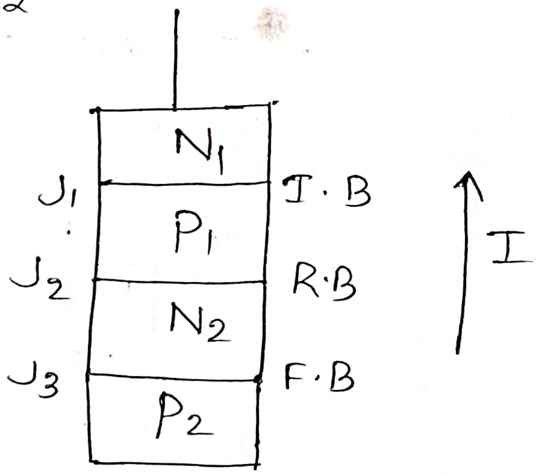


Working :-

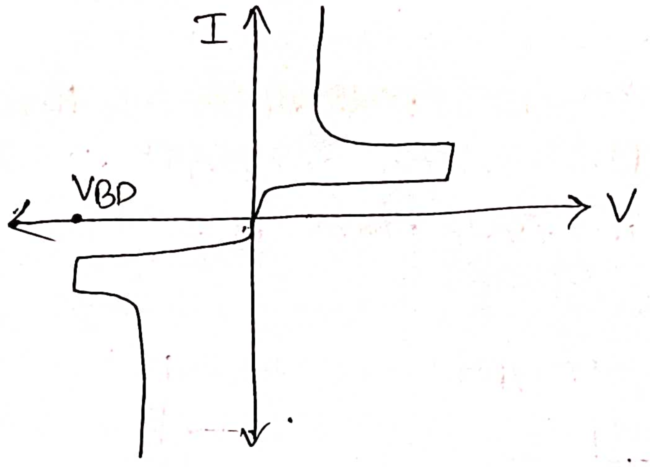
A_1 is more +ve than A_2



A_2 is more +ve than A_1



V-I characteristics :-



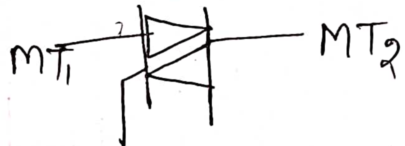
Application :-

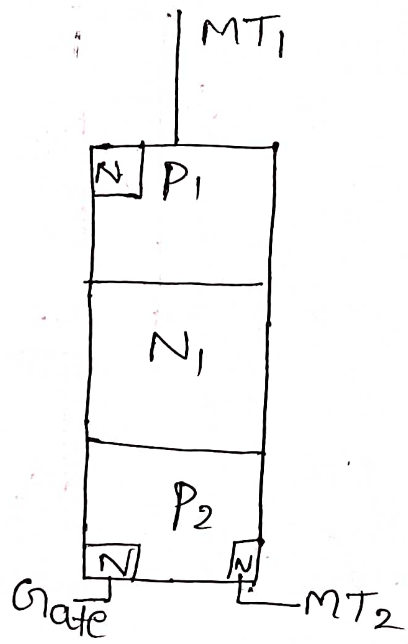
→ Using SCR / Triac to trigger
→ Large power control.
→ Heat control circuit.

TRIAC

→ Triac is the controlling terminal.
→ Two ~~diode~~ SCR connected in Anti parallel.
→ TRIAC can trigger in both direction.

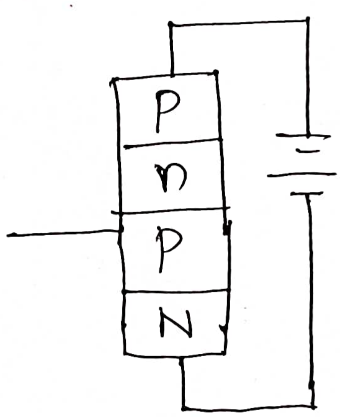
Symbol :-





using mode :-

→ used as a switch.



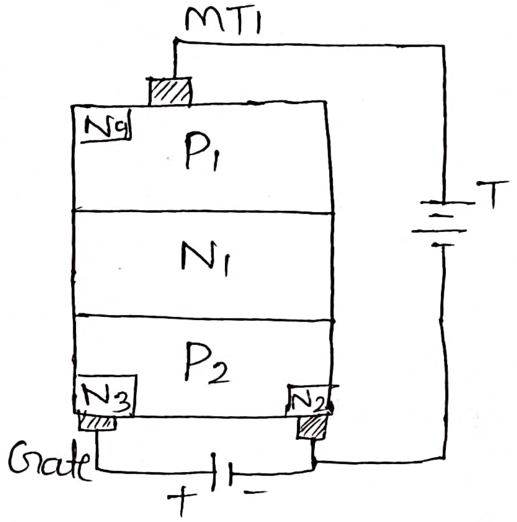
Application :-

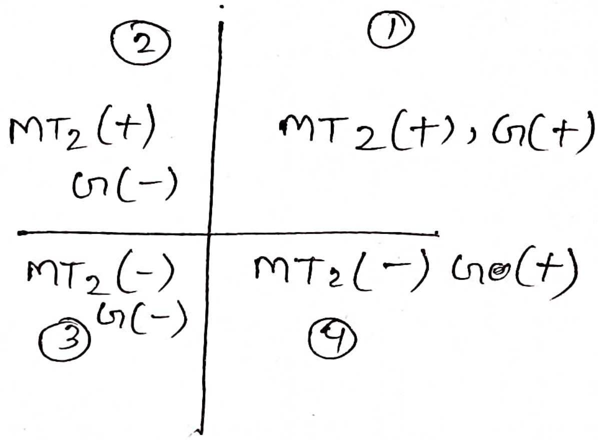
→ Lamp control.
→ Speed control.
→ Chopper
→ As phase control.

Defination :-

TRIAC is a ~~bi three ele~~ three terminal electronic component that conducts current in either direction when triggered.
→ A Triac can work both direction.
→ It is a bidirectional device.

Working :-





Quadrant :- I

is the most sensitive (i.e least gate current) required to turned ON the device.

Quadrant - II

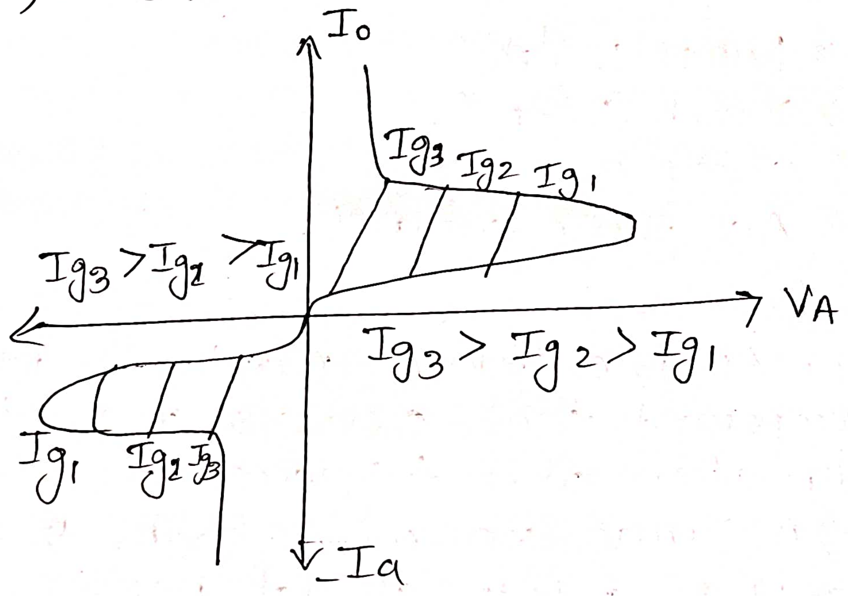
MT_2, G - Moderate.

Quadrant - III

$MT_2(-)$, $G(-)$ is the least sensitive (Most gate current required to turned ON the device).

Quadrant (IV)

$MT_2(-)$, $G(-)$

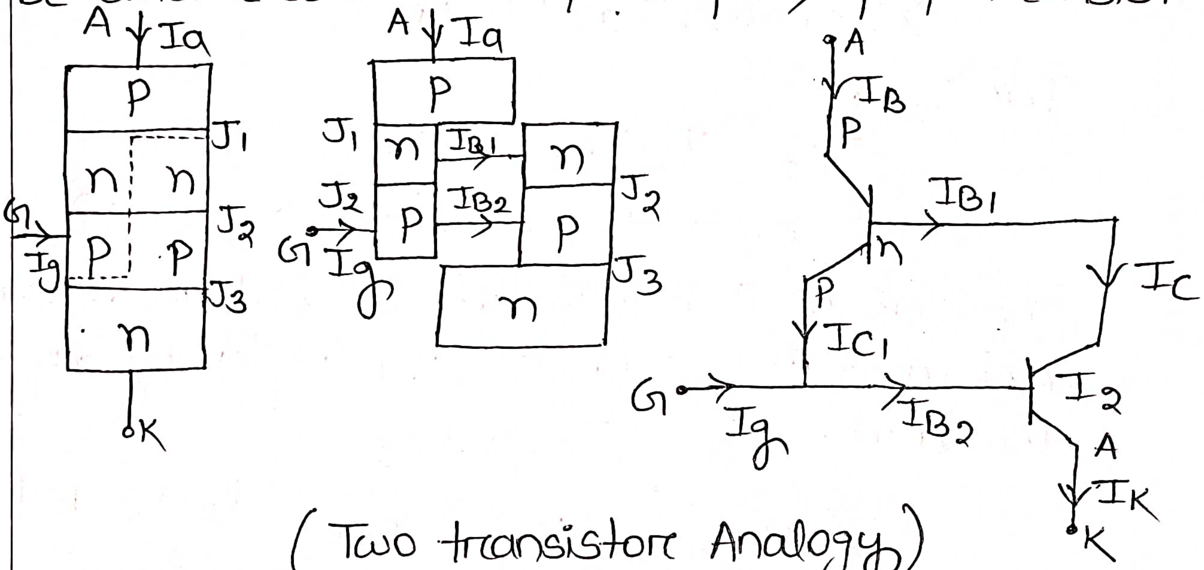


Objectives of the Lecture	Two transistor analogy of SCR.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

The operation of SCR can also be explained by considering it in terms of two transistors, known as two transistor analogy of thyristor.

→ This model is obtained by spilling the two middle layers of SCR into two separate parts & SCR can be considered as an open npn & pnp transistor.



(Two transistor Analogy)

For Transistor T_1, Emitter current $I_E = I_A$

Collector current $I_C = I_{C_1}$

Base current $I_B = I_{B_1}$

For Transistor T_2 $I_{E_2} = I_K$

$I_{B_2} = I_{B_2}$

$I_{E_1} = I_{B_1}$

From the above figure it is observed that the collector current of T_1 becomes base current of T_2 & viceverse. also

$$I_K = I_A + I_G$$

In the OFF state of a transistor,

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

α = Common base current gain

I_{CBO} = Common base leakage current of collector base junction.

For T_1,

$$I_{C_1} = \alpha_1 I_{E_1} + I_{CBO1}$$

$$\Rightarrow I_{C_1} = \alpha_1 I_a + I_{CBO_1} \quad \text{--- (1)}$$

For T_2,

$$I_{C_2} = \alpha_2 I_{E_2} + I_{CBO_2}$$

$$\Rightarrow I_{C_2} = \alpha_2 I_K + I_{CBO_2} \quad \text{--- (2)}$$

The sum of two collector current is equal to the external ckt current I_a entering at anode terminal. $I_a = I_{C_1} + I_{C_2}$

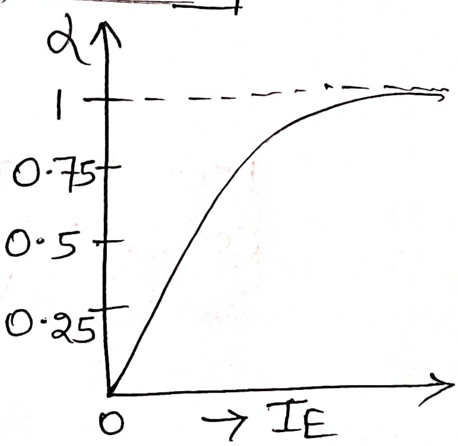
$$\Rightarrow I_a = \alpha_1 I_a + I_{CBO_1} + \alpha_2 I_K + I_{CBO_2}$$

$$\Rightarrow I_a = \alpha_1 I_a + \alpha_2 (I_a + I_g) + I_{CBO_1} + I_{CBO_2}$$

$$\Rightarrow I_a (1 - \alpha_1 - \alpha_2) = \alpha_2 I_g + I_{CBO_1} + I_{CBO_2}$$

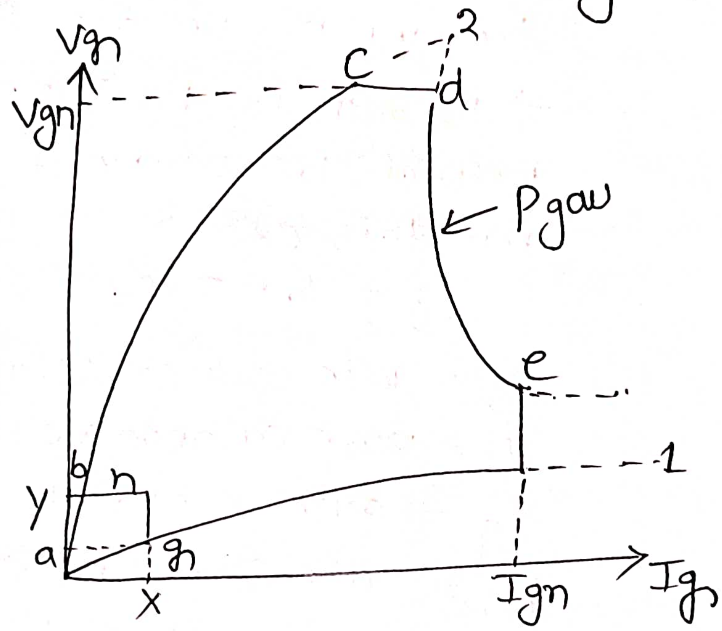
$$\Rightarrow \boxed{I_a = \frac{\alpha_2 I_g + I_{CBO_1} + I_{CBO_2}}{1 - (\alpha_1 + \alpha_2)}} \quad \text{--- (3)}$$

→ For a Silicon transistor α is very low, at low voltage value of I_E. α build up rapidly as the emitter current increases.



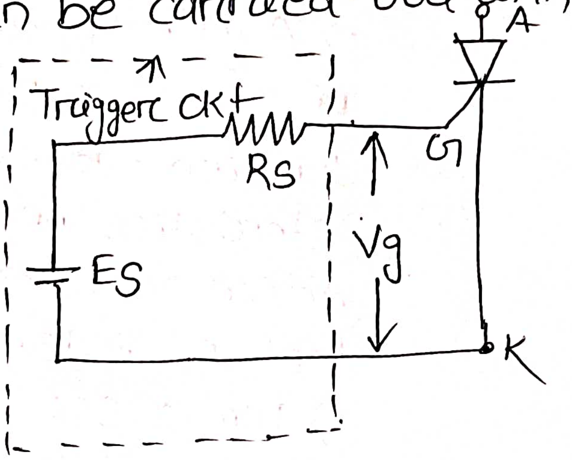
→ With $I_g = 0$, if emitter current of two transistor are increased so, that $\alpha_1 + \alpha_2 = 1$, then as per eqn — ③, I_a would be tend to become infinity.

→ As the anode current attains high value, the device suddenly latches into conduction (ON) state from OFF state. This characteristics of device is known as Regenerative Action.

Objectives of the Lecture	Gate characteristics of SCR.
Learning Outcomes	.
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	The forward gate characteristics of a thyristor is shown below. → A gate cathode ckt of SCR is a p-n junction, gate characteristics of the device are similar to that of diode. → For a SCR, V_g-I_g characteristics has a spread between two curves 1 & 2 as shown in fig.  → The spread is due to difference in doping level of p & n layers. → Curve 1 represents lowest voltage value applied to turn-on SCR. Curve-2 represents highest voltage value that can be safely applied to gate circuit. → Each thyristor has max^m limits as V_{gm} & I_{gm} & rated power dissipation P_{gav} specified for each other SCR. Oy, Ox = Minimum gate V & I to trigger an SCR. V_{gn}, I_{gm} = Max^m permissible gate V & I Oa = Non-triggering gate voltage.

→ If firing CKt generates positive gate signal prior to triggering, it should be ensured that the unwanted signal must be less than the non-triggering voltage Oa.

→ Design of Firing CKt can be carried out with help of following CKt.



For this CKt

$$E_S = V_g + I_g R_S$$

E_S = gate source voltage
V_g = gate cathode voltage
I_g = gate-current
R_S = gate source resistance

→ The value of RS is such that the current (E_S/R_S) not harmful to source when SCR is turned on.

→ For low power CKt, operating point is obtained by utilizing V–I characteristics of both source & the device.

→ The load line in AD.

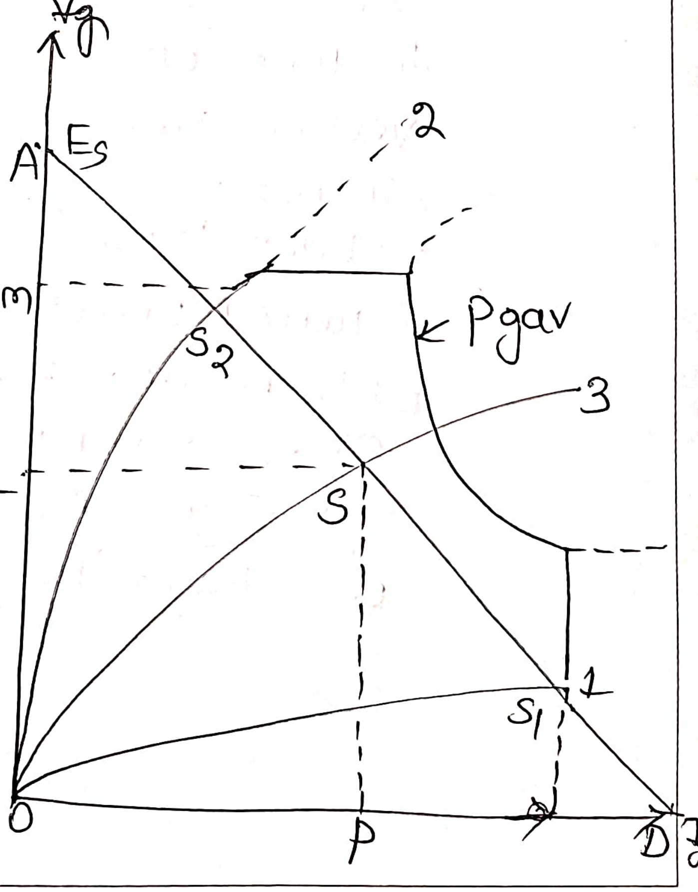
→ $V_g - I_g$ characteristics of the device is curve 3

→ OA = E_S = Gate Source volt

OD = trigger CKt

→ Intersection of load line AD & curve-3 gives operating point S.

→ Thus operating point
gate voltage = PS
gate current = OP



→ The operating point 's' may change from S_1 to S_2 & it must lie within curve 1 & curve 2.

→ The gradient of load line AD will give the required rate of source resistance R_S.

→ Frequency of firing for trigger pulse can be obtained by taking pulse of

(i) Amplitude (P_{gm}).

(ii) pulse width (T)

(iii) periodicity (T_1)

~~Pgm~~ $\dfrac{P_{gm} T}{T_1} \geq P_{gav}$ $\qquad F = \dfrac{1}{T_1}$ = Frequency of Firing (Hz)

$\Rightarrow P_{gm} \cdot T \cdot F \geq P_{gav}$ $\qquad T$ = pulse width (sec)

$\Rightarrow \dfrac{P_{gav}}{FT} \leq P_{gm}$

In the limiting case, $P_{gm} = \dfrac{P_{gav}}{FT}$, $f = \dfrac{P_{gav}}{T \cdot P_{gm}}$

→ Duty cycle is defined as the ratio of pulse on period to periodic time of pulse.

$$S = \frac{T}{T_1} = FT.$$

$$\frac{P_{gav}}{S} \leq P_{gm}$$

$$\Rightarrow \frac{P_{gav}}{S} = P_{gm}$$

Objectives of the Lecture	Switching characteristics of SCR during turn on.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	See below

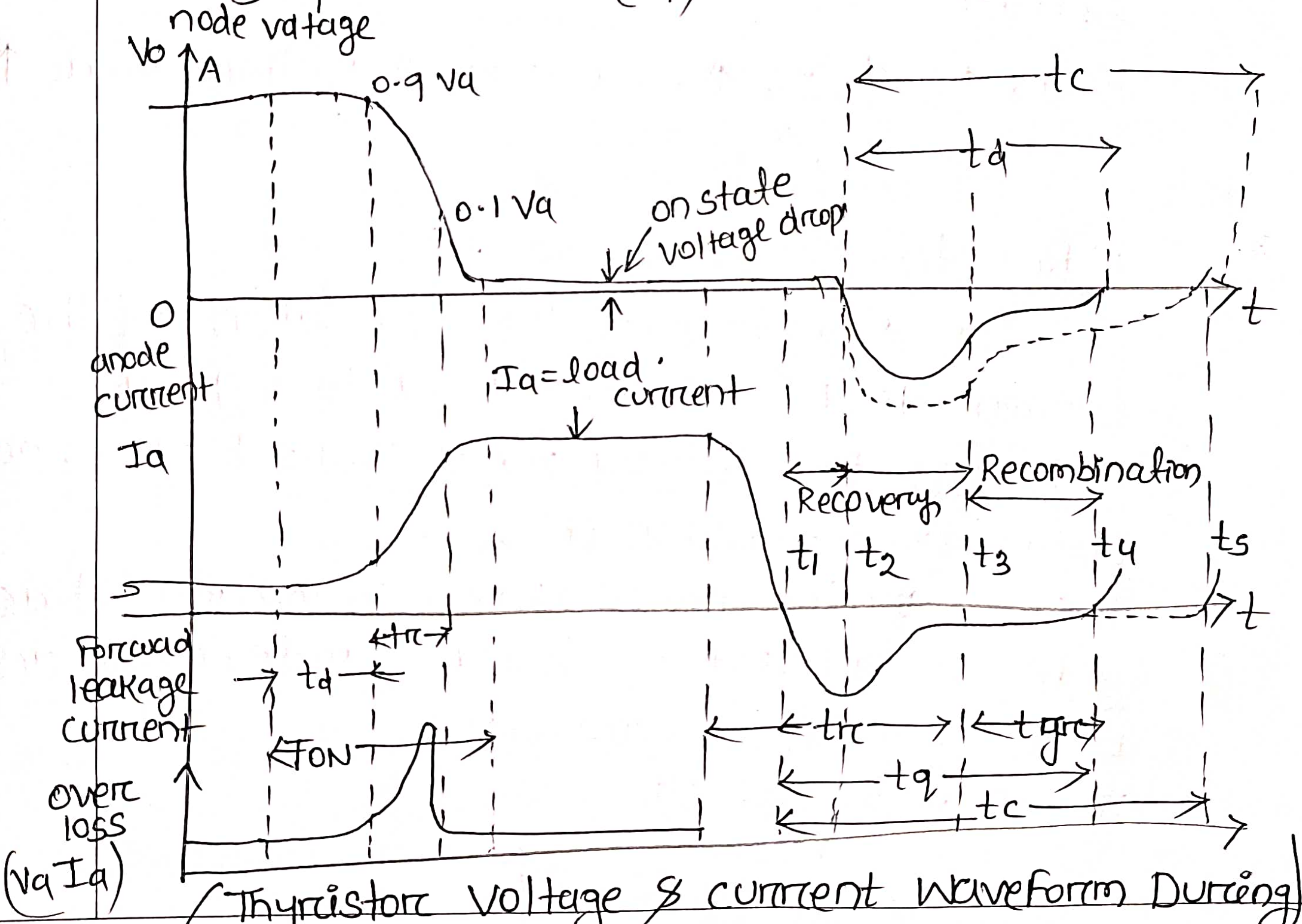
Turn -ON

→ A forward biased thyristor is turned ON by applying a positive gate ~~terminal~~ signal betn gate & cathode.

→ The time during which the SCR changes from forward blocking state to forward conduction state is called as turn-ON time.

→ Turn-on time is divided into three intervals.

i) Delay time (t_d)
ii) Rise time (t_r)
iii) Spread time (t_p)



(Thyristor Voltage & current Waveform During Turn ON & Turn OFF)

i) Delay Time :-

It is defined as the time during which anode voltage falls from Va to 0.9 Va where Va is the initial value of anode voltage.

→ It may be defined as the time during which anode current rises from forward leakage current to 0.1 Ia. Ia = final value of anode current.

→ Delay time = time period between 0.9 Ig to 0.1 Ia.

→ During delay time, anode current flows in a narrow region near the gate where current density is highest.

→ Delay time can be decreased by applying high gate current & more forward anode to cathode voltage.

$I_g \uparrow$, $\frac{d}{dt} I_g \uparrow$, cathode conduction area ↑

$\Rightarrow t_d \downarrow$

ii) Rise time :-

The Rise time is the time taken by the anode current to rise from 0.1 Ia to 0.9 Ia.

→ During this period, anode current flows almost entire cross-section of SCR.

→ tr, inversly proportional to the magnitude of gate current and its build up rate, which depends on the load CKt parameters.

→ For a RL CKt, if L is high

$\frac{dI_g}{dt} \downarrow$, $t_r \uparrow$

iii) Spread time :-

It is the time taken by the anode current to rise from 0.9 I_a to I_a.

→ During this time conduction spreads over the entire - crosssection of SCR.

→ It depends on the structure of the device.

$$T_{ON} = t_d + t_r + t_p.$$

→ Turnon time depends on following parameters.

i) Gate current

$$I_g \uparrow, \frac{d}{dt} I_g \uparrow, t_d \downarrow, t_{ON} \downarrow$$

ii) Load ckt parameter.

Objectives of the Lecture	Switching characteristics of SCR during turn ~~ON~~ OFF.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	**Turn OFF (t_q):-** The process of turning off a thyristor is called as commutation. → The dynamic process of SCR from conduction state to forward blocking state is called turn-OFF process. → Once the thyristor is on, gate loses control, SCR turned off by reducing anode current below holding current i.e by applying a reverse voltage. → Turn OFF time, t_q of a thyristor is defined as the time between the instant $I_a = 0$ and the instance SCR regains forward blocking capability. → Turn OFF time divided into two intervals. i) Reverse recovery time (t_{rr}) ii) Gate recovery time (t_{gr}) $t_q = t_{rr} + t_{gr}$ **i) Reverse Recovery time:-** The time taken to remove the charge carriers from the outer layers of SCR is called reverse recovery time (t_{rr}) i.e betn t_1 & t_3 → At t_1, $I_A = 0$ and during reverse recovery time, t_1 to t_3. I_a flows in reverse direction. (due to sweeping out of charge carriers from outer 2 layers). → At t_2 60% of stored charges are removed and reverse recovery current starts decaying due to

anode voltage is developed & reverse recovery current continues to decrease.

→ At t_3, J_1, J_3 are able to block reverse voltage.

(ii) Gate Recovery time :-

The time required to develop potential barrier in J_2 is called Recombination time or gate recovery time (t_{gr}) betⁿ t_3 & t_4.

→ At t_3, J_2 still contains charged carriers i.e trapped charges. so SCR isn't able to block forward voltage.

→ The trapped charges around J_2 i.e inner two layers are removed by Recombination (automatic neutralisation of charges among themselves is called Recombination).

→ During turn off time all the excess charge carriers are completely removed.

→ t_q depends on magnitude of anode current, $\frac{di}{dt}$ & junction temp.

(iii) Ckt turn-off time (t_c) :-

→ It is the time for which the comutation circuit applies a reverse voltage across the device after the anode current is zero.

$$t_c > t_q.$$

→ The commutation ckt must apply a reverse voltage across the device during turn off for successfull commutation.

→ $\boxed{t_c = (SM)\, t_q}$

SM = saffy margin.

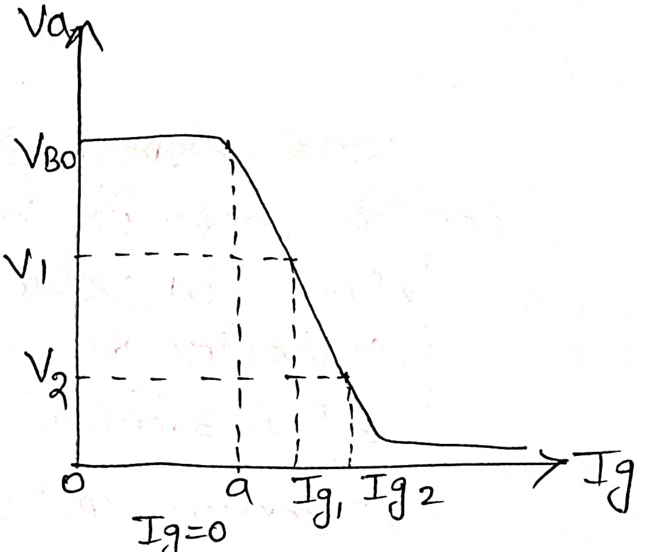
Objectives of the Lecture	Turn ON methods of SCR.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	With anode positive w.r.t cathode, a thyristor can be turned ON by one of the following methods i) Forward voltage triggering ii) Gate triggering. iii) $\frac{dv}{dt}$ triggering iv) Temerature triggering v) Light triggering. (i) Forward voltage triggering :- When anode to cathode voltage is increased with gate circuit open, the reverse biased junction J_2 will have avalanches breakdown at a voltage called forward Break over voltage (VBO). → At VBO, the thyristor changes from OFF state to ON state. → The forward voltage-drop across the SCR during the ON state is 1 to 1.5 V and increases slightly with load current. ii) Gate Triggering :- → Simple, reliable & efficient method of triggering. → By applying a positive signal to gate w.r.t cathode the device can be triggered much before the specified breakover voltage. → At $I_g = 0$, Forward breakover voltage = VBO

→ As $I_g \uparrow$, $V_a \downarrow$

$I_{g2} > I_{g1}$

$V_2 < V_1 < V_{BO}$

→ The conduction period of SCR can be controlled by varying the gate signal within specified value of maximum & minimum gate current.



(Effect of gate current on forward breakover voltage)

→ The gate signal may be DC signal, ac signal or pulse signal.

→ But if $I_g = 0$, before the rising anode current attains a value called latching current, the thyristor turn off again.

So, $I_A > I_L$

→ The latching current may be defined as the minm value of anode current which it must attain during turn-on process to maintain conducting when gate signal is removed.

→ Thyristor turn OFF when $I_A < I_H$.

→ Thus, holding current may be defind as the minimum value of anode current below which it must fall for turning off the thyristor.

$$\boxed{I_L > I_H}$$

→ I_L is related to turn-ON & I_H related to turn OFF process.

(iii) $\frac{dv}{dt}$ Triggering :-

With forward voltage across the anode & cathode of SCR, J_1 & J_3 are forward biased but inner junction J_2 is ~~rete~~ reverse biased.

→ The reverse biased junction J_2 behaves as a capacitor due to charge existing across the junction.

→ If forward voltage is suddenly applied, a charging current through junction capacitance C_j may turn on the SCR.

→ If forward voltage V_a appears across J_2 charging current $i_c = \frac{dQ}{dt} = \frac{d}{dt}(C_j \cdot V_a)$

$$= C_j \frac{dV_a}{dt} + V_a \frac{dC_j}{dt}$$

$$\left(\frac{dC_j}{dt} = 0\right)$$

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

→ So, if $\frac{dV_a}{dt}$ is high, i_c is high. and turns on the SCR even though $I_g = 0$.

(iv) Temperature Triggering :-

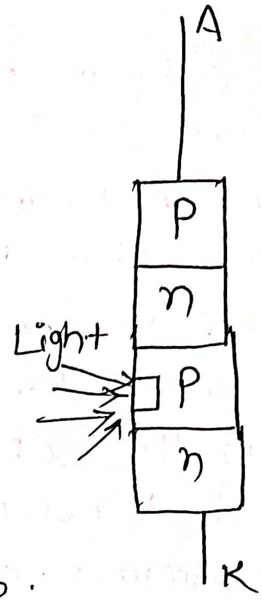
The width of the depletion layer of SCR decreases on increasing the junction temperature.

→ When temperature is increased near the reverse biased junction more number of e^- & holes pairs are produced.

→ At a point, this initiates turn on process of the device.

(V) Light Triggering :-

For light triggered SCR a recess/niche is made in the inner p-layer.



→ When recess is irradiated energy particles, neutrons/photons are bombarded with the SCR and e^-, hole pairs are generated in the device.

→ Thus, the number of charge carriers are increased which lead to instantaneous flow of current and the device is triggered.

→ Used in LASCR (Light Activated SCR).

Objectives of the Lecture	Turn OFF methods OF SCR (Line Commutation & Forced Commutation) Load Commutation.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	(see below)

Turn of Methods of SCR

The turning OFF process of thyristor is called as commutation. Thyristor commutation techniques use resonant LC or underdamped RLC circuits, to force the current / voltage of a thyristor to zero to turn off the device.

→ There are two methods of commutation.

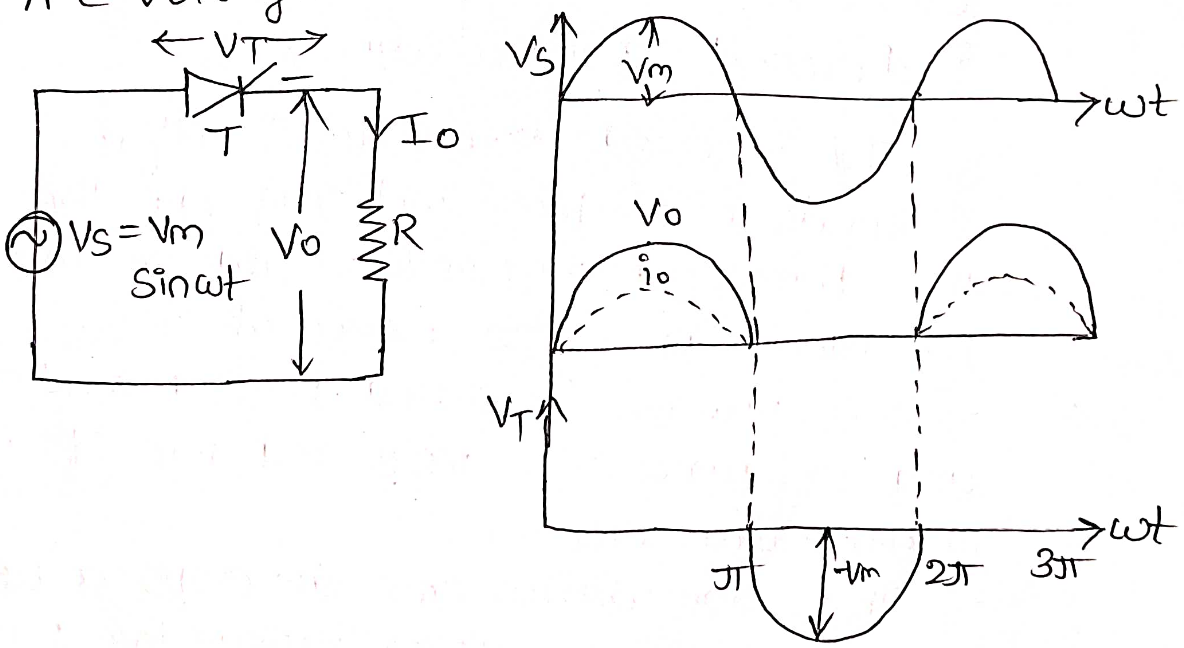
i) Natural commutation

ii) Forced commutation

(i) Natural commutation:-

→ Simplest & most widely used method.

→ This method uses alternating, reversing nature of A.C Voltages to effect the current transfer.



→ During positive half cycle of SCR is triggered and conducts currents. When ac voltage = 0 at $\omega t = \pi$, Also $I_a = 0$, for R load.

→ After anode current has reduced to zero, ac source applies a negative voltage across the SCR for sometime for turning off the SCR naturally.

→ This method is applied to phase-controlled converters, ac voltage controller line commutated inverters.

→ Thyristor is reverse biased for a period π.

$$\pi = \omega t_c$$

$$\Rightarrow \boxed{t_c = \pi/\omega} \qquad \boxed{t_c > t_q}$$

→ This method is also known as Line commutation or Class-F commutation.

ii) Forced commutation:-

→ It is used for dc supply.

→ In dc ckt for switching off the thyristor, the forward current should be forced to zero by means of some external ckt.

→ This process is called forced commutation and external ckt required for it is called commutation ckt.

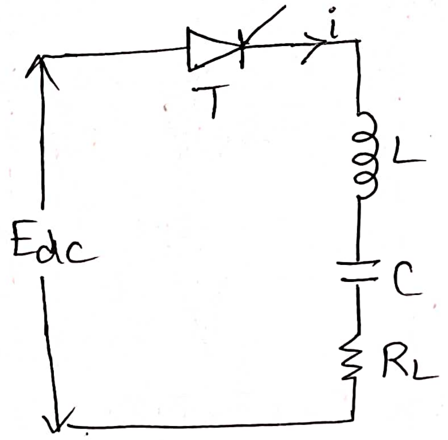
→ The commutation ckt develops a reverse voltage across the SCR which brings the forward current to zero, thus turning off the device.

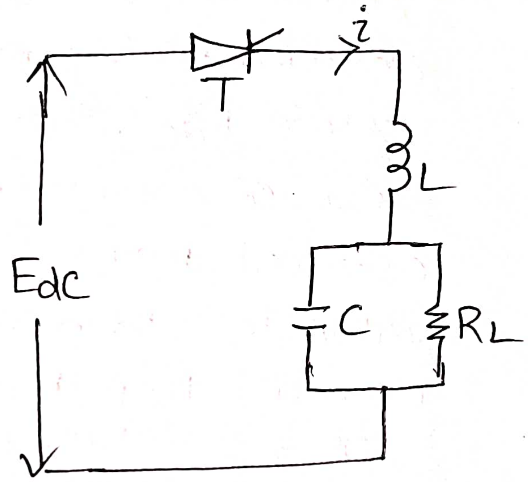
→ Forced commutation is divided into following types depending on the arrangement of commutating components.

(i) Class A / Load Commutation
(ii) Class B / Resonant-pulse Commutation
(iii) Class C / Complementary Commutation
(iv) Class D / Impulse Commutation
(v) Class E / External Pulse Commutation.

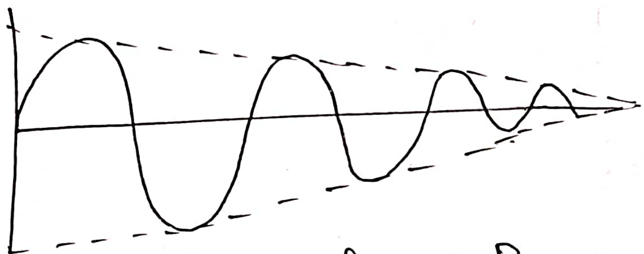
(i) Load commutation :-

→ In this method, commutating components L & C are connected in series with R_L for flow value of R_L, L, C & C connected across R_L for high value of R_L.





N.B
Underdamped resonant ckt (in series RLC)



δ = damping ratio $= \frac{R}{2L}$

$I = \frac{V_s}{\omega R_L} e^{-\delta t} \sin \omega_r t$

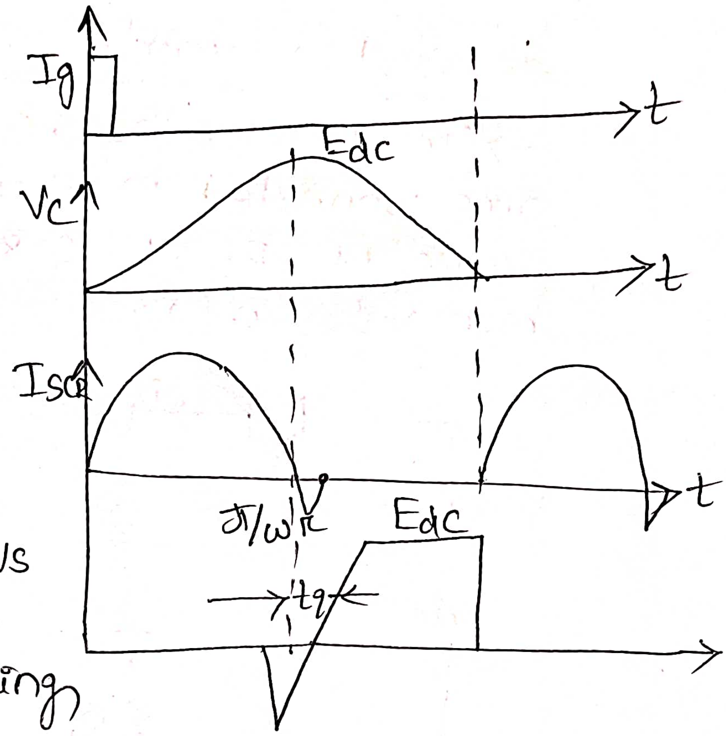
$\omega_r = \sqrt{\omega_0^2 - \delta^2}$

$= \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

→ The Load Resistance R_L & Commutating components L & C , so, selected that their combination forms an underdamped resonant ckt.

→ In this ckt, SCR conducts & carries the charging current in the first half cycle.

→ When the capacitor charged up to supply voltage Edc, the value of charging current decays to a value less than holding current of device.



→ This switches off the thyristor.

→ In series RLC ckt, for underdamped condition.

$$\omega_r > 0$$

$$\Rightarrow \frac{1}{LC} - \frac{R_L^2}{4L^2} > 0$$

$$\Rightarrow \frac{1}{LC} > \frac{R_L^2}{4L^2}.$$

$$\Rightarrow R_L < \sqrt{\frac{4L}{C}}$$

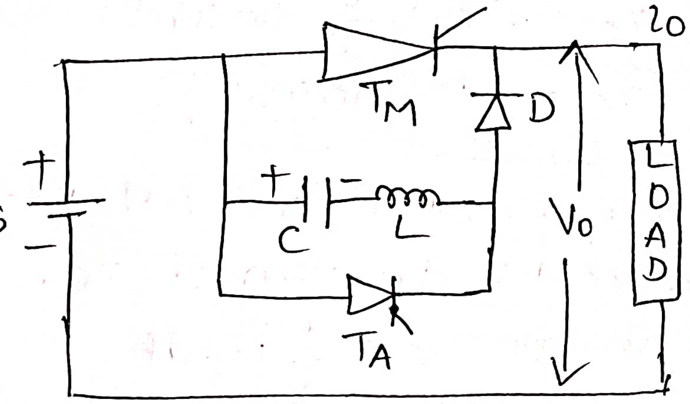
& SCR operated for π/ω_r sec.

→ It is also known as self commutation

Objectives of the Lecture	Resonant Pulse commutation.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

In this method main SCR commutates due to an equal amount of capacitor discharges current in opposite direction to the main SCR current.



→ T_m = Main thyristor which carries Load current.

→ T_A = Auxilliary thyristor which helps to commutate T_m.

→ Initially T_m & T_A are OFF and the capacitor is charged to Vs with left plate positive.

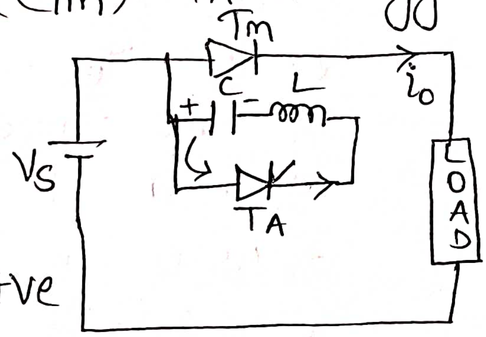
$$V_C = V_S \ (+||)$$

→ At $t=0$, T_m is triggered and constant load current i_o is established in the load ckt.

$$\text{So, } i_{Tm} = i_o,\ V_C = V_S,\ i_C = 0$$

To commutate the main SCR (T_m), T_A is triggered. at $t = t_1$, T_A = ON.

→ Hence, capacitor finds a closed path & discharges through ($C^+ - T_A - L - {}^-C$) & then charges with right plate +ve



$$\text{i.e } V_C = V_S \ (||^+)$$

→ Hence, capacitor finds a closed path & discharge through ($C^+ - T_A - L - C^-$) and then charges with right plate +ve.

i.e $V_C = V_S$ (1 1$^+$)

The magnitude of the discharge current

i.e $i_C = -V_S\sqrt{\frac{L}{C}} \sin \omega_0 t$

$$i_C = -I_p \sin \omega_0 t$$

-ve sign indicates that current flows opposite to the reference +ve direction of i_C.

Capacitor voltage $V_C = \frac{1}{C}\int i_C \, dt$

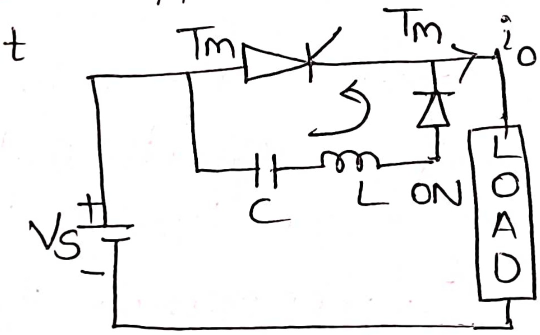
$$V_C = V_S \cos \omega_0 t$$

→ $t = t_2$, $V_C = -V_S$ i.e (after π radians from t_1)

T_A is reverse biased & commutated.

→ After T_A OFF, capacitor finds a closed ckt. L, D & T_m & capacitor discharge in opposite dirⁿ to i_{T_m}.

So, net forward current



$i_{T_1} = i_o - i_C$

As $i_C \uparrow$ $i_{T_1} \downarrow$

→ When i_C attains value of i_o, i_{T_m} is reduced to zero value & T_m is turned off at t_3.

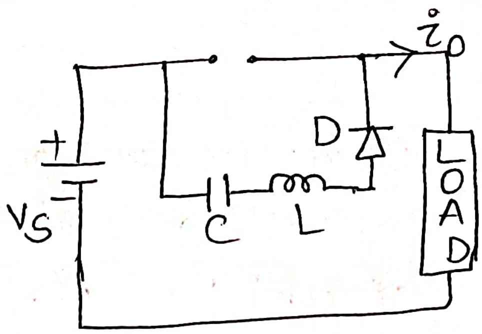
→ After T_m = OFF, I_o flows from V_S to load through C, L & D. & capacitor charges with left plate positive. i.e $V_C = V_S$ (+1 1)

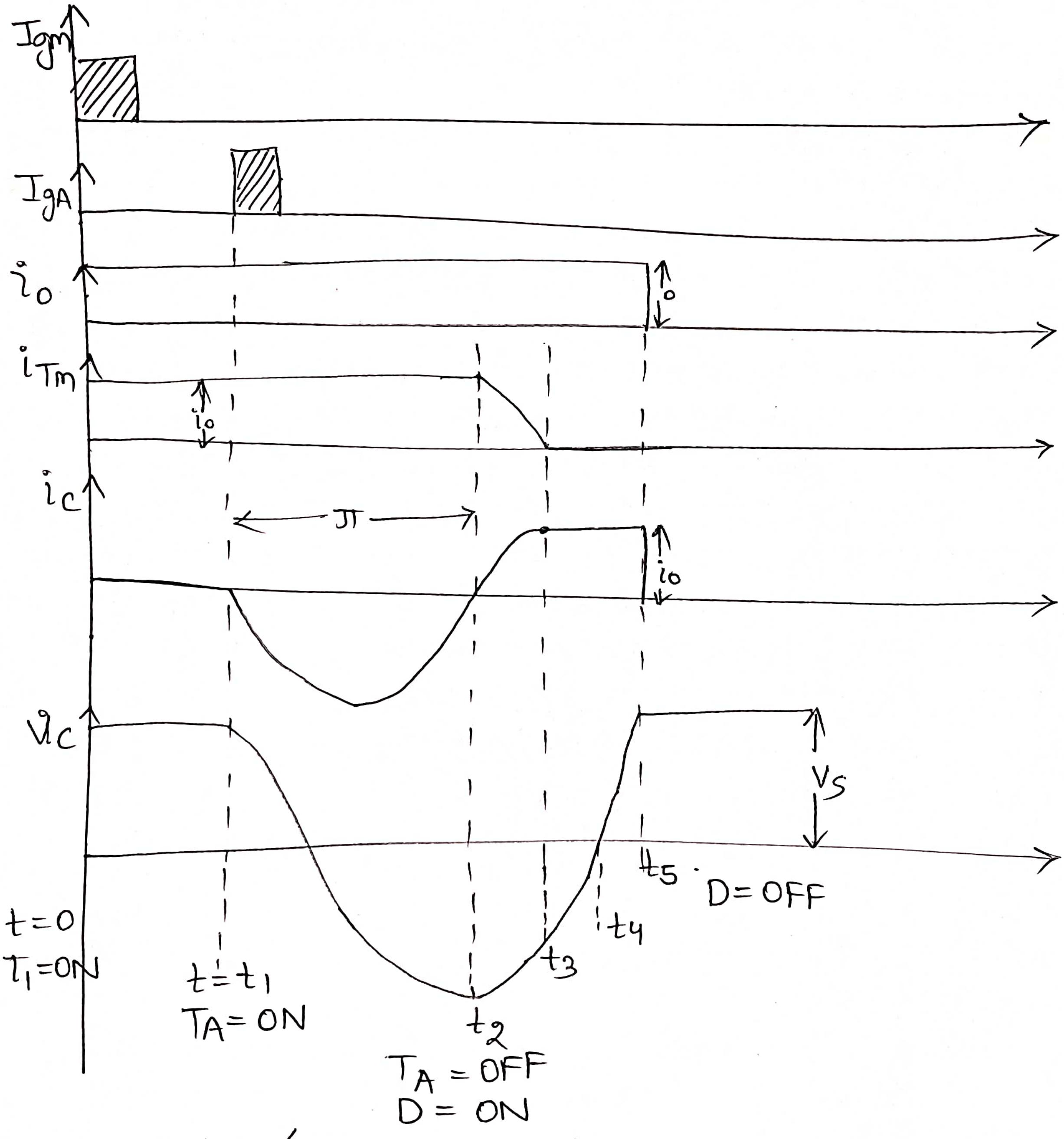
& at $V_C = V_S$

$i_0 = 0$, D=OFF

→ At $t = t_3$, T_M = OFF

$$V_S \sqrt{\frac{C}{L}} \sin \omega_0 (t_3 - t_2) = i_0$$





(Wave form)

Capacitor voltage at which Tm turns OFF

$\Rightarrow V_{cq} = V_s \cos \omega_0 (t_3 - t_2)$

circuit turn OFF time $= t_c = t_4 - t_3$

$= C \cdot \frac{V_{ab}}{i_0}$

Objectives of the Lecture	Protection of SCR, over voltage protection, over current Protection.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	All power devices have specific ratings & for reliable satisfactory operation its ratings must not be exceeded. If a device experiences over voltage or high current, It may be destroyed. So, the device must be protected against abnormal condition. $\frac{di}{dt}$ protection:- When SCR is forward biased by a gate value, the current spreads across the whole area of Junction. → If $\frac{di}{dt}$ rating > spread velocity of charge carriers, local hotspot will be formed & the device may be damaged. → To limit the $\frac{di}{dt}$ a small inductor is connected in series with the SCR. → This inductor called as $\frac{di}{dt}$ inductor/current snubber. $\frac{dv}{dt}$ protection:- → If $\frac{dV}{dt}$ is high, the SCR may get turned ON, when leads to fall operation of the SCR ckt. → To limit the $\frac{dV}{dt}$, snubber ckt is connected in parallel with the device.

Objectives of the Lecture	Firing Circuits, General layout diagram of firing circuit.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	· An SCR can be switched from OFF state to ON state by several ways i.e forward voltage triggering, Light triggering, dV/dt triggering, Temp. triggering, gate triggering. → The CKt which produces necessary gate signal to turn on the SCR at desired instant of time is called firing circuit / Triggering CKt. **Firing of Thyristor:-** The basic requirement for successful firing of a thyristor are that the current supplied to the gate should i) to be adequate amplitude & short rise time. ii) be of adequate duration iii) Occure at a time when main CKt conditions are favourable of conduction. **Gate Current Amplitude:-** → Igmin is the minimum gate current required to Fil all thyristor of same type at a standard temperature. → Including a safe margin 1·4 Igmin of firing current is satisfactory so long as main CKt don't have special requirements. → Firing current is high then turn-on time reduces → As the specification of gate current amplitude is incomplete without rise time.

→ Effectiveness of pulse increases as the rise time is reduced.

Gate pulse duration :-

→ A thyristor may be triggered successfully by a gate pulse of a duration approximatly equal to turn-on time of the device.

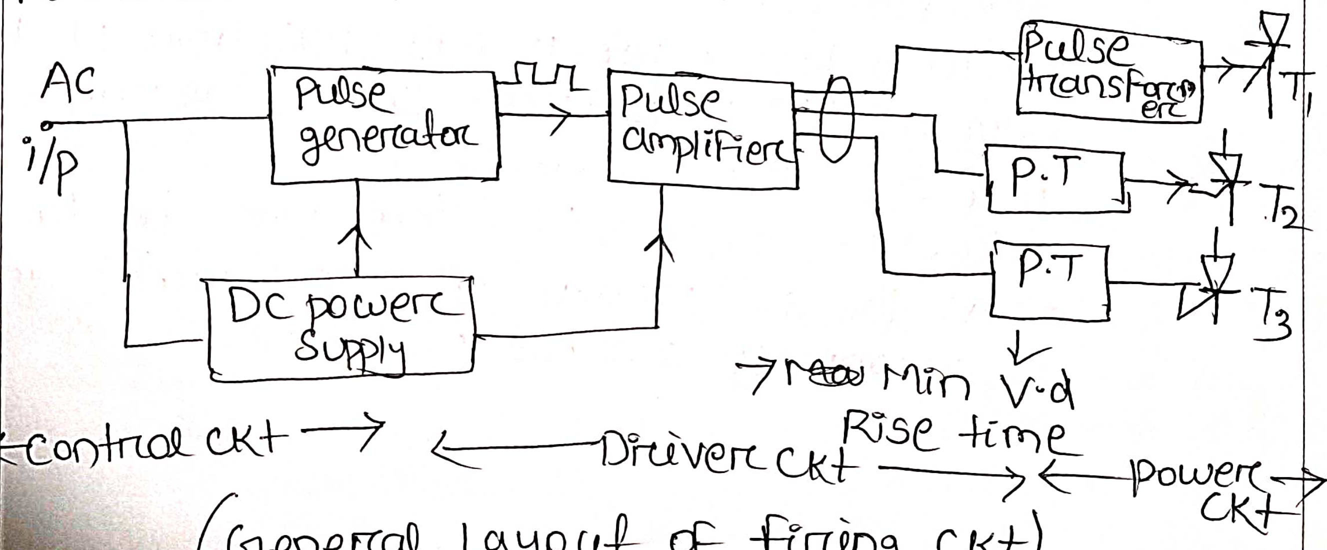
→ But longer pulse duration is desirable for the following reasons.

i) A relatively long period may be required for the anode current to rise to the latching current level.

ii) Oscillation reflections or other distrubances may conspire to turn off the SCR shortly after it is first triggered.

→ In general pulse duration of less than 10ws requires in the design of anode ckt, while a duration of 30-60 days is sufficient to avoid problems as long as anode ckt condn are favourable to conduction.

Gate Triggering ckt :-



(General Layout of firing ckt)

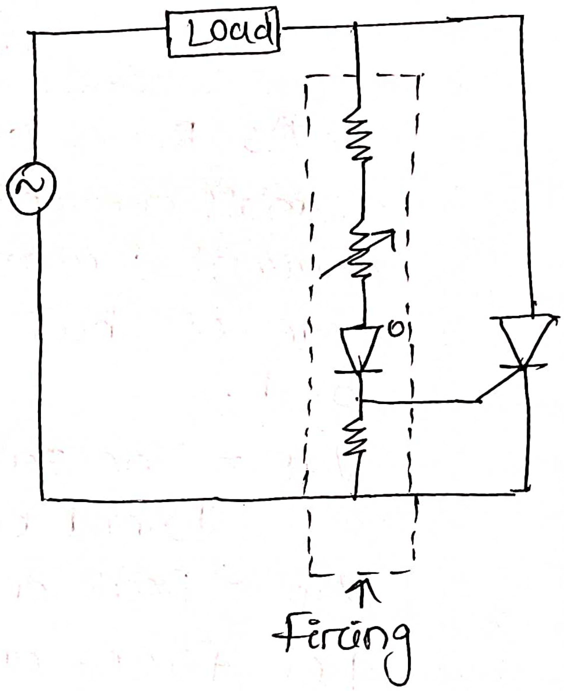
→ Firing ckt has two functions :-

i) If power ckt has ~~to~~ more than one SCR, the firing ckt should produce pulse for each SCR at desired instant for proper operation.

Objectives of the Lecture	·R Firing circuits.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

R_2 = Variable resistance which charges Firing of gate value i.e gives the variable timing angle:



R = stabilizing P
= used to limit the Vs gate voltage with in permissible value.

R_1 = is added to limit the gate current within permissible value.

In case $R_2 = 0$

gate current flows from source, through load R_L & gate to cathode. The current shouldn't entered ~~maxm~~ permissible gate current I_{gm}.

Load resistance = .

Max^m voltage = V_m

$$\frac{V_m}{R_1} \leq I_{gm} \quad \text{or} \quad \boxed{R_1 \geq \frac{V_m}{I_{gm}}}$$

R should have such value that max^m current across it doesn't exceed max^m gate voltage V_{gm}. Max^m current passing throug R,

$$= \frac{V_m}{R_1 + R}$$

So, $\left(\frac{V_m}{R_1+R}\right) \cdot R \leq V_{gm}$.

i.e $\boxed{R \leq \frac{V_{gm} R_1}{V_m - V_{gm}}}$

→ As R_1, R_2 are large, gate trigger ckt draws a small current. Diode D allows the flow of current during +ve half cycle only & the amplitude of half wave dc pulse V_g can be controlled by R_2.

V_{gt} = The gate voltage at which the SCR is turned ON.

V_{gp} = Peak of gate voltage V_g

Let firing angle $= \alpha$

The relationship betn V_{gt} & V_{gp}

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

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

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

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

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

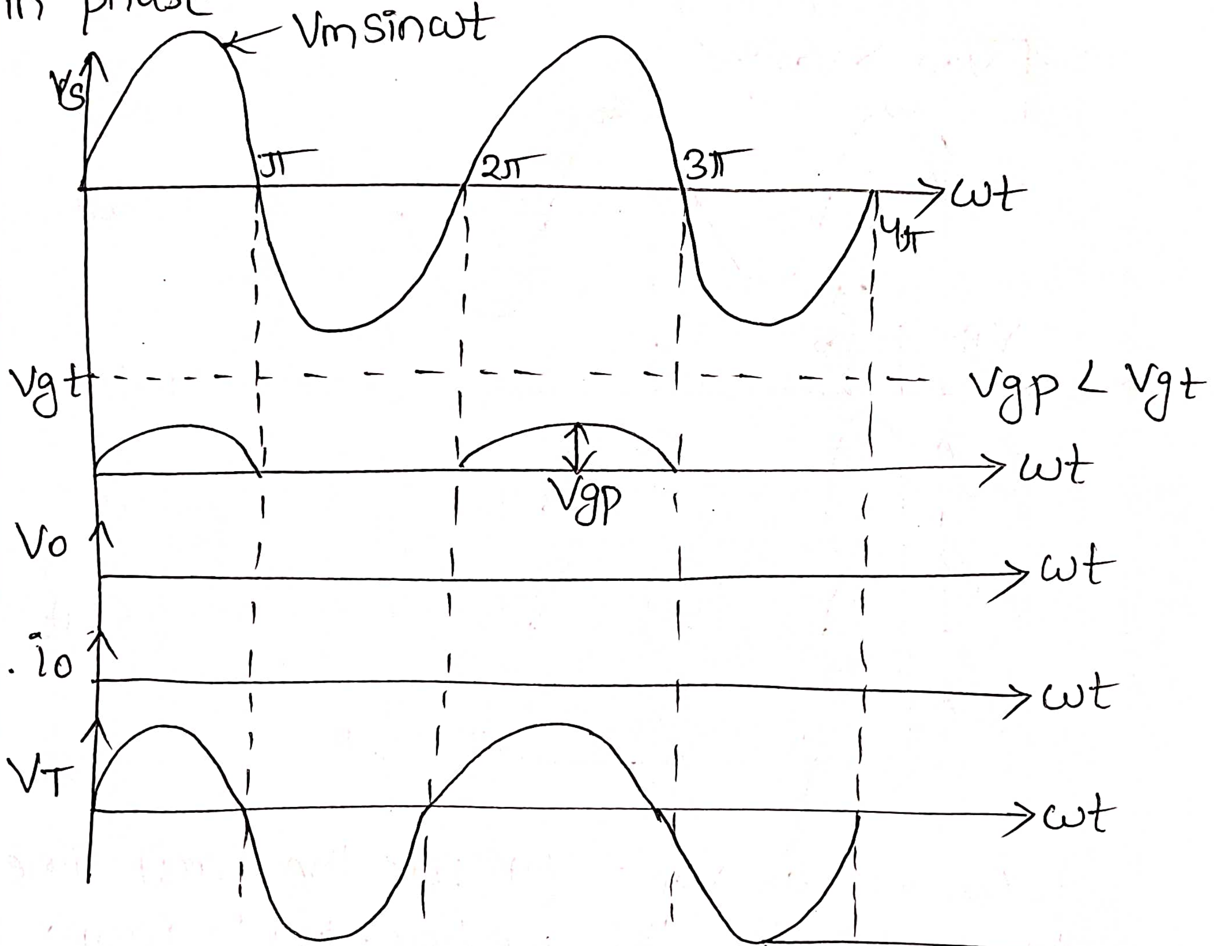
As V_m, R_1, R, V_{gt} constant i.e fixes

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

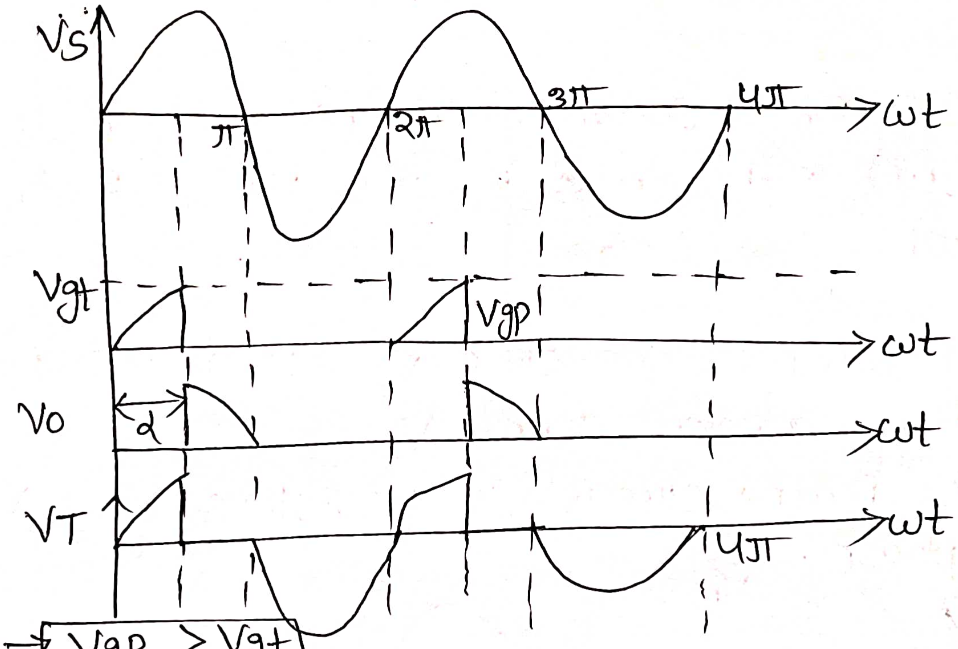
→ If R_2 is large, current i is small, as the result v.d across R, i.e $V_g = i \cdot R$ is also small. $V_{gp} < V_{gt}$

SCR will n't turn ON & $V_0 = 0$, $i_0 = 0$ & supply voltage appears across V_T.

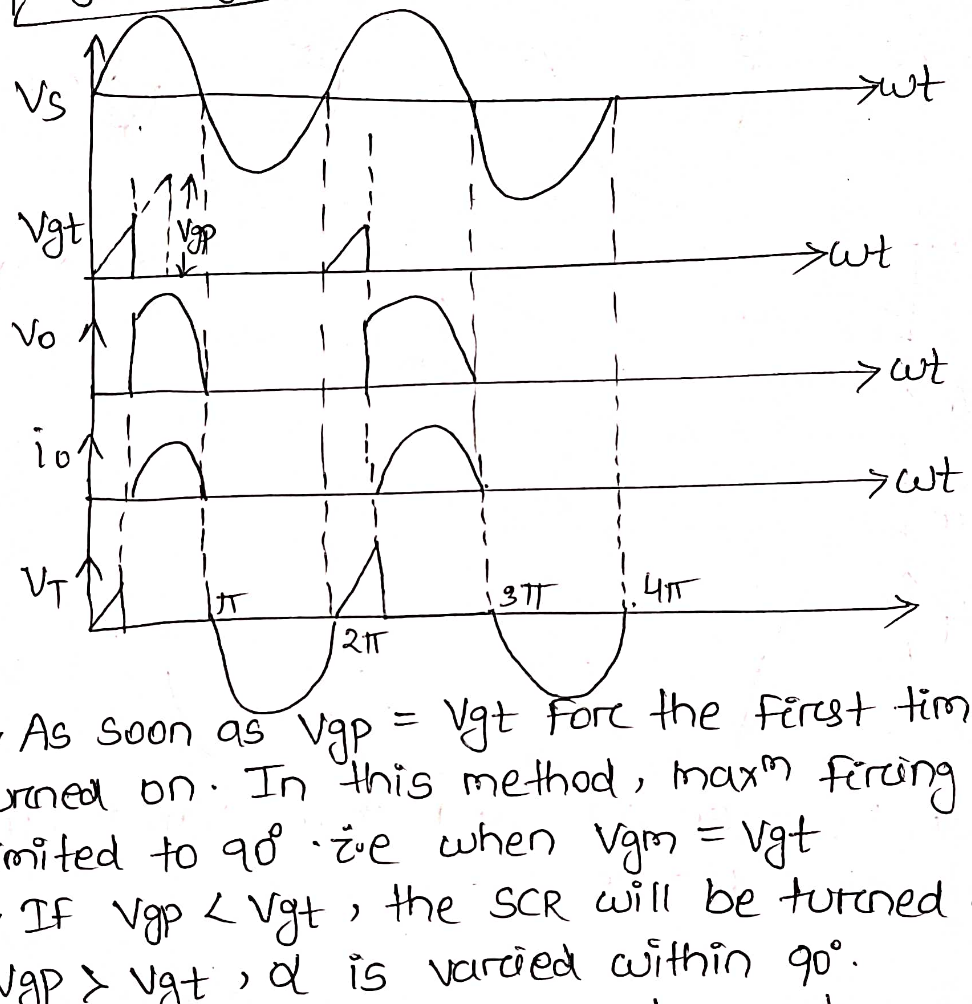
→ As firing circuit is resistive V_g & V_s are in phase.



→ If R_2 is so adjusted that $V_{gp} = V_{gt}$ then $\alpha = 90°$



→ Vgp > Vgt



→ As soon as Vgp = Vgt for the first time SCR is turned on. In this method, max^m firing angle is limited to 90° i.e when Vgm = Vgt

→ If Vgp < Vgt, the SCR will be turned OFF.

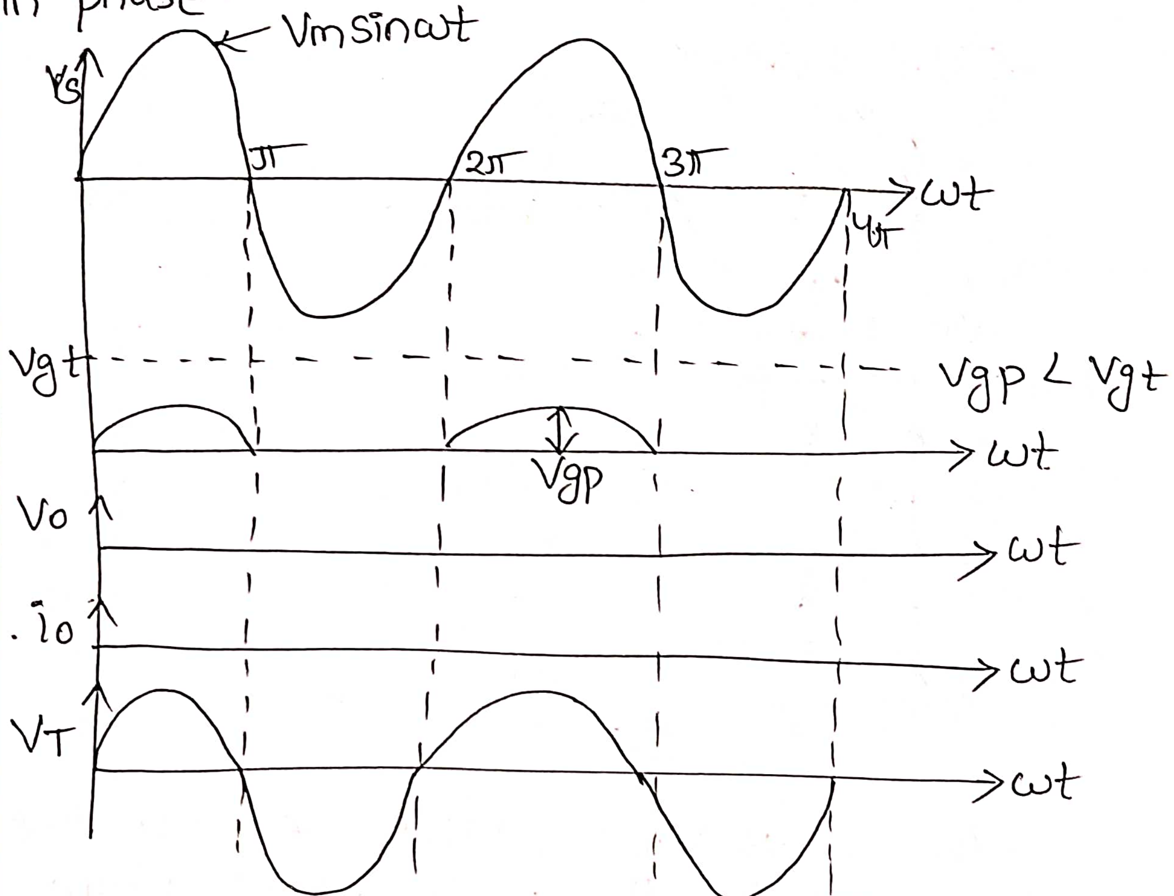
Vgp > Vgt, α is varied within 90°.

α never be equal to zero degree however large Vgp may be It is near to 2° to 4.

→ If R_2 is large, current i is small, as the result v.d across R, i.e $V_g = i \cdot R$ is also small. $\boxed{V_{gp} < V_{gt}}$

SCR will n't turn ON & $V_o = 0$, $i_o = 0$ & supply voltage appears across V_T.

→ As firing circuit is resistive V_g & V_s are in phase.



→ If R_2 is so adjusted that $\boxed{V_{gp} = V_{gt}}$ then $\alpha = 90°$

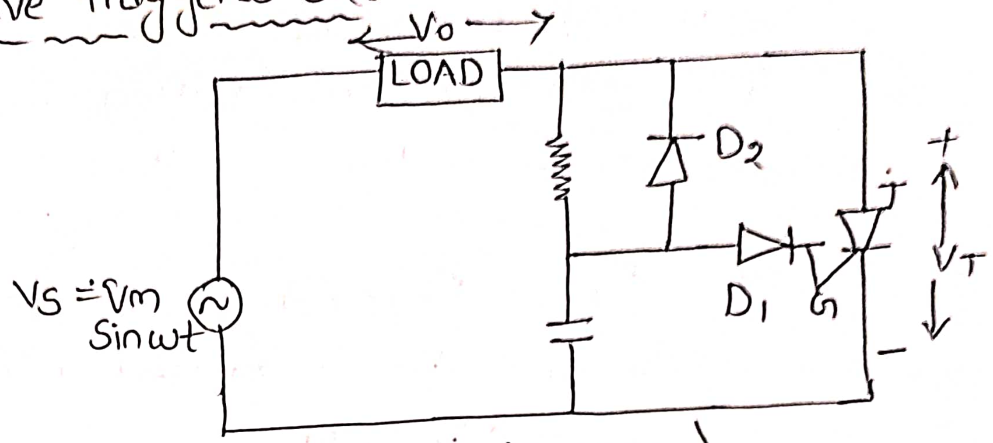
Lesson Plan-16

Objectives of the Lecture	R-C Firing circuit.
Learning Outcomes	
Tools Used	Marker Pen. Duster. White board. Projector

Actual lecture in details with fig.

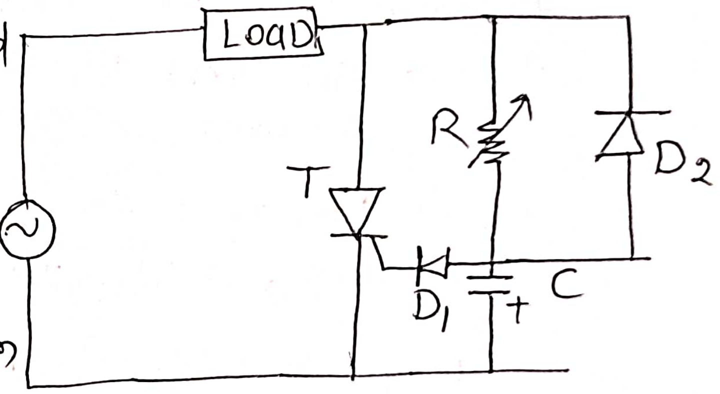
The limited range of firing angle control by resistance firing CKt can be overcome by RC Firing CKt.

RC half wave triggers CKt:-



(CKt diagram)

By varying R Firing angle can be controlled from 0° to 180°.



→ In negative half cycle, D_2 is forward biased and C charges to peak voltage $-V_m$ through D_2 with lower plate +ve at $\omega t = -\pi/2$

→ Vs depends /decreases from $-V_m$ to 0 at 0°. during this Vc fall from $-V_m$ to a lower value $-oa$. at $\omega t = 0°$.

→ In positive half cycle, D_2 is reverse biased, and capacitor charges through 'R'.

→ When $V_c = V_{gt}$, SCR is fired & after this capacitor holds a small +ve voltage.

→ D_1 is used to prevent the breakdown of gate cathode junⁿ during -ve half cycle.

→ In the range of power frequencies the RC for zero output voltage is given by

$$RC = \frac{1.3T}{2} \simeq \frac{4}{\omega}$$

$T = 1/F$ = Period of AC line frequency in sec.

→ SCR will be triggered when

$$V_1 = V_Y + V_d$$

V_d = Voltage drop across D_1

Assume V_c = const. at the instant of triggering

I_{gt} = supplied by voltage source through R, D_1 & gate cathode ckt.

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

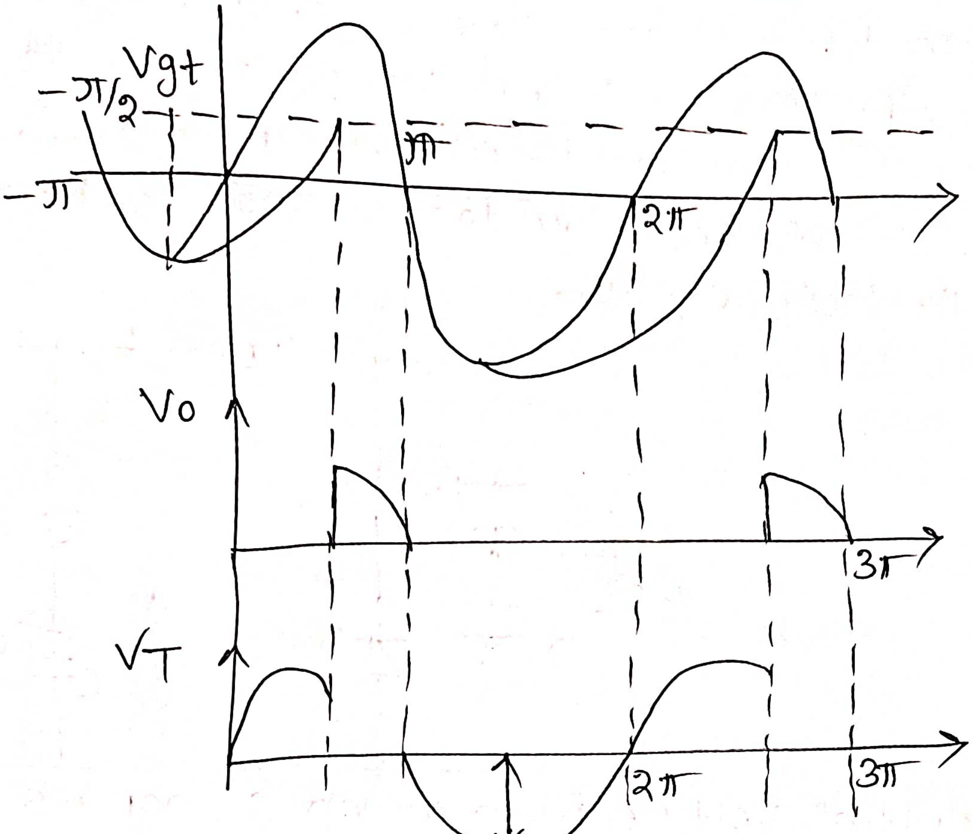
$$\geq R I_{gt} + V_{gt} + V_d$$

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

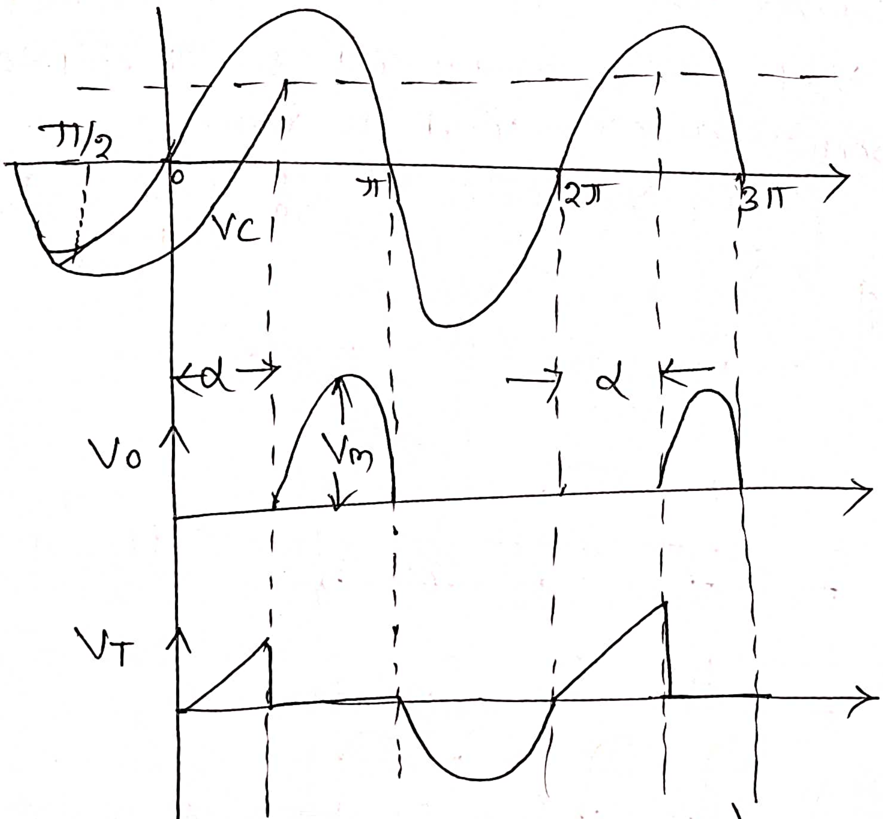
Where V_s is source voltage at which SCR turn ON

→ If R ↑ firing angle ↑

R ↓ firing angle ↓



(High value of R)

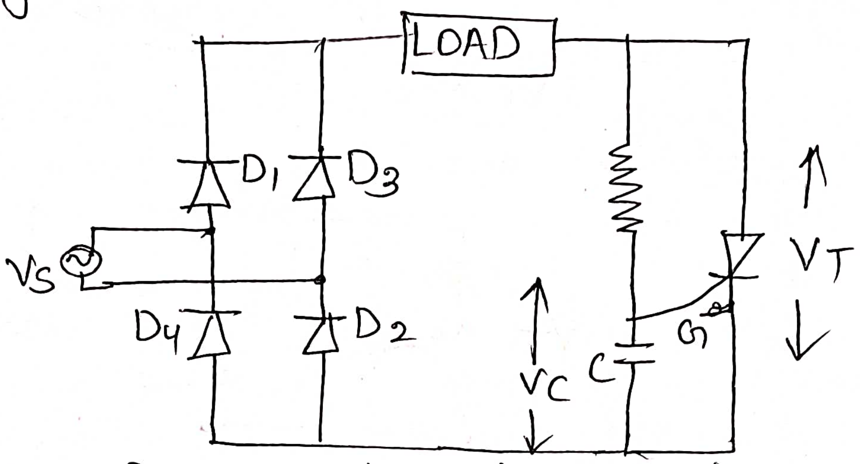


(Low value of R)

RC Full wave trigger circuit:-

→ Power can be delivered to the load during +ve half cycle because SCR conduct only when it is forward biased. This limitation can be overcome by this method.

→ AC line voltage is converted to pulsating dc by full wave diode bridge & SCR is triggered for both half cycles.

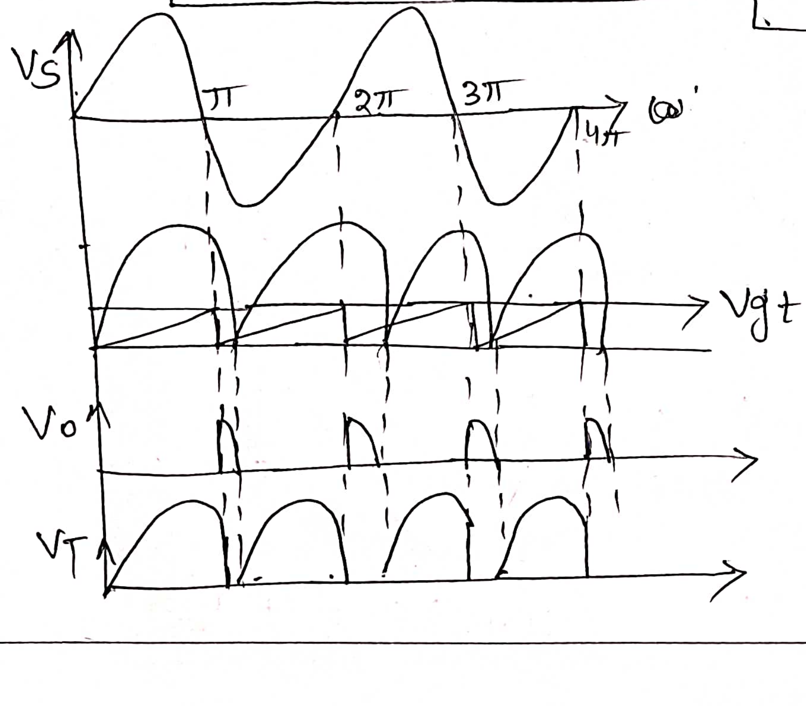


→ Initial voltage from which C charges is zero. C set to a low positive voltage.

→ When $V_c = V_{gt}$ i.e C charges to a voltage equal to V_{gt}, SCR triggered & Rectified voltage V_d appears across load as V_o.

$$RC \geq 50T/2 \cong \frac{157}{\omega}$$

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

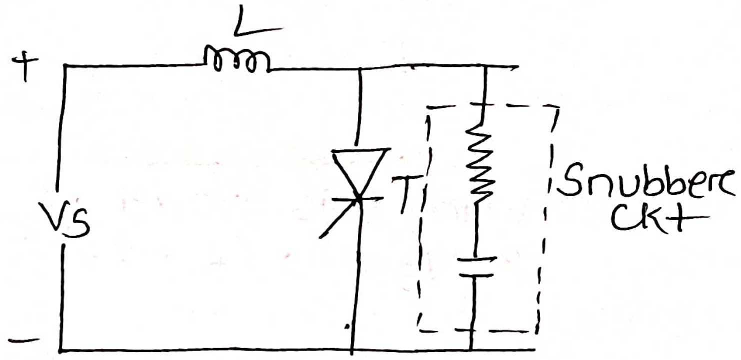


Lesson Plan-18

Objectives of the Lecture	Design of snubber circuits.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

A Snubber ckt consists of a series combination of resistance Rs & capacitance Cs is parallel with the SCR.



→ When voltage is applied to the ckt, capacitor behaves as short ckt, Therefore voltage across SCR = 0

→ Then voltage across capacitor build up at a slower dv/dt, so, across SCR dv/dt is less than the specified rating.

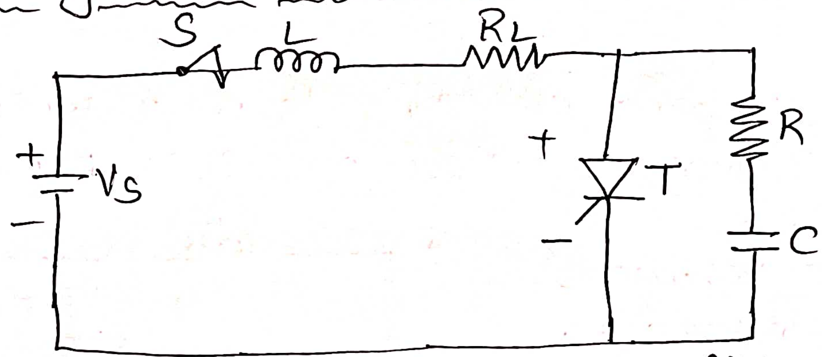
→ When SCR is turned off the reverse recovery current rises to peak value at which the device blocks. without RC snubber, the reverse, recovery current cause a transient overvoltage, $L\frac{di}{dt}$ in series inductance L which may destroy the device.

→ If RC snubber is connected reverse recovery currents transfer to RC path when the device blocks.

→ Before SCR is fired by gate pulse, Cs charges to full voltage Vs. When SCR is on, Cs discharges & send current equal to Vs/(Resistance of local path formed by Cs & SCR).

→ Normally Rs, Cs L & load ckt parameters form an understanddamped ckt. So, that dv/dt limited to acceptable value.

Design of Snubber network for dc circuit



When S is closed, C behaves like short circuit & $V_S = i(R+R_L) + \frac{di}{dt}$ SCR in forward blocking state offers high resistance.

The sol^n of above eq^n is

$$i = I(1-e^{-t/\tau}) \quad \text{——— (1)}$$

$$I = \frac{V_S}{R+R_L} \quad \& \quad \tau = \frac{L}{R+R_L}$$

$$\frac{di}{dt} = I \cdot e^{-t/\tau} \cdot \frac{1}{\tau}$$

$$= \frac{V_S}{R+R_L} \cdot \frac{R+R_L}{L} \cdot e^{-t/\tau}$$

$$\frac{di}{dt} = \frac{V_S}{L} e^{-t/\tau}$$

→ The value of $\frac{di}{dt}$ is maximum when $t = 0$

$$\left(\frac{di}{dt}\right)_{max} = \frac{V_S}{L}$$

$$\boxed{L = \frac{V_S}{(di/dt)_{max}}}$$

→ Voltage across SCR

$$V = R \cdot i$$

$$\Rightarrow \frac{dv}{dt} = R\frac{di}{dt}$$

$$\Rightarrow \left(\frac{dv}{dt}\right)_{max} = R\left(\frac{di}{dt}\right)_{max}$$

$$\Rightarrow R = \frac{(dv/dt)_{max}}{V_s/L}$$

$$\Rightarrow \boxed{R = \frac{L}{V_s}\left(\frac{dV}{dt}\right)_{max}} \quad \text{——— (A)}$$

The parameters L, R_L, R, C should be so selected that the circuit becomes critically damped. (capacitor charges in minimum time for this condition).

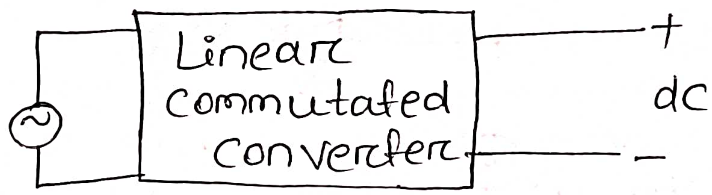
$$\therefore \boxed{R_L + R = 2\sqrt{\frac{L}{C}}} \quad \text{——— (B)}$$

We can determine the snubber components R & C from eq^n (A) & (B)

Objectives of the Lecture	Controlled rectifiers Techniques(phase angle, Extinction angle control, Single quadrant Semi converter.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

These are line commutated ac to dc power converters which are used to convert fixed voltage, fixed frequency ac power supply into variable dc o/p voltage.

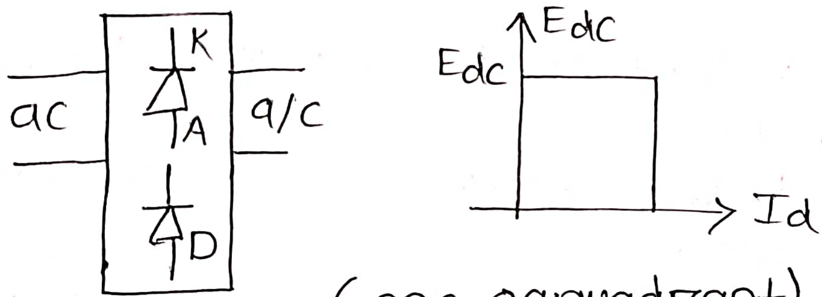


→ Rectification — AC to dc

The rectifier ckts are → Uncontrolled (only diodes)
→ fully controlled (SCR) amplitude varied
→ half controlled SCR & Diode

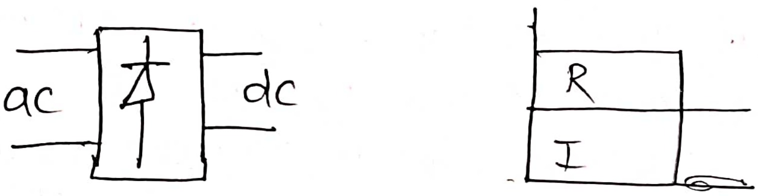
→ A phase controlled Rectifier may provide either a one quadrant, two quadrant or four quadrant operation at its dc terminals.

→

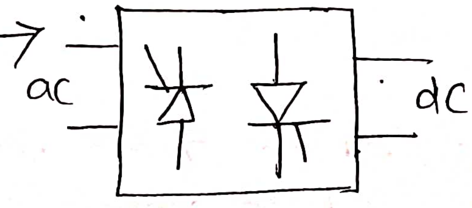


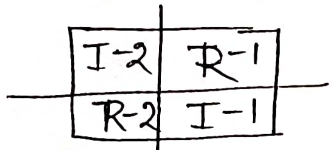
(one quadrant)

→



(2nd Quadrant)

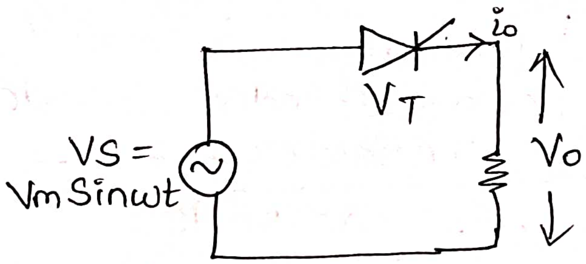
→ 



(4 quadrant)

→ phase angle control.

Single phase half-wave converter with R-Load



Source voltage $V_s = V_m \sin \omega t$

→ An SCR conducts only when anode voltage is +ve cord cathode & gate signal is applied.

→ A SCR blocks the flow of load current until it is triggered.

→ At same delay angle α, it is triggered by applying +ve voltage in between G & K.

→ At instant of delays angle, α, Vo rises to $V_m \sin \alpha$.

→ For R load, v_o & i_o are in phase with each other.

→ A firing angle may be defined as the angle between the instant SCR would conduct if it were a diode & the instant it is triggered.

→ once SCR on, load current flows, until it is turned OFF by reversal of voltage at

$\omega t = \pi, 3\pi, 2\pi$.

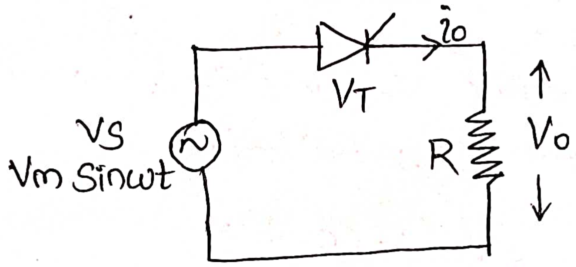
→ Single phase half wave ckt produces one pulse of load current during one cycle of Vs.

→ SCR conducts $\omega t = \alpha$ to π, - - -

→ Over firing angle α, $v_0 = 0$

θ conduction angle $\pi - \alpha$ $v_0 = v_s$.

Objectives of the Lecture	Working of single phase half wave controlled converter with Resistive load.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector
Actual lecture in details with fig.	



→ An SCR conducts only when anode voltage is +ve & gate signal is applied. A SCR blocks the flow of load current until it is triggered.

→ At some delay angle α, it is triggered by applying +ve voltage in between G & K.

→ At instant of delay angle, α, V_o rises to $V_m \sin\alpha$

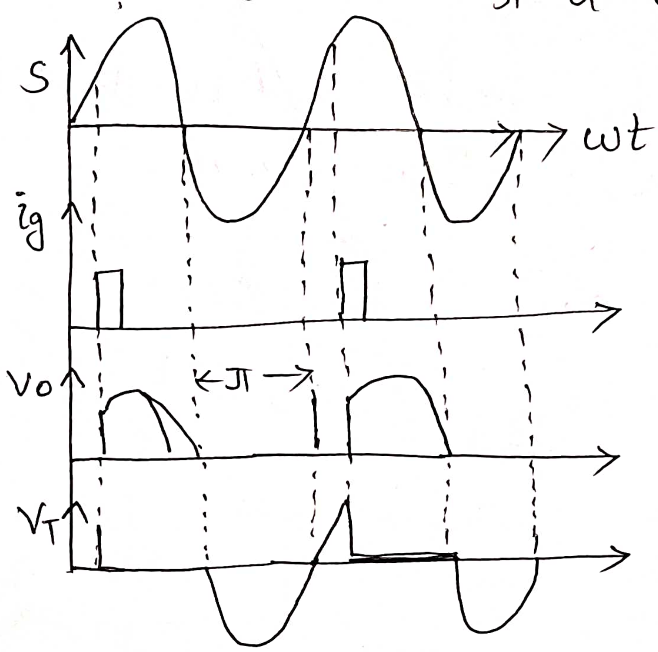
for R load, v_o, i_o are in phase with each other

→ once SCR on, load current flows, until it is turned off by reversal of voltage at $\omega t = \pi, 3\pi$.

→ SCR conducts from $\omega t = \alpha$ to π - - - -

→ over firing angles α, $v_o = 0$

$\pi - \alpha$ $v_o = v_s$



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

$$= \frac{V_m}{2\pi}(-\cos\omega t)_{\alpha}^{\pi} = \frac{V_m}{2\pi}(1+\cos\alpha)$$

Max^m avg value V_o occurs at $\alpha = 0$

$$V_{om} = \frac{V_m}{2\pi}\cdot 2 = V_m/\pi$$

$$I_o = \frac{V_o}{R} = \frac{V_m}{2\pi R}(1+\cos\alpha)$$

$$V_{or} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2}$$

$$V_{or}^2 = \frac{V_m^2}{2\pi}\int_{\alpha}^{\pi} \frac{1-\cos 2\omega t}{2} \cdot d\omega t$$

$$= \frac{V_m^2}{4\pi}\left[(\pi-\alpha) - \left(\frac{\sin 2\omega t}{2}\right)_{\alpha}^{\pi}\right]$$

$$= \frac{V_m^2}{4\pi}\left((\pi-\alpha) + \frac{1}{2}(\sin 2\alpha)\right)$$

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

$$I_{or} = \frac{V_{or}}{R}$$

$P = V_{or} \cdot I_{or}$ = Power delivered to R load

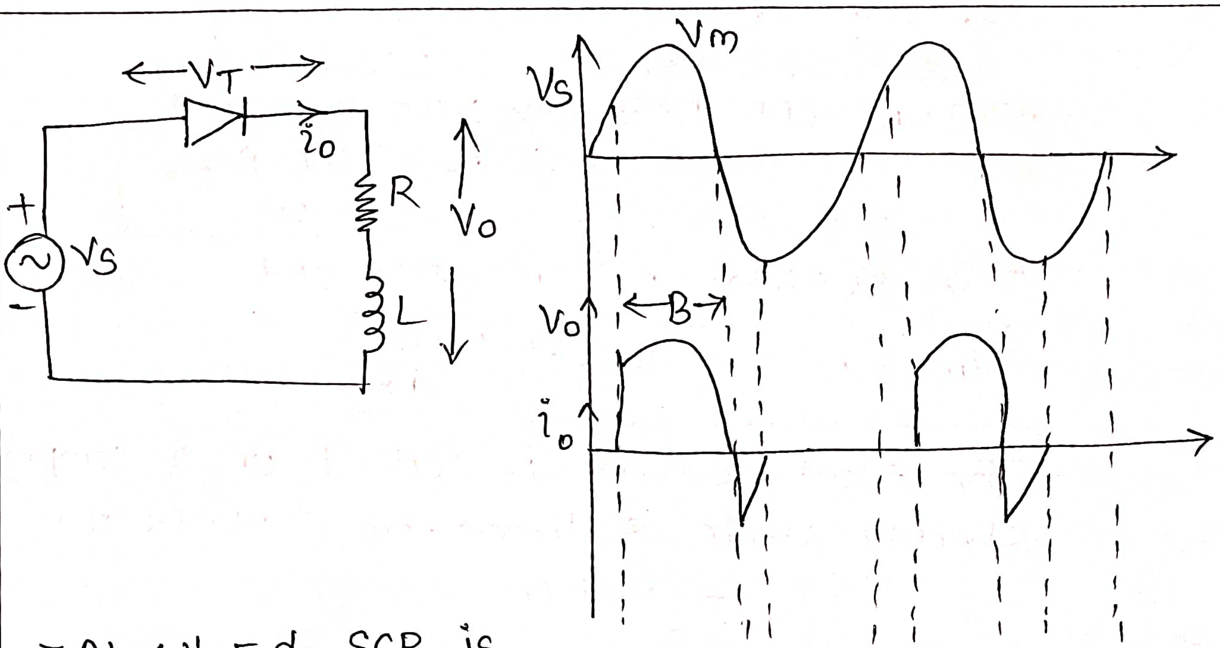
i/p VA = $(V_s)_{rms} I_{or}$ i/p VA

$$P/F = \frac{P}{VA} = \frac{V_{or}}{V_s} = \frac{V_m}{2\pi} / V_m/\sqrt{2}$$

$$= \frac{1}{\sqrt{2\pi}}\left[(\pi-\alpha) + \frac{1}{2}\sin 2\alpha\right]$$

Objectives of the Lecture	Working of single-phase half wave controlled converter with R-L Load ~~load~~ & understand need of freewheeling diode.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.



→ At $\omega t = \alpha$, SCR is triggered.

→ But, the inductance L forces the load / O/P current to rise gradually & energy is stored in inductor.

→ After & some time i_o reaches max^m value & then begins to decrease.

→ −ve ha cycle, current continues till the energy stored in L is dissipated in R & a part of energy is fed back to source.

→ At $\omega t = \pi$, $V_s = 0$, $V_o = 0$, but $i_o \neq 0$ because of the load inductance L.

→ After $\omega t = \pi$, SCR is subjected to reverse anode voltage but not turned off as i_o not less than I_H.

→ At some angle $\beta > \pi$, $i_o = 0$ & SCR turned off as it is already reverse biased.

→ After $\omega t = \beta$, $V_o = 0$, $i_o = 0$.

→ β is called extiction angle.

⇒ $\gamma = \beta - \alpha$ = conduction angle

→ Turn off time → $\omega t_c = 2\pi - \beta$

⇒ $t_c = \frac{2\pi - \beta}{\omega}$ sec

The voltage eq^n of this ckt

$$V_m \sin\omega t = R i_o + L\frac{di_o}{dt}$$

The load current i_o consist of 2 components, steady state & transient component.

$$i_o = i_s + i_t$$

$$i_s = \frac{V_m}{\sqrt{R^2 + X^2}} \sin(\omega t - \phi)$$

⇒ $\phi = \tan^{-1}\frac{X}{R}$ is large Vs by ϕ.

→ Transient component i_t obtained

$$R i_t + L\frac{di}{dt} = 0$$

$$i_t = A e^{-Rt/L}$$

$$i_o = \frac{V_m}{Z}\sin(\omega t - \phi) + A e^{-R/L\, t}$$

A can be obtained from boundary condition.

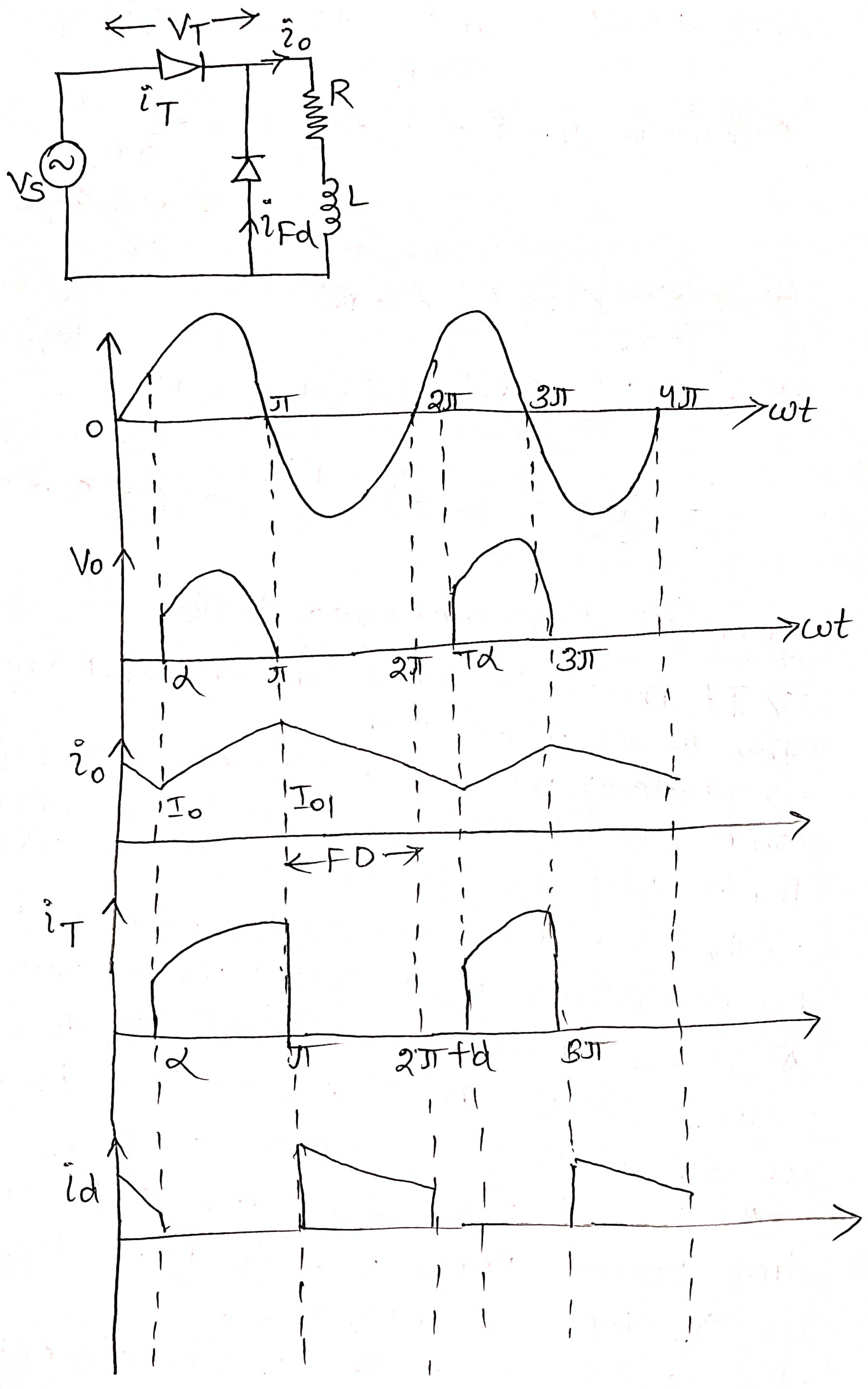
At $\omega t = \alpha$, $i_o = 0$

$$0 = \frac{V_m}{Z}\sin(\alpha - \phi) + A e^{-R\alpha/L\omega}$$

$$A = -\frac{V_m}{Z}\sin(\alpha - \phi) e^{R\alpha/L\omega}$$

$$i_o = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{V_m}{Z}\sin(\alpha - \phi)\exp\left\{\frac{-R}{\omega L}(\omega t - \alpha)\right\}$$

→ During freewheeling ~~di~~ period, load current doesn't delay to zero untill SCR is triggered again at $2\pi + \alpha$.



At $\omega t = \beta$, $i_0 = 0$

$\Rightarrow \sin(\beta - \phi) = \sin(\alpha - \phi) \exp\left\{\frac{-R}{\omega L}(\beta - \alpha)\right\}$

↳ (B)

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

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

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

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

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

Need of Freewheeling diode :-

→ It prevents reversal of load voltage except for small diode v.d.

→ It transfers load current away from the main rectifier ckt thereby allowing it to regain their blocking capability.

→ The waveform of load current 'i_0' is improved by connecting freeheeling diode across load.

Also called as commutating diode / by-pass diode.

→ In positive half cycle, SCR is triggered at 'α' & source voltage appears across load.

→ At $\omega t = \pi$, $V_s = 0$, & after through SCR transfered from SCR to Freewheeling diode as V_s tends to reverse.

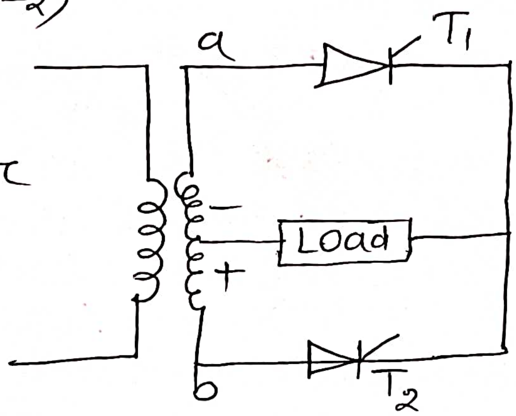
→ At same time, SCR is subjected to reverse voltage & zero current. So turned off at $\omega t = \pi$.

Objectives of the Lecture	Working of single phase ~~bo~~fully controlled converter with resistive load.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

Single phase Full wave converter :-

(Mid point converter (M-2))



→ Also called two pulse converter.

→ Single phase transformer with centre tapped ~~+~~ secondary winding.

2 SCR employed.

→ Terminal 'a' is +ve w.r.t n, n is +ve w.r.t b,

$V_{an} = V_{nb}$

$V_{an} = -V_{bn}$

Resistive load :-

→ During +ve half cycle, terminal a is +ve w.r.t b i.e V_{an} +ve, T_1 is forward biased & triggered at delay angle α.

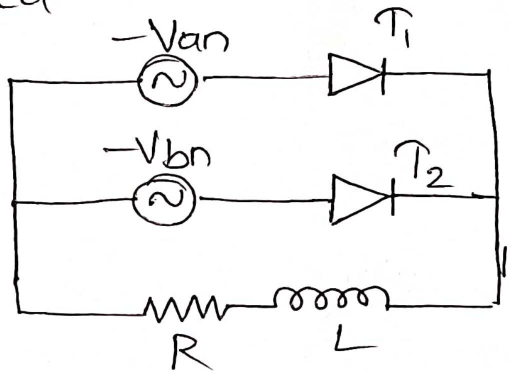
$$V_{an} = V_m \sin\omega t$$

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

$$V_{ab} = V_{an} + V_{nb} = 2V_m \sin\omega t$$

At $\omega t = \alpha$, T_1 is triggered

Reverse voltage across T_2.



$$V_{T_2} - V_{bn} + V_{an} - V_{T_1} = 0$$

$$V_{T_2} = V_{bn} - V_{an} + V_{T_1}$$

$$= V_{bn} - V_{an}$$

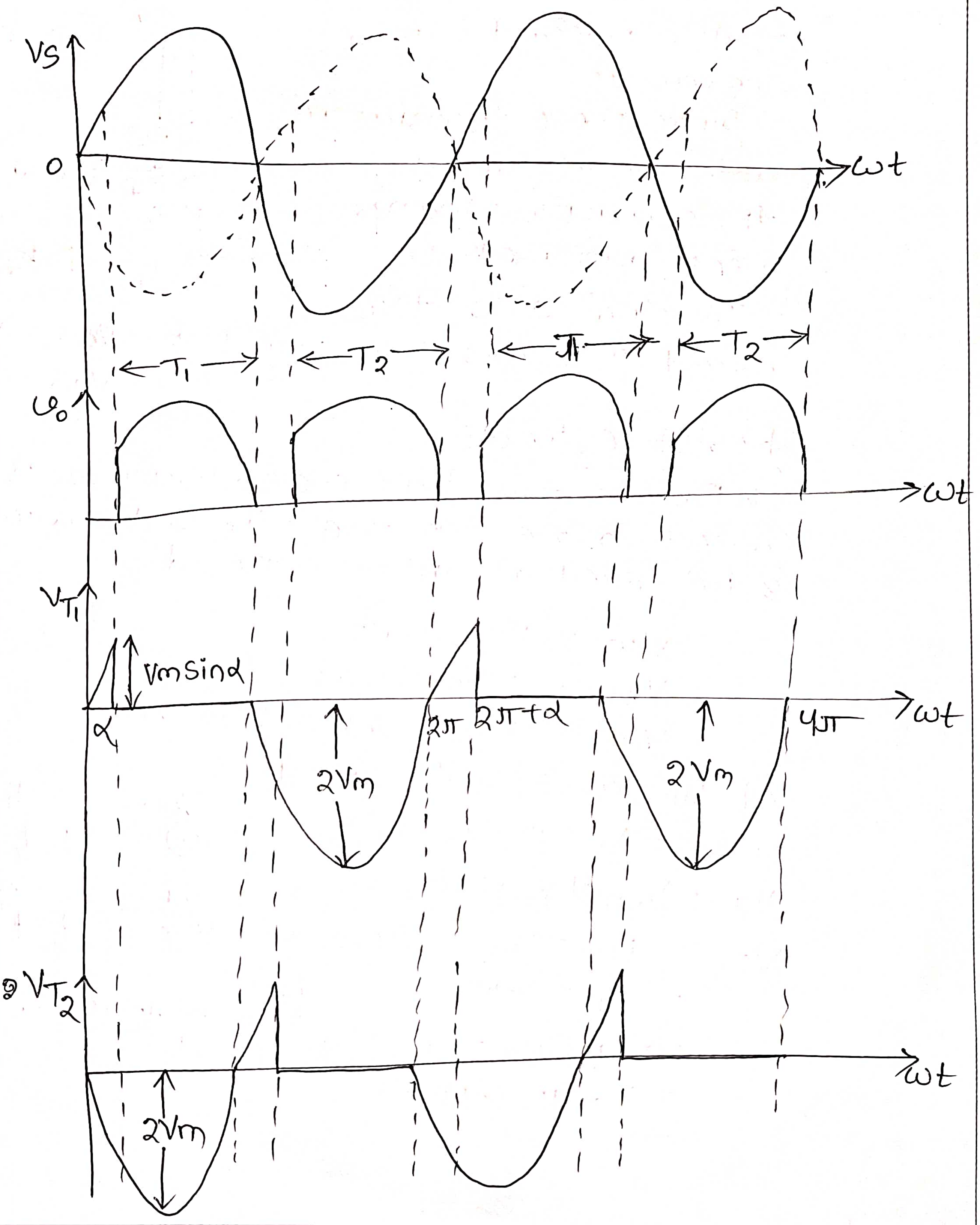
$$= -V_n \sin\alpha - V_m \sin\alpha$$

$$= -2V_m \sin\omega t$$

→ T_1 conducts from 0 to π.

→ At $\omega t = \pi$, T_1 is reverse biased, T_2 is triggered at $\pi + \alpha$.

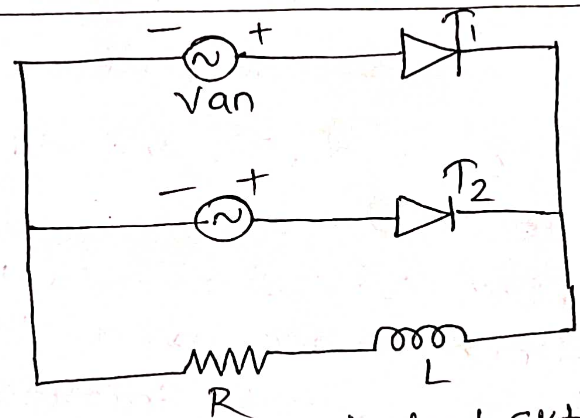
Reverse voltage across $T_1 = 2 V_m \sin \omega t$



Objectives of the Lecture	Working of single phase fully controlled converter with R-L Load.
Learning Outcomes	
Tools Used	Marker Pen, Duster, White board, Projector

Actual lecture in details with fig.

→



(equivalent ckt)

→ Supply is provided through a transformer whose Secondary is centre tapped.

→ Turn ratio of primary to each secondary 1 : 1.

→ n is the centre and a, b are two terminals.

→ $V_{an} = V_{nb}$ or $V_{an} = -V_{bn}$

→ from the equivalent circuit,

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

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

$$V_{ab} = V_{an} + V_{nb} \quad 2 V_m \sin \omega t$$

→ Suppose T_2 is already conducting.
After $\omega t = 0$, T is forward biased and triggered at an delay angle α. At $\omega t = \alpha$, T_2 is subjected to a reverse voltage $2 V_m \sin \alpha$ & turned OFF.

→ The magnitude of reverse voltage obtained by applying KVL to the load,

$$V_{T_2} - V_{bn} + V_{an} - V_{T_1} = 0$$

$\Rightarrow V_{T_2} = V_{bn} - V_{an} + V_{T_1}$ ($V_{T_1} = 0$ as T_1 is conducting)

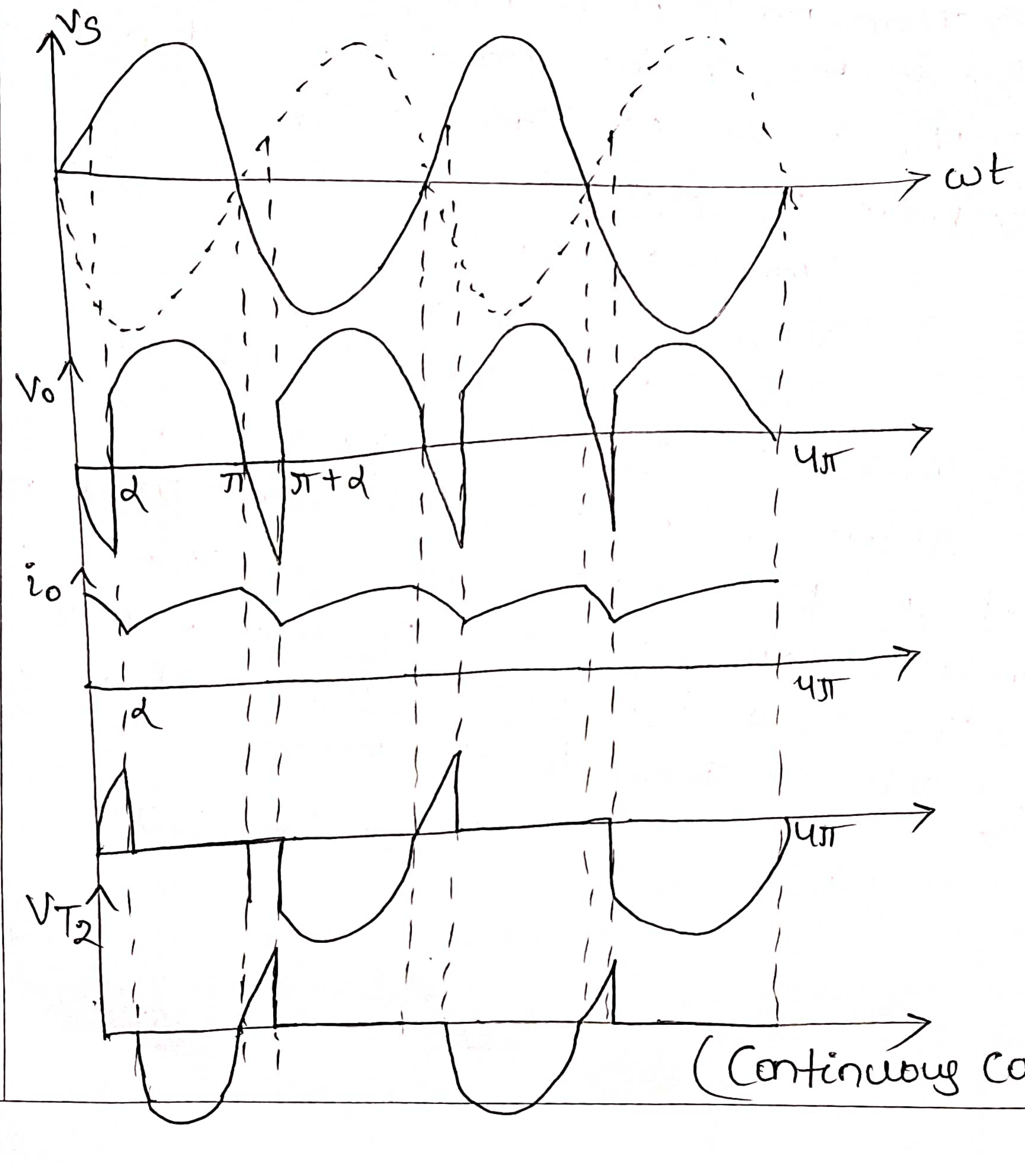
$\Rightarrow V_{T_2} = -V_m \sin\alpha - V_m \sin\alpha$

$= -2V_m \sin\alpha.$

→ At $\omega t = \alpha$, T_1 turned ON and conducts from α to $\pi+\alpha$.

→ After $\omega t = \pi$, T_1 is reverse biased but it'll continue conducting as the forward biased SCR T_2 is not triggered.

→ At $\omega t = \pi+\alpha$ T_2 is triggered & T_1 is reverse biased by voltage of magnitude $2V_m \sin\alpha$ and current is transferred from T_1 to T_2.



(Continuous condition)

→ T_2 is turned OFF at $\omega t = \alpha$, it is reverse biased from $\omega t = \alpha$ to π.

so, $t_c = \frac{\pi - \alpha}{\omega}$

→ T_1 is turned off at $\omega t = \pi + \alpha$ & it is reverse biased from $\omega t = \pi + \alpha$ to 2π.

$t_c = \frac{2\pi - \pi - \alpha}{\omega} = \frac{\pi - \alpha}{\omega}$

→ Average value of output voltage

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

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

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

$$= -\frac{V_m}{\pi} \left(-2\cos\alpha\right)$$

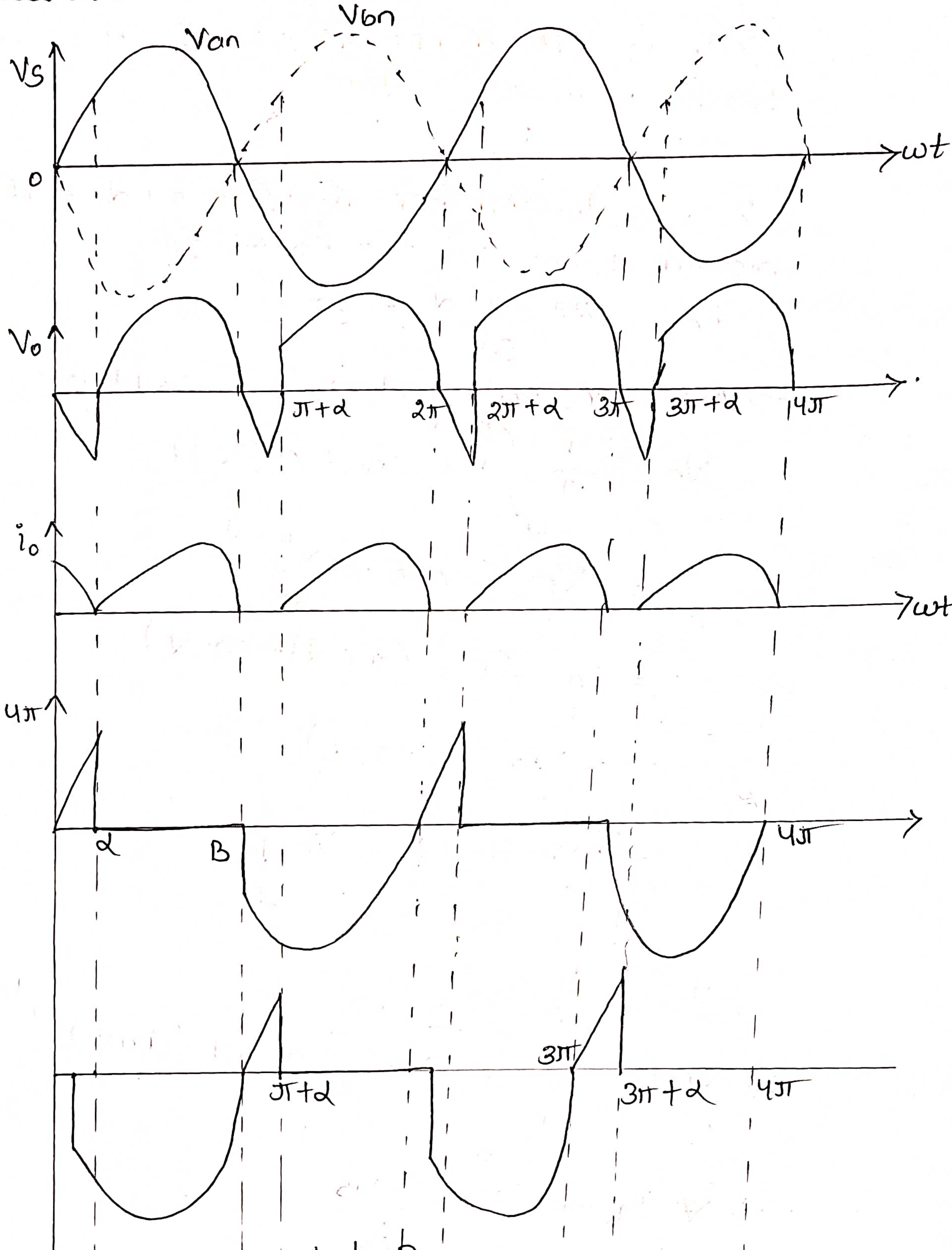
$$= \boxed{\frac{2V_m}{\pi} \cos\alpha = V_o}$$

⇒ $I_o = \frac{V_o}{R}$

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

⇒ $I_{rms} = \frac{V_{rms}}{R}$

Discontinuous condition ($\beta < (\pi+\alpha)$):



Condition Period α to β

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