

LECTURE NOTES OF

POWER ELECTRONICS & PLC

5TH SEMESTER ETC



PREPARED BY-

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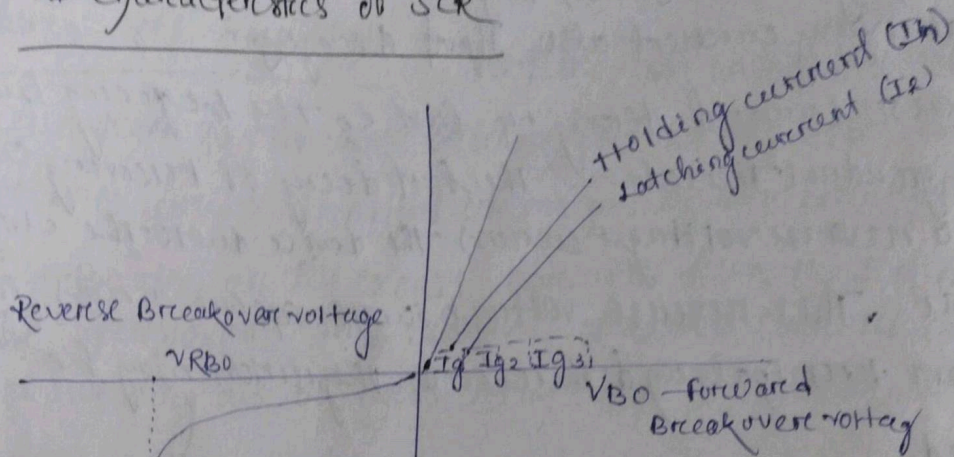
GOVERNMENT POLYTECHNIC DHENKANAL

DEPARTMENT OF ELECTRONICS AND TELECOMMUNICATION ENGINEERING

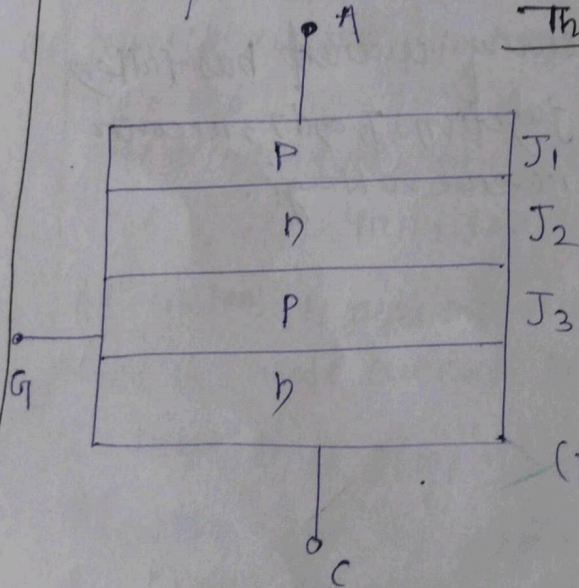
Thyristore

→ Two-transistor theory.

VI characteristics of SCR

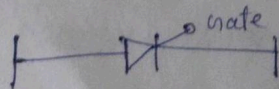


Thyristore (SCR)



(Pnp, npn)-transistor

(1) SCR is 3-terminal 4 layer 3 junction pnpn semiconductor device



Important terminals

- I_g - gate current
- This is the current by which increase or decrease voltage level of the SCR.
- When gate current is increase the voltage value increase inside the reverse P_n junction J_2 .
- The maximum value of voltage on which junction J_2 breakdown is known as forward Breakover voltage.
- I_H - Holding current → The minimum current below which SCR gets triggered off.
- I_L - Latching current → The minimum current after above which current continuous to flow inside the SCR.

V_{RBO} (Reverse Breakover voltage)

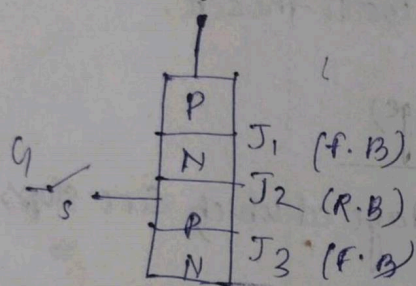
It is the maximum reverse voltage at which SCR stops to operate or damage.

Thyristor Basic mode

- Reverse blocking mode → When cathode is make positive with respect to anode then SCR is reverse biased, so junction J_1 and J_3 are reverse biased where as J_2 is forward bias.
- ~~A small leakage current, order of μA~~ Now the SCR behaves as if two diodes are connected in series with reverse voltage applied across them so a small leakage current with this is reverse blocking mode of SCR.
- If reversed voltage is increased then at a critical breakdown point called Reverse break down voltage (V_{RBO}). And avalanched occurs at J_2 and J_3 so the reverse current increases rapidly.
- This leakage current increases the temperature of the junction which may increased by its permissible temperature due to which the SCR may damage.

→ when reversed voltage is less than V_{BR} , the device offers high impedance in the reverse direction to the SCR behaves like an open switch. The VI characteristics after avalanche break down during reverse blocking mode is applicable only when load resistance is zero. When the load resistance is zero when the load resistance is present the large anode current is associated with avalanche break down at V_{BR} which causes a voltage drop across the load. So the VI characteristics in 3rd quadrant will bend to the right of vertical line drawn at V_{BR} .

forward blocking mode :-



(1) When anode is made +ve with respect to cathode with gate left open, the SCR is said to be forward biased. Now Junction J_1 and J_3 are forward biased and Junction J_2 is reverse biased.

A small leakage current will flow across SCR.

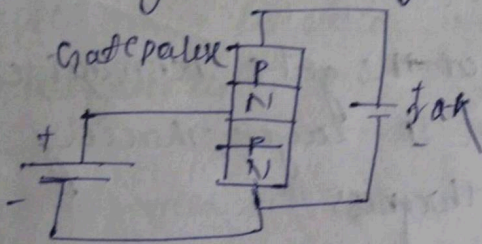
Now if the forward voltage is increased the Junction J_2 will have an avalanche break down at a voltage called forward break over voltage (V_{BO}).

When forward voltage is less than V_{BO} SCR offers high impedance so the thyristor can be treated as an open switch even in the forward blocking mode.

forward conduction mode:-

A thyristor is brought from forward blocking mode to forward conduction mode by turning it on by exceeding the break over voltage or by applying a gate pulse between gate and cathode. In this mode a thyristor is in on state and behaves like a closed switch.

The voltage drop across the thyristor in the on state is of the order of 1 to 2 volt depending upon the thyristor rating.



SCR terminal methods

With anode positive with respect to cathode a SCR can be turned on by any one of following ~~the~~ triggerings.

- (1) forward voltage triggering
- (2) gate triggering.
- (3) $\frac{dV}{dt}$ Triggering
- (4) temperature triggering
- (5) Light triggering.

forward triggering voltage

When forward voltage is applied with anode and cathode - with gate circuit open I_A is reversed biased.

As a region depletion layer

When the anode terminal is positive with respect to cathode (V_{AK}), Junction J_1 and J_3 is forward biased and junction J_2 is reverse biased.

- No current flows due to depletion region J_2 is reverse biased (except leakage current).
- As V_{AK} is further increased, at a voltage V_{BO} (forward break-over voltage) the junction J_2 undergoes avalanche breakdown and so a current flows and the device tends to turn ON (even when gate is open).

Gate Triggering :-

- This is most widely used SCR triggering method.
- Applying a positive voltage between gate and cathode can turn ON a forward biased thyristor.
- When a positive voltage is applied at the gate terminal, charge carriers are injected in the inner p-layer, thereby reducing the depletion layer thickness.
- As the applied voltage increases, the carrier injection increases, therefore the voltage at which forward break-over occurs decreases.

(d) dv/dt Triggering

- When the device is forward biased, J_1 and J_3 are forward biased, J_2 is reverse biased.
- Junction J_2 behaves as a capacitor, due to the charges existing across the junction.
- If voltage across the device is v , the charge q and capacitance by C then,

$$q = dq/dt$$

$$q = CV$$

$$ic = d(CV)/dt$$

$$C \cdot dV/dt + V \cdot dC/dt$$

$$as dC/dt = 0$$

$$i_c = C \cdot dV/dt$$

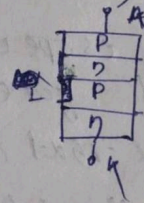
Therefore when the rate of change of voltage across the device becomes large, the device may turn ON, even if the voltage across the device is small.

Temperature Triggering

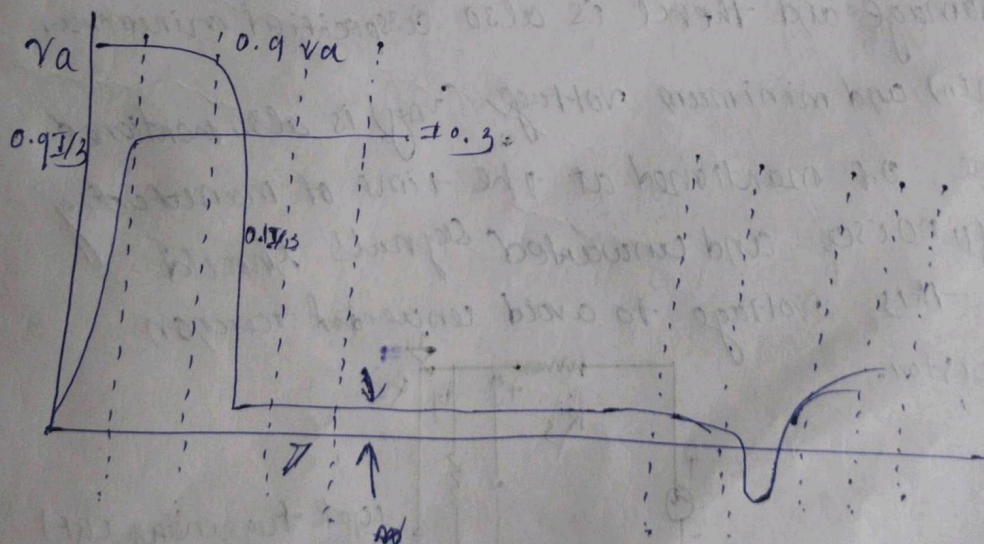
- * The width of depletion layer of SCR decreases with increase in junction temperature.
- * Therefore in SCR when V_R is very near its break down voltage, the device is triggered by increasing the junction temperature.
- * By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

Light Triggering

- * For light triggered SCR's a special terminal niche is made inside the inner P layer instead of gate terminal.
- * When light is allowed to strike this terminal, free charge carriers are generated.
- * When intensity of light becomes more than a normal value, the thyristor starts conducting.
- * This type of SCR's are called as LASCR.



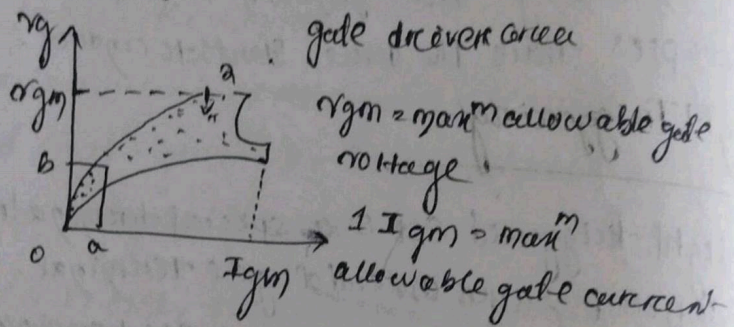
Temperature capture



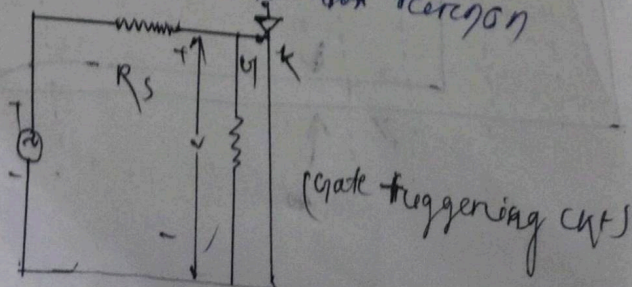
It is also called thermal runaway.

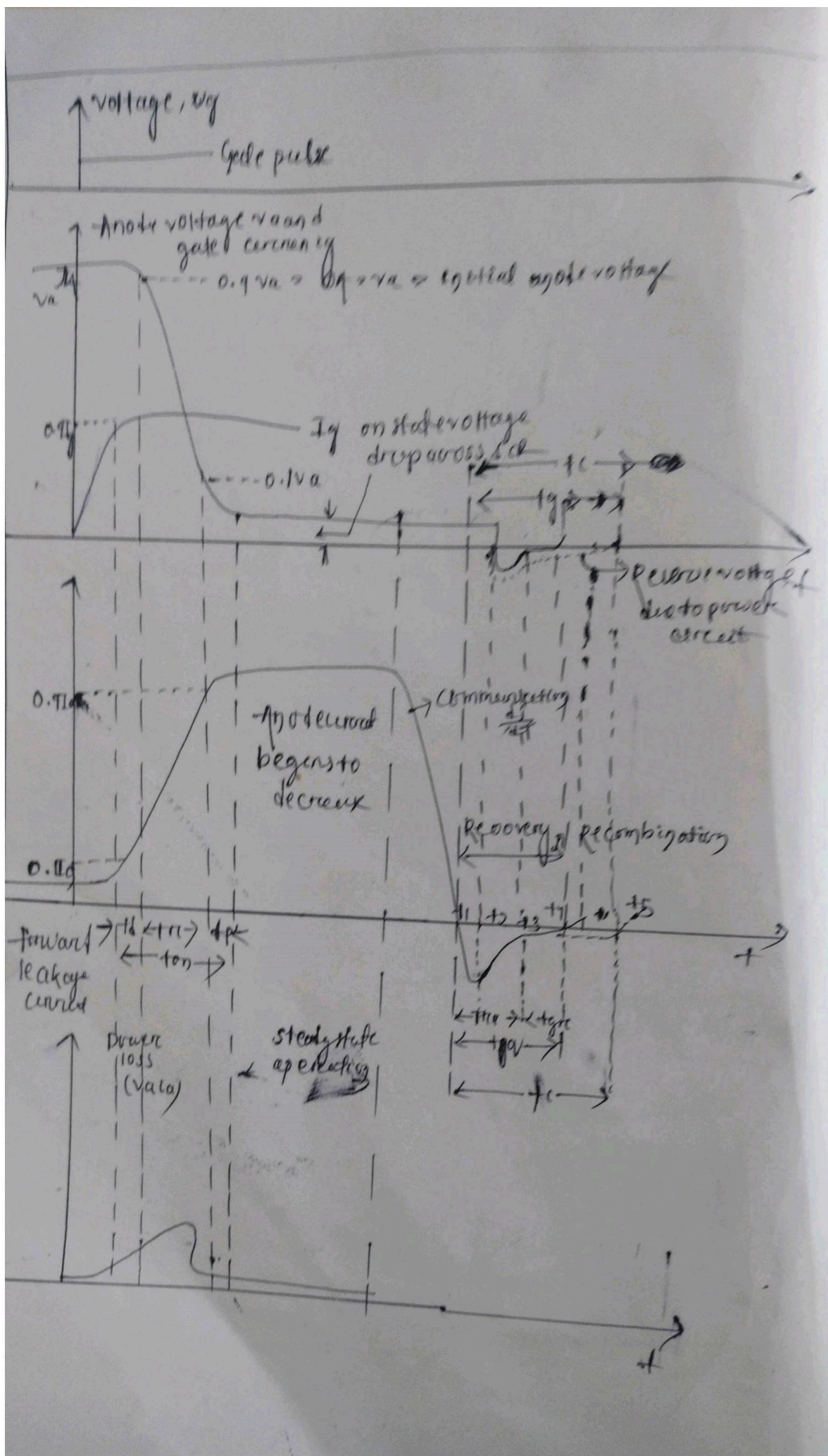
During forward blocking mode most of the applied voltage appears across junction (2) as the junction is associated with leakage current it would raise the temperature of junction. With increase in temperature the depletion layer decreases gradually. This leads to more leakage with its probe and some high temperature, the depletion of reverse biased junction (2) vanishes and the device gets turned on.

Gate characteristics of an SCR



This characteristics of SCR gives a very brief idea to operate it with in a safe region of applied gate voltage and current. so this is a very important characteristics of SCR. At the time of manufacturing SCR is specified with maximum gate voltage limit ($rgm \text{ max}$) and gate current limit ($Igm \text{ max}$) and maximum power average that is gate power dissipation limit ($Pgoav$). These limit should not be exceeded to protect the SCR from damage and there is also a specified minimum voltage ($rg \text{ min}$) and minimum voltage (rng) is also mentioned at the time of manufacturing of the device. noises and unwanted signals should be under this voltage to avoid unwanted turn on of the thyristor.





SWITCHING CHARACTERISTICS OF THYRISTOR

- During turn-on & turn-off process, a thyristor is subjected to different voltage across it and different current through it.
- The time variations of the voltage across a thyristor and the current through it during turn-on & turn-off processes give the dynamic or switching characteristics of a thyristor.

SWITCHING CHARACTERISTICS DURING TURN-ON

- A forward biased thyristor is usually turned on by applying a positive gate voltage between gate and cathode.
- There is transition time from forward off state to forward on state. This transition time is called thyristor turn-on time & is defined as, the time during which it changes from forward blocking mode to on-state.
- Total turn-on time can be divided into three intervals, (i) Delay time (t_d) (ii) Rise time (t_{rr}) & (iii) Spread time (t_{sp}).
 - (i) Delay time (t_d) - The delay time t_d is measured from the instant at which gate current reaches $0.9 I_g$ to the instant at which anode current reaches $0.1 I_a$.
- Here I_g and I_a are respectively the laval values of gate and anode currents.
- The delay time may 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.
- In another way, delay time is the time, during which anode current rises from forward leakage current to $0.1 I_a$, where I_a = laval value of anode current.
- With the thyristor initially in the forward blocking state, anode voltage is V_a and anode current is small leakage current.
- The turn-on process is indicated by a rise in anode current from small forward leakage current and a fall in anode-cathode voltage from forward blocking voltage V_a .

As gate current begins to flow from gate to cathode with the application of gate signal, the gate current has non-uniform distribution of current density over the cathode surface due to the p-layer.

→ The delay time can be decreased by applying high gate current and more forward voltage between anode and cathode.

(ii) Rise time (t_r):

→ The rise time t_r is the time taken by the anode current to rise from 0.1 to 0.9. 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 final value V_o .

→ The rise time is inversely proportional to the magnitude of gate current and its build up rate.

→ Thus, t_r can be reduced, if high and steep current pulse are applied to the gate.

→ From the beginning spreading from the narrow conducting region near the gate.

→ The anode current spreads at a rate of about 0.1 mm/ms.

As the rise is small, the anode current is not able to spread over the entire cross-section of cathode.

→ During rise time t_r , turn-on losses in the thyristor are the highest due to high anode voltage V_o and large anode current (I_a) occurring together in the thyristor.

→ As these losses occur over a small conducting region, local hotspots may be formed and the device may be damaged.

(iii) Spread time (t_s):

- The spread time is the time taken by the anode current to rise from 0.9 I_a to I_a . It is also defined as the time for the forward blocking voltage to fall from 0.1 of its initial value to the on-state voltage drop (1 to 1.5V).
- During this time, conduction spreads over the entire cross section of the cathode of SCR.
- The spreading interval depends on the area of cathode and on the gate structure of the SCR.
- After the spread time, anode current attains steady state value and the voltage drop across SCR is equal to the on-state voltage drop of the order of 1 to 1.5V.
- Total turn on time of an SCR is equal to the sum of delay time, rise time, and spread time.

(B) Switching Characteristics during turn-off:

- Thyristor turn-off means that it has changed from on to off state and is capable of blocking the forward voltage. This dynamic process of the SCR from conduction state to forward blocking state is called commutation process or turn-off process.
- Once, the thyristor is on, gate loses control. The SCR can be turned off by reducing the anode current below holding current.
- If forward voltage is applied to the SCR at the moment its anode current falls to zero, the device will not be able to block this forward voltage as the carriers (holes and electrons) in the bulk layer are still favourable for conduction.

Therefore, the device will go into conduction immediately, even though the gate signal is not applied, in order to avoid such an occurrence. It is essential that the thyristor is ~~resp~~ reverse biased for a finite period after the anode current has reached zero.

→ Turn-off time (t_q): The turn-off time, t_q of a thyristor is defined as the time between the instant, anode current becomes zero & the instant SCR regains forward blocking capability.

→ During t_q , all the excess carriers from the SCR must be removed. This removal of excess carriers consists of sweeping out of holes from outer p-layer and electron from outer n-layer.

→ The carriers around the junction J_2 , can be removed only by recombination.

→ The turn-off time is divided into two intervals.

(i) reverse recovery time t_{rr} , and (ii) gate recovery time, t_{gr} .

(ii) gate recovery time, t_{gr} .

e.e., $t_q = t_{rr} + t_{gr}$

→ At instant t_1 , anode current becomes zero.

→ After t_1 , anode current builds up in the reverse direction with the same di/dt slope as before t_1 .

→ The reason for the reversal of anode current after t_1 is due to the presence of carriers stored in the base layer. The reverse recovery current removes excess carriers from the end junctions J_1 and J_3 between the instants t_1 and t_2 .

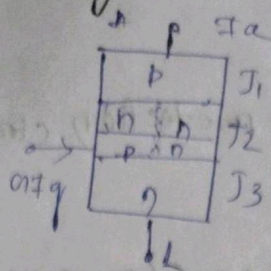
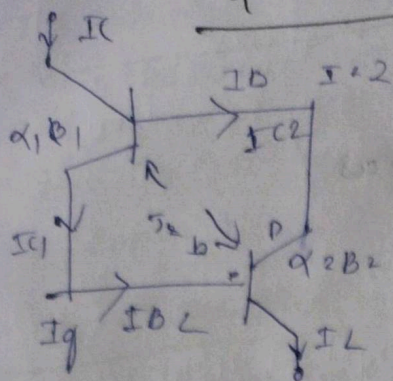
→ In other words, reverse recovery current, flow due to the sweeping out of holes from top p-layer and electrons from bottom n-layer. At instant t_2 , when about 60% of the stored charges are removed from the outer two-layers, carrier density across J_1 & J_3 begins to decrease and with this, reverse recovery current also starts decaying.

→ The reverse current decay is fast at the beginning but becomes gradual thereafter. The fast decay of recovery current causes a reverse voltage across the device due to the circuit inductance. This reverse voltage surge appears across the thyristor terminals and therefore thyristor may be damaged.

→ This can be avoided by using protective RC elements across SCR.

→ At instant t_3 , when reverse recovery current has fallen to nearly zero value, both junctions J_2 and J_3 recover and SCR is able to block the reverse voltage.

2 Transistor or thyristor



The principle of thyristor operation can be explained with the aid of two transistor model or two transistor analogy. From the schematic diagram of thyristor we can see that two thyristor mode is obtained by cutting the two middle layers along the dashed line into two separate halves.

In this figure J_1 and J_2 and J_2 , J_3 be considered to constitute pnp and npn transistor separately. The circuit representation of the two transistor model is shown in the fig.

In the off state of a transistor.

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

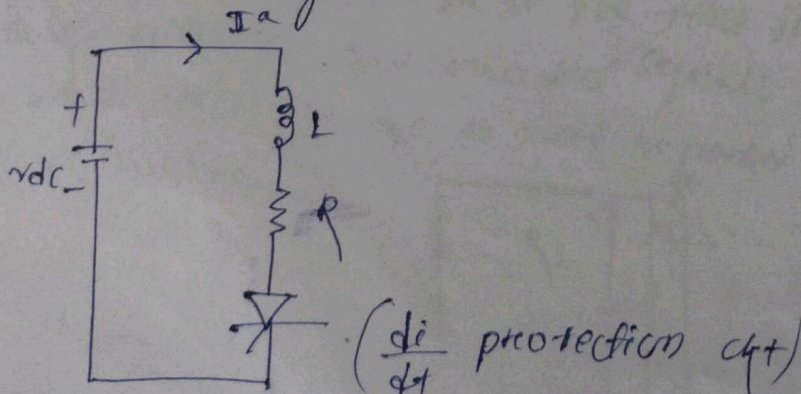
protection of SCR

Different types of protection circuit such as

- (i) $\frac{di}{dt}$ protection.
- (ii) $\frac{dv}{dt}$ protection (snubber circuit)
- (iii) metal oxide ~~thyristor~~ thyristor
- (iv) Semiconductor fuses.

di/dt protection

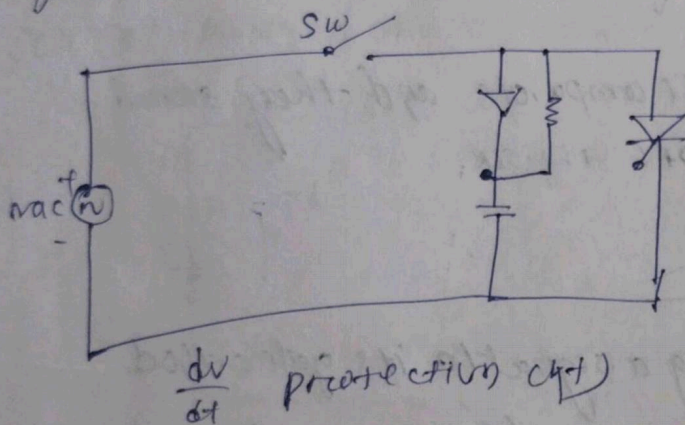
- * di/dt is the rate of change of current in a device.
- * When SCR is forward biased and is turned ON by the gate signal, the anode current flows.
- * The anode current requires some time to spread inside the device. (spreading of charge carriers).
- * But if the rate of rise of anode current (di/dt) is greater than the spread velocity of charge carriers then local hot spots are created. Heat is generated due to increased current density. This localised heating may damage the device.
- * Local spot heating is avoided by ensuring that the conduction spreads to the whole area very rapidly. (OR) The di/dt value must be maintained below a threshold (limiting) value.
- * This is done by means of connecting an inductor in series with the thyristor.



The inductance L opposes the high di/dt variation.
 When the current variation is high, the inductor smooths it and protects the SCR from damage. (Though di/dt variation is high, the inductor L smooths it because it takes some time to change). $L \geq [V_s / di/dt]$

dv/dt protection

- α dv/dt is the rate of change of voltage in SCR.
- * We know that $I_c = C \cdot dv/dt$, i.e. when dv/dt is high, I_c is high.
- * This high current I_c may turn ON SCR even when gate current is zero. This is called as dv/dt -turn ON or false turn ON of SCR.
- * To protect the thyristor against false turn ON or against high dv/dt a "snubber circuit" is used.



Commutation techniques of thyristor.

- Line commutation / Natural commutation.
- Force commutation.

Depending upon the source voltage to the thyristor circuit the commutation technique is classified into two types.

- Line commutation / Natural combination.
- Force commutation.

commutation \rightarrow Line commutation.

\rightarrow forced commutation \rightarrow voltage commutation
 \rightarrow current commutation

Voltage commutation

Voltage commutation is the commutation technique of SCR in which the anode cathode voltage will be reversed till SCR can achieve forward blocking mode.

Current commutation

It is the commutation technique of SCR the anode current kept below holding current.

When an external circuit is required turn off the SCR the process of turning off ^{of} SCR is called ~~com~~ current commutation.

The commutation circuit used LC components and they stored energy and used it to turn off the SCR.

Necessary of commutation

A SCR is turn on by applying a signal to its gate cathode circuit. turn off a SCR is not possible very easily and is required some special circuit condition to the satisfied for successful combination.

\rightarrow The anode to cathode current value of SCR must be reduced below holding current value.

\rightarrow The anode cathode voltage must be reversed.

\rightarrow The rate of change of anode cathode voltage must be less than $\frac{dv}{dt}$ rating of SCR to avoid retriggering.

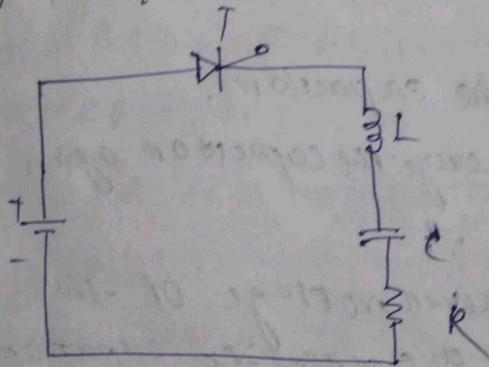
Type of force commutation

- (1) class A commutation
- (2) class B commutation
- (3) class C commutation
- (4) class D commutation
- (5) class E commutation
- (6) class F commutation

A. Class A commutation

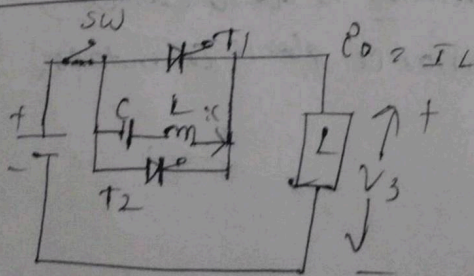
When DC voltage is applied the current (I) rises to its maximum value and then begins to fall.

→ When current leakage to zero and takes to reverse the circuit SCRs are turned off on the source.



→ Due to negative current it arises the definite commutation of the device.

B. Class B commutation



in this circuit we used a secondary thyristor called as auxiliary thyristor to turn off the main thyristor.

In this circuit the commutation component L and C are connected across the thyristor.

When the supply voltage is switched on the capacitor charges to the voltage V_c .

The main SCR (T_1) as well as the auxiliary SCR (T_2) are in off condition.

When T_1 is turned on and ($T_1 = 0$).

A constant load current I_o when flows through the load when t_1 is switched on a current begins to flow from capacitor C through (T_2) then to load and back to C .

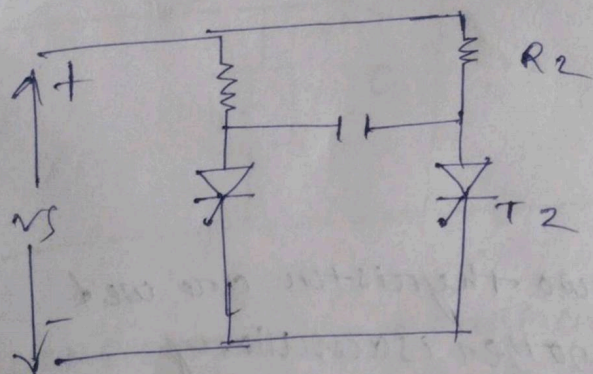
At the end of discharge of the capacitor.

The inductance energy will charge the capacitor again in reverse direction.

Since SCR (T_1) conducting the reverse voltage of the capacitor. it will produce a current I_c capacitor. it will produce a current I_c which opposes the load current I_L .

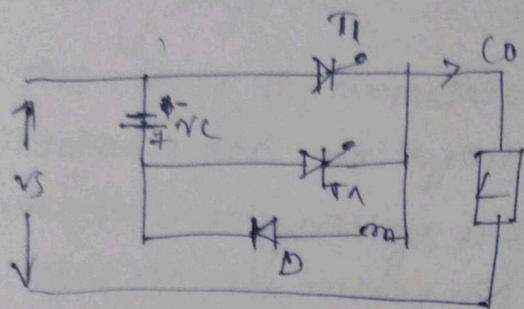
As soon as the I_c becomes equal to I_o the SCR (T_1) is turned off. This type of commutation is also called as current commutation. It is also resonance phase commutation.

Class C commutation (complementary)



- In this type of commutation a SCR + inductive load current is commutated by transferring the load current to another incoming thyristor.
- In this figure to firing turn on of SCR T1 commutates/turns off T2 and subsequently turning on of SCR T2 would turn off T1.
- When the SCR T1 is turned on the load current flows to R1 and T1 at the same time capacitor C is charged to the supply voltage V_s through resistor R2.
- Now the capacitor will be charged in the opposite direction through resistor R1 and SCR T2.
- The circuit is now ready to commutate SCR T2 when SCR T1 is turned on.

Class D commutation



→ In case of class D commutation two thyristors are used here is main thyristor T_1 another is auxiliary thyristor (T_A). In this method auxiliary thyristor (T_A) is required for commutating the main thyristor (T_1).

→ Initially the auxiliary thyristor T_A turns on so that the capacitor is charged up to V_s .

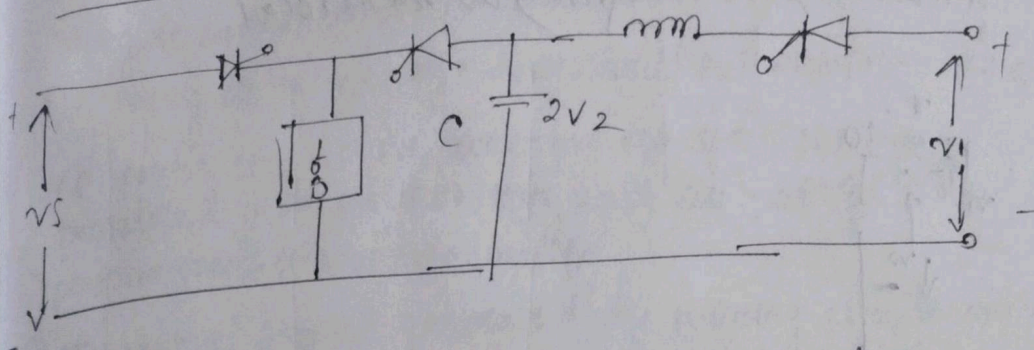
→ The SCR T_A turns off when capacitor is fully charged because the current through T_A falls below the holding current.

→ When SCR T_1 is turned on the load current (I_L) flows to SCR T_1 and load and the same time the capacitance C discharge through thyristor (T_1 and D) and O .

→ At the end of discharge the capacitor will be charged towards to the supply voltage with reverse polarity.

→ When thyristor (T_A) is turned on,

Class E commutation ON External pulse commutation



→ In class E commutation a pulse current is supplied from a separate voltage source to turn off the conducting SCR. The peak value of this current pulse must be more than the load current. In this circuit V_s is the voltage of the main source and V_1 is the auxiliary supply.

→ Thyristor T_1 is conducting and load is connected to the source that is V_s .

→ When the thyristor T_3 is turned at small $t > 0$ (time) then V_1 , T_3 , L and C forms an oscillative circuit.

→ Therefore capacitor charges to a voltage V_1 with its positive plate positive (+) and oscillatory current pulse too.

→ Now Thyristor T_3 gets commutation.

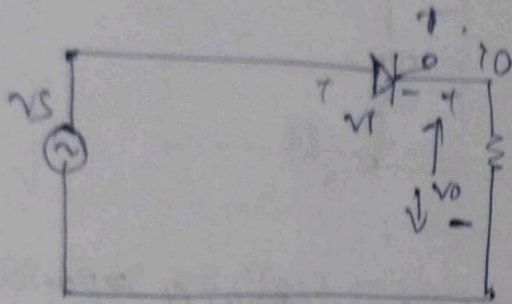
→ Now for the ~~turning off~~ turning off of which main thyristor T_1 thyristor T_2 is turned on.

→ With T_2 on the T_1 is subjected to reverse voltage equal to $(V_s - 2V_1)$ and therefore thyristor T_1 gets turned off.

→ After T_1 is turned off the capacitor (C) discharges through load.

Class 1 commutation or Natural

This type of commutation is also known as natural commutation.



This type of commutation is also known as natural commutation. This can occur only when an SCR is energized from an AC source. The current has to pass through its natural at the end of every positive half cycle.

Then the AC source applies reverse biased across the thyristor. As a result, the SCR gets turned off. This is called as natural commutation because

no external circuit is applied to turn off the thyristor.

This method of commutation is applied to phase controlled converters, line commutated converters, voltage controllers and step down cycle converter.

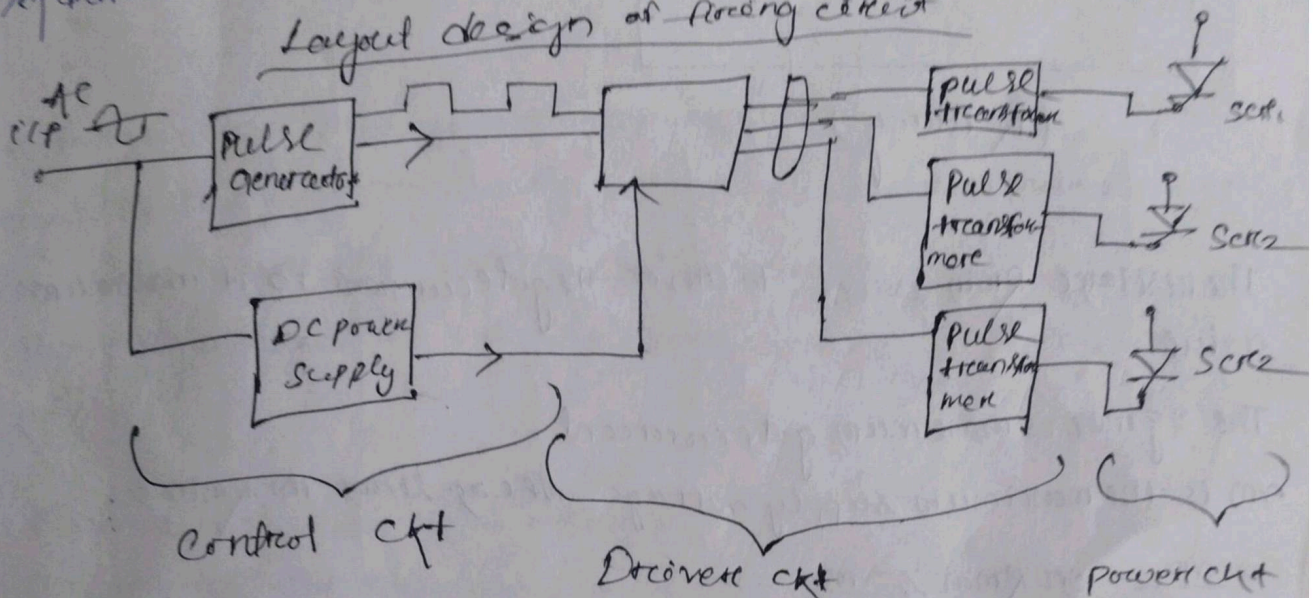
Firing Circuit of thyristor

The gate control circuit is also called as firing or triggering circuit.

A firing or triggering circuit should fulfill the following function.

- ① If power circuit is more than one SCR, the firing circuit should produce gate pulses for each SCR at the desired instant for the proper operation of the circuit.
- ② The control signal generated by a firing circuit may not be able to trigger an SCR. It is therefore common to feed the V_{GT} of pulses to driver circuit and then to gate cathode circuit.
- ③ A driver circuit consists a pulse amplifier and a pulse transformer.

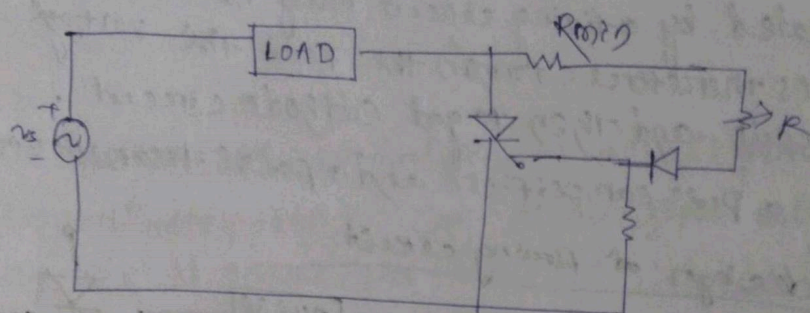
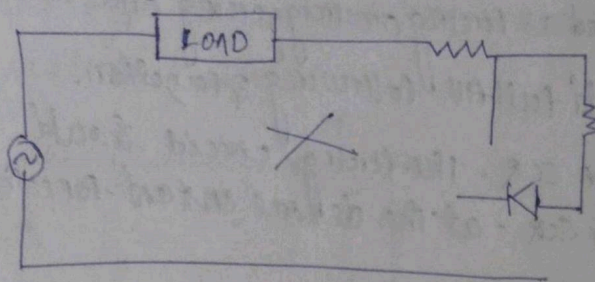
Layout design of firing circuit



Firing circuit of SCR

- (i) R - firing ckt
- (ii) RC - firing ckt
- (iii) WT - Triggering / firing ckt
- (iv) Ram ckt

R-firing circuit



(R-firing)

The resistance R_{min} is used to limit the gate current to its maximum value.

The I_{gmax} is maximum gate current.

V_m is the maximum supply voltage. We can limit the R_{min} as

$$\frac{V_m}{I_{gmax}} \text{ or } R_{min} \geq \frac{V_m}{I_{gmax}}$$

R_b is the stabilizing resistance.

→ the voltage across should not exceed V_{gmin} (minimum gate voltage).

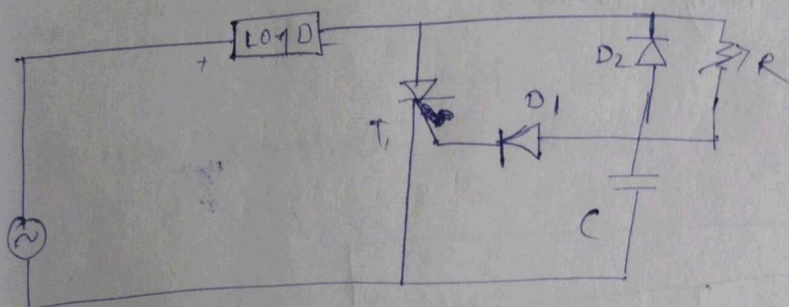
→ the variable resistor (R) is used to trigger the thyristor. When R is 0 then the firing angle is minimum.

→ firing angle (α) → firing angle of SCR can be defined as the angle in the AC cycle at which thyristor starts

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- conducting when positive voltage is applied across its gate terminal.
- The anode cathode voltage and gate current are in phase
- Triggering angle firing angle range should be between 0 to 90° .

RC firing circuit (half wave rectifier)



- RC firing circuit → The capacitor charges through diode D_2 in the negative cycle of the supply voltage. The capacitor charges up to $-V_m$ that is negative peak of the supply voltage.

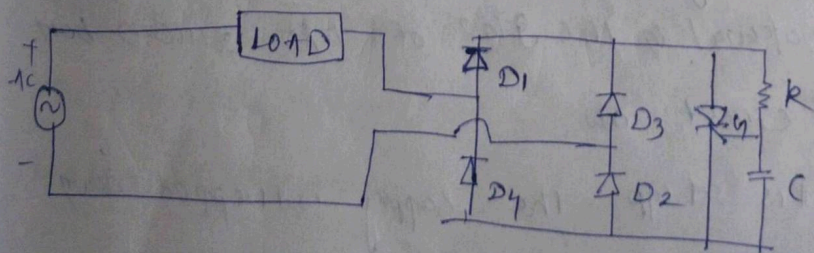
→ The firing angle in this case will range up to 0 to 180° .

$$\rightarrow RC \geq \frac{1.3}{2f}$$

→ f = frequency of the supply voltage
(Condition for minimum firing angle)

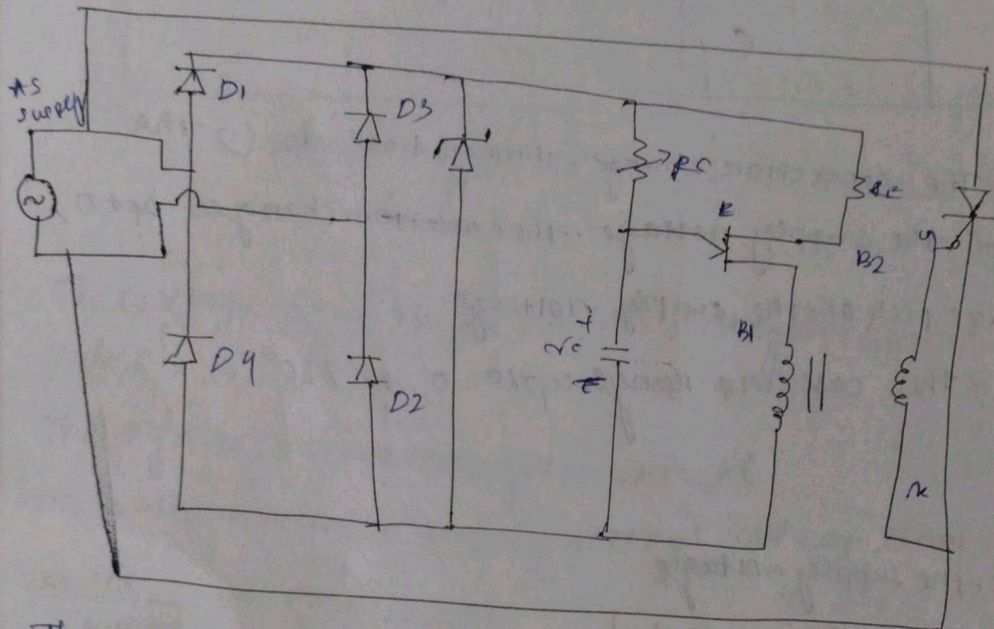
→ The triggering is control only in half cycle of the supply voltage so this is called half wave firing circuit.

RC firing circuit (using full wave)



Power can be delivered to the load in half wave during the positive half-cycle of e_s because the scf conducts only when it is forward biased. This limitation can be overcome in several ways, one of which is shown in fig. Here, the ac line voltage is converted to pulsating dc by the full-wave diode bridge. This allows the scf to be triggered "on" for both half-cycle of the line voltage, which doubles the available power to the load.

VJT triggering of scf



The VJT is a two layer pn device with three terminals. The terminals are called emitter (E), base-1 (B_1) and base-2 (B_2). It consists of an n -type silicon bar with ohmic contacts for the two base terminals. A single p -type emitter junction is formed by alloying a p -type material on the side of the silicon bar. Its structure, equivalent circuit.

The VJT triggering circuit is set up. The supply is stepped down to a suitable value to get the synchronizing signal, which is fed to the triggering circuit. The waveforms