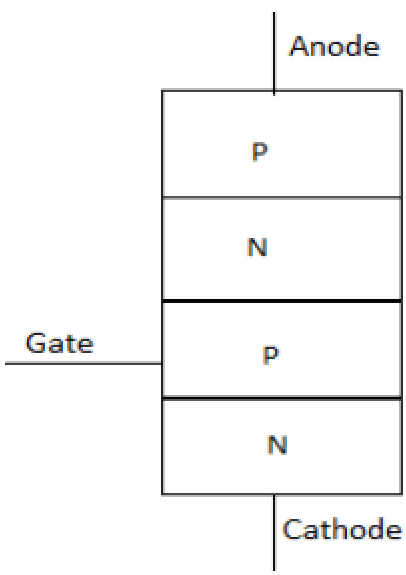
Study Notes on Thyristor & Their Operational Characteristics

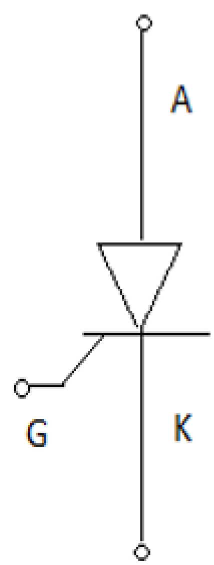
Thyristors are semiconductor devices widely used in various applications, including power electronics, motor control, voltage regulation, and switching circuits. They have unique operational characteristics that make them suitable for specific tasks.

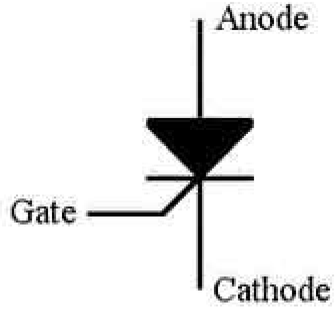
Here you will find the study notes on Thyristor & Their Operational Characteristics which will cover the topics such as Thyristor, V-I Characteristic of Thyristor, Different Mode of Operation of SCR, Turn-ON Methods of SCR, Switching Characteristic, Thyristor Protection, Series & Parallel Operation.

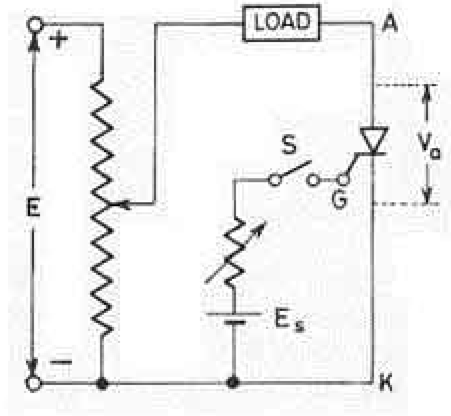
Thyristor

Thyristor is a four layer three junction pnpn semiconductor switching device. It has 3 terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact, possess high reliability and have low loss. SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forward direction and high resistance in the reverse direction. It is a unidirectional device.





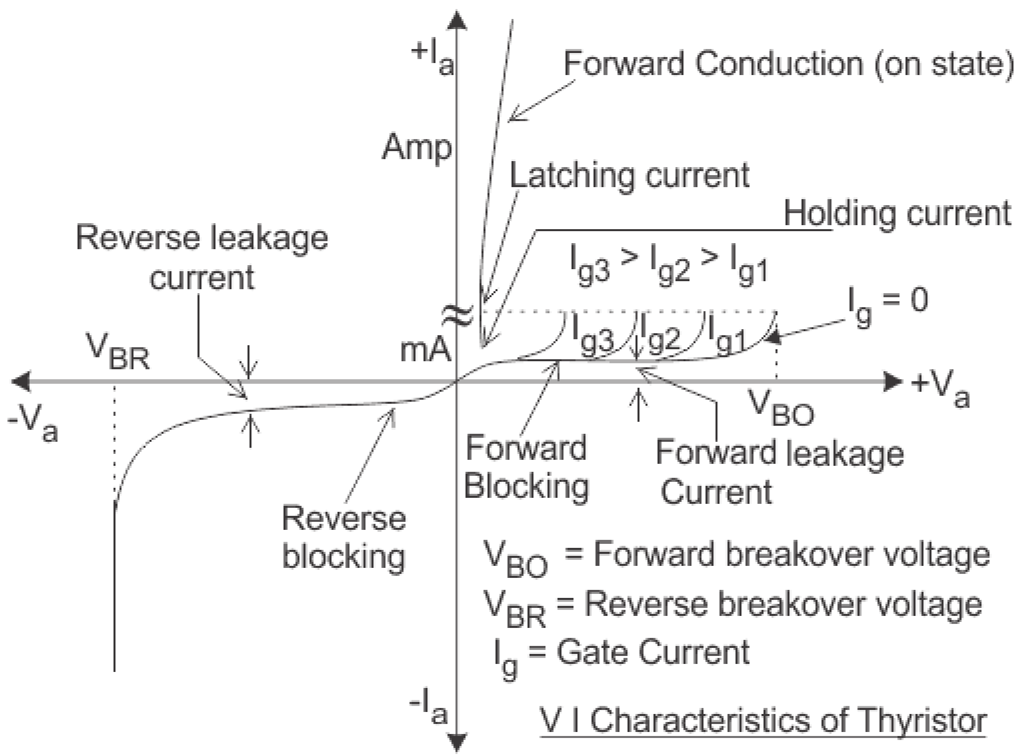




Thyristor Symbol Circuit diagram of thyristor.

Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source E_S. A typical SCR V-I characteristic is as shown below:

V-I characteristic of SCR



V_{BO}=Forward breakover voltage

V_{BR}=Reverse breakover voltage;I_g=Gate current

V_a=Anode voltage across the thyristor terminal A,K; I_a**=Anode current**

I_t can be inferred from the static V-I characteristic of SCR.

SCR have 3 modes of operation:

- Reverse blocking mode
- Forward blocking mode (**OFF state**)
- Forward conduction mode (**ON state**)

Reverse Blocking Mode

When the cathode of the thyristor is made positive with respect to anode with switch open, the thyristor is reverse biased. Junctions J_1 and J_2 are reverse biased where junction J_2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.

- A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.
- Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage V_{BR},an avalanche occurs at J_1 and J_3 and the reverse current increases rapidly. As a large current is associated with V_{BR} and hence more losses to the **SCR**.
- This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

Forward Blocking Mode

- When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased.
- Thus junction J_1 and J_3 are forward biased and J_2 is reverse biased. As the forward voltage is increased, junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltage V_{BO}.
- When forward voltage is less then V_{BO} thyristor offers high impedance. Thus a thyristor acts as an open switch in forward blocking mode.

Forward Conduction Mode

Here the thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:

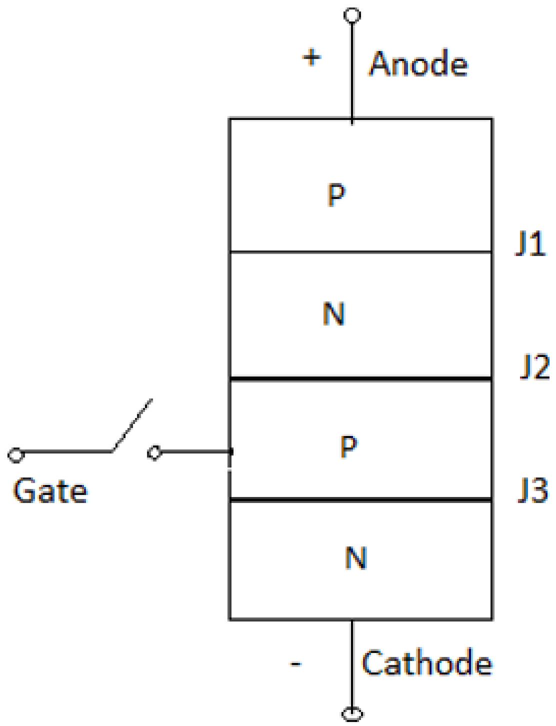
- By exceeding the forward breakover voltage.
- By applying a gate pulse between gate and cathode.

During forward conduction mode of operation the thyristor is in one state and behaves like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

Turn ON methods for SCR

- Forward voltage triggering
- Gate triggering
- **dv/dt** triggering
- Light triggering
- Temperature triggering

Forward voltage triggering



A forward voltage is applied between anode and cathode with the gate circuit open.

- Junction J_1 and J_3 is forward biased.
- Junction J_2 is reverse biased.
- As the anode to cathode voltage is increased, breakdown of the reverse biased junction J_2 occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward breakover voltage.
- The conduction of current continues even if the anode cathode voltage reduces below V_{BO} till I_a will not go below I_h. Where I_h is the **holding current** for the thyristor.

Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding V_{BO} is never employed as it may destroy the device. The magnitude of V_{BO}, so forward breakover voltage is taken as the final voltage rating of the device during the design of SCR application.

- Make the thyristor forward breakover voltage (**say 800V**) higher than the normal working voltage. The benefit is that the thyristor will be in a blocking state with normal working voltage applied across the anode and cathode with the gate open.
- When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied.
- The point to be noted is that **the cathode n- laye**r is **heavily doped as compared** to **gate p-layer**. So when gate supply is given between gate and cathode gate, the p-layer is flooded with electrons from the cathode n-layer. Now the thyristor is forward biased, so some of these electrons reach junction J_2 .
- As a result, the width of J_2 breaks down **or** conduction at J_2 occurs at a voltage less than V_{BO}.As I_g increases V_{BO} reduces which decreases then turns ON time. Another important point is duration for which the gate current is applied should be more than **turn ON** time.

- If the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can't turn ON. In this process power loss is less and also low applied voltage is required for triggering.

dv/dt triggering

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided.

- When **SCR is forward biased**, junction J_1 and J_3 are **forward biased** and junction J_2 **is reversed** biased so it behaves as if an insulator is placed between two conducting plates.
- Here J_1 and J_3 acts as a conducting plate and J_2 acts as an insulator. J_2 is known as junction capacitor.
- Now if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction J_2 breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from high **dv/dt**.

Since Q=CV

$I_a = C(dv/dt)$

$I_a \propto dv/dt$

Temperature triggering

- During forward biased, J_2 is reverse biased so a leakage forward current always associated with SCR.
- Since leakage current is temperature dependant,so if we increase the temperature the leakage current will also increase and heat dissipation of junction J_2 occurs. When this heat reaches a sufficient value J_2 will break and conduction starts.

Disadvantages

- This type of triggering causes local hot spot and may cause thermal run away of the device.
- This triggering cannot be controlled easily.

- It is very costly as protection is costly.

Light Triggering

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn ON of SCR. Such SCR are known as **Light activated SCR (LASCR)**.

Latching current: The latching current may be defined as the minimum value of anode current which must attain during turn ON process to maintain conduction even if gate signal is removed.

Holding Current: It is the minimum value of anode current below which if it falls, the SCR will turn OFF.

Switching characteristics of Thyristors

The time variation of voltage across the thyristor and current through it during turn on and turn off process gives the dynamic or switching characteristic of SCR.

Switching characteristic during turn on:

Turn on time: It is the time during which it changes from forward blocking state to ON state. Total turn on time is divided into 3 intervals.

Delay time If I_g and I_a represent the final value of gate current and anode current. Then the delay time can be explained as the time during which the gate current attains **0.9** I_g to the instant anode current reaches **0.1** I_g or the anode current rises from forward leakage current to **0.1** I_a.

- 1. Gate current $0.9I_g$ to $0.1\ I_a$.
- Anode voltage falls from V_a to $0.9V_a$.
- Anode current rises from forward leakage current to $0.I_a$.

Rise time (t_r): Anode current rises from $0.1I_a$ to $0.9I_a$. Forward blocking voltage falls from $0.9V_a$ to $0.1V_a$. V_a is the initial forward blocking voltage.

Spread time (t_p): Time taken by the anode current to rise from **$0.9I_a$** to **I_a**.Time for the forward voltage to fall from **$0.1V_o$** to on state voltage drop of **1 to 1.5V**. During turn on, SCR is considered to be a charge controlled device.

Switching Characteristics During Turn Off

Thyristor turn off means it changed from ON to OFF state. Once thyristor is ON there is no role of gate. As we know thyristor can be made turn OFF by reducing the anode current below the latching current. Here we assume the latching current to be zero ampere. If a forward voltage is applied across the SCR at the moment it reaches zero then SCR will not be able to block this forward voltage.

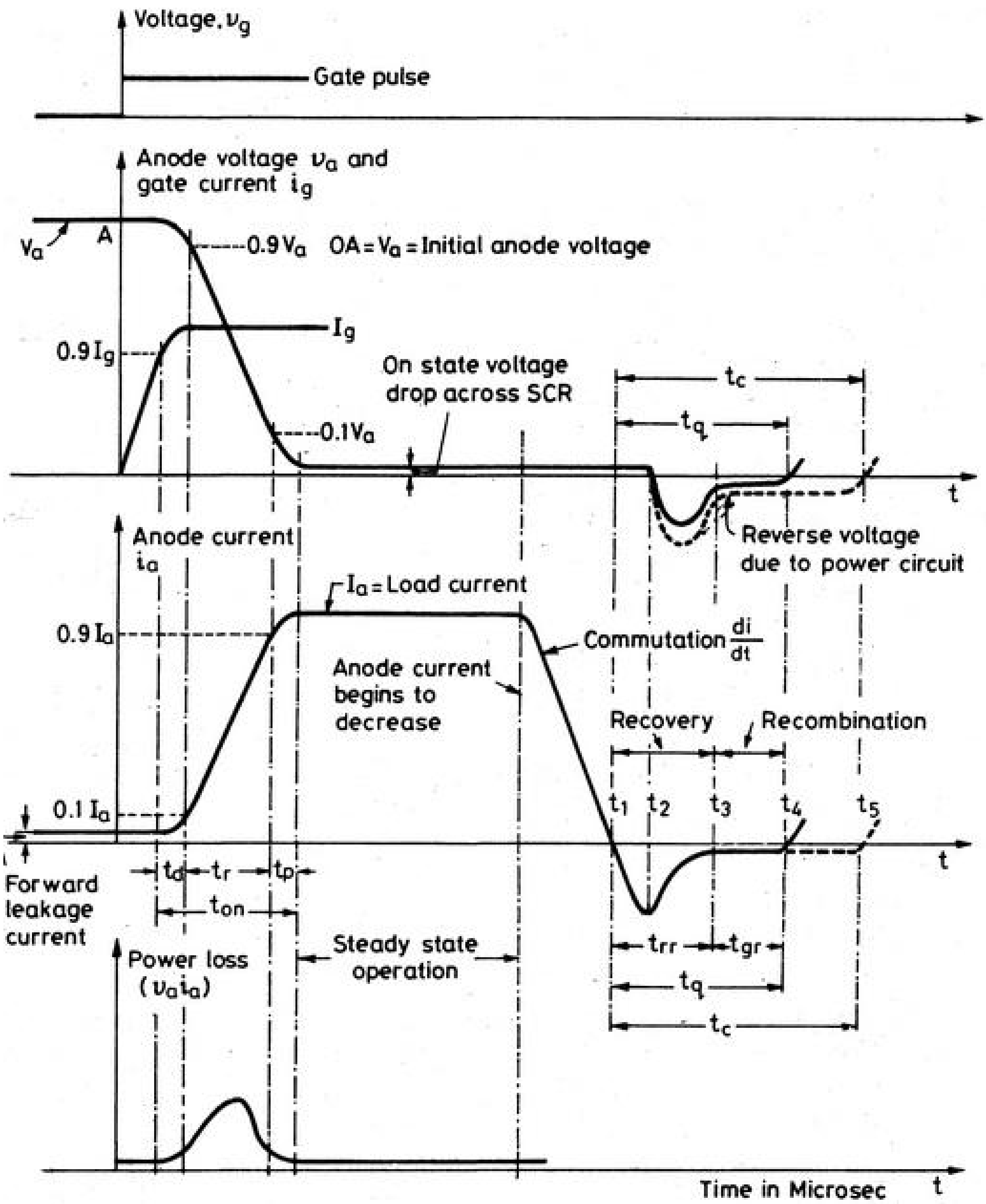
So now the turn off time can be different as the instant anode current becomes zero to the instant when SCR regains its forward blocking capability.

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

t_q is the turn off time,**t_{rr}** is the reverse recovery time, **t_{qr}** is the gate recovery time.

The turn off time is affected by:

- Junction temperature
- Magnitude of forward current **di/dt** during commutation.
- Turn off time decreases with the increase of magnitude of reverse applied voltage.



Thyristor Protection

Over Voltage Protection: Over voltage occurring during the switching operation causes the failure of SCR.

Internal Overvoltage Protection: It is due to the operating condition of SCR.During the commutation of SCR ,when the anode current decays to zero anode current reverses due to stored changes. First the reverse current rises to peak value, then reverse current reduces abruptly with large **di/dt**. During series inductance of SCR large transient large voltage i.e **Ldi/dt**. is generated.

External Overvoltage: This is due to external supply and load condition. This is because of

- The interruption of current flow in an inductive circuit.
- Lightning strokes on the lines feeding the thyristor systems.

These overvoltages cause random turns ON of a SCR. The effect of overvoltage is minimized using

- RC circuits
- Non linear resistor called voltage clamping device.

When voltage surge appears, the voltage clamping device offers a low resistance and it creates a virtual short circuit across the SCR. Hence voltage across SCR is clamped to a safe value. When surge condition over voltage clamping device returns to high resistance state. e.g. of voltage clamping device

- Selenium Thyrector diodes
- Metal Oxide varistors
- Avalanche diode suppressors

Overcurrent Protection: Long duration operation of SCR, during overcurrent **causes junction temp.** of SCR to rise above the rated value,causing permanent damage to device.

SCR is protected from overcurrent by using

- Circuit breakers
- Fast acting fuses Proper coordination is essential because Fault current has to be interrupted before SCR gets damaged.
- Only faulty branches of the network have to be replaced.

Electronic Crowbar Protection

For overcurrent protection of power converters using SCR, electronic crowbars are used. It provides rapid isolation of the power converter before any damage occurs.

HEAT PROTECTION- To protect the SCR

1. From the local spots **2.** Temp rise SCRs are mounted over heat sinks.

GATE PROTECTION-Gate circuit should also be protected from

1. Overvoltages **2.** Overcurrents

Overvoltage across the gate circuit causes the false triggering of SCR Overcurrent to raise the junction temperature. Overvoltage protection is by zener diode across the gate circuit.

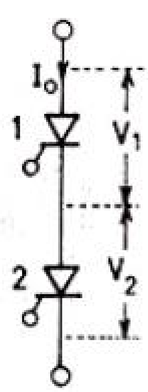
Series and Parallel operation of SCR

SCR are connected in series for h.v demand and in parallel for fulfilling high current demand. Sting efficiency can be defined as a measure of the degree of utilization on SCRs in a string.

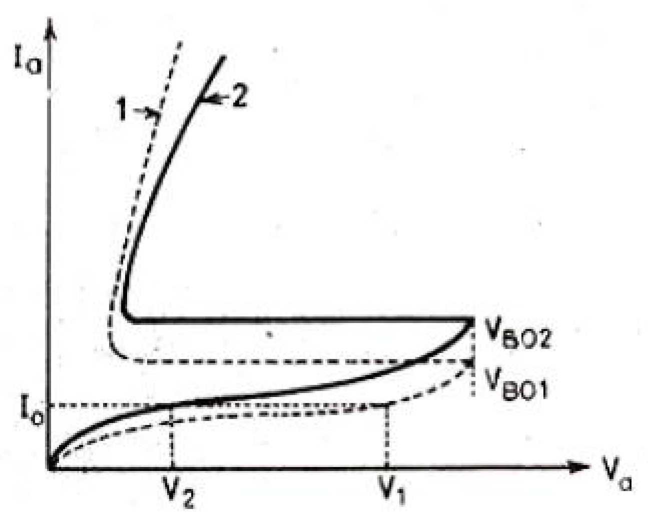
String efficiency < 1.

- **Derating factor (DRF) = 1 – string efficiency.**
- If DRF more then no. of SCRs will be more, so string is more reliable.

Series Operation: Let the rated blocking voltage of the string of a series connected SCR is $2V_1$ as shown in the figure below, But in the string two SCRs are supplied a maximum voltage of V_1+V_2.



(a)



(b)

$\eta = V1+V2/2V1$

Significance of String Efficiency

- Two SCRs have the same forward blocking voltage ,When system voltage is more than the voltage rating of a single SCR.
- SCRs are connected in series in a string. There is an inherent variation in characteristics.
- The voltage shared by each SCR may not be equal. **Suppose, SCR_1 leakage resistance > SCR_2 leakage resistance**. For the same leakage current I_0 in the series connected SCRs. For the same leakage current SCR_1 supports a voltage V_1, SCR_2 supports a voltage V_2.

So string η for two SCRs = $V_1+V_2/ 2V_2$
= $1/2(1+V_2/V_1)$ which is < 1

so $V_1 > V_2$

- The above operation is when SCRs are not turned ON. But in steady state of operation,A uniform voltage distribution in the state can be achieved by connecting a suitable resistance across each SCRs , so that parallel combinations have the same resistance.
- But this is cumbersome work. During steady state operation we connect the same value of shunt resistance across each SCRs. This shunt resistance is called a state equalizing circuit.

Let SCR_1 have lower leakage current I_{bm} , It will block a voltage comparatively larger than other SCRs.

- **Voltage across SCR1 is $V_{bm} = I_1R$.**
- **Voltage across (n-1)SCR is $(n-1) I_2R$,**
- **The voltage equation for the series circuit is**

$Vs = I_1R+(n-1)I_2R = V_{bm} + (n-1)R(I - I_{bmx})$

as $I_1 = I - I_{bmn}$

$I_2 = I - I_{bmx}$

So, $V_s = V_{bm}+(n-1)R[I_1-(I_{bmx}-I_{bmn})]$

If $\Delta I_b = I_{bmx} - I_{bmn}$

Then $V_s = V_{bm} + (n-1)R\,(I_1 - \Delta I_b)$

$V_s = V_{bm} + (n-1)R\,I_1 - (n-1)R\,\Delta I_b$

$RI_1 = V_{bm}$

So, $V_s = V_{bm} + (n-1)\,V_{bm} - (n-1)R\,\Delta I_b$

$= n\,V_{bm} - (n-1)R\,\Delta I_b$

$$R = \frac{nV_{bm} - V_S}{(n-1)\Delta I_b}$$

- SCR data sheet usually contain only maximum blocking current , I_{bmx}.

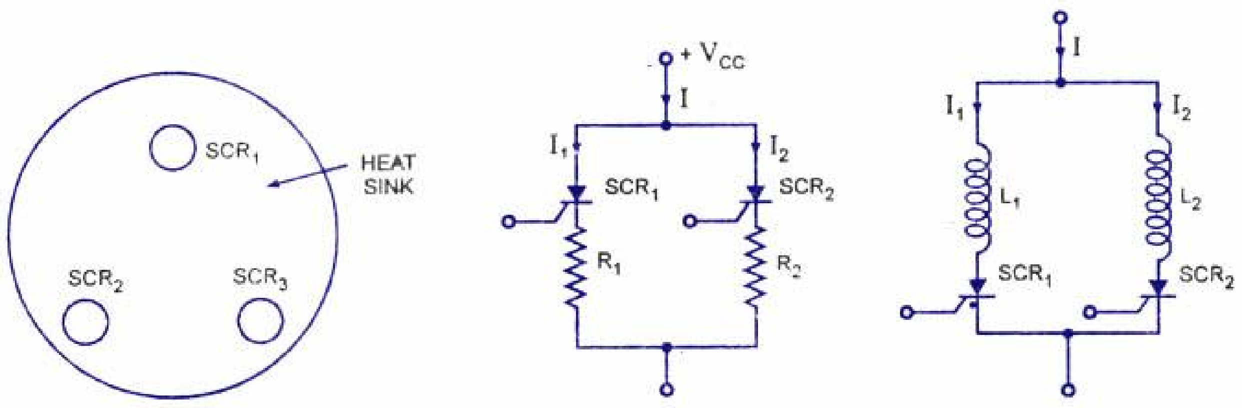
so we assume $I_{bmn} = 0$

So $\Delta I_b = I_{bmx}$

So the value of R calculated is lower than actually required.

Parallel Operation

When current required by the load is more than the rated current of a single thyristor , SCRs are connected in parallel in a string.



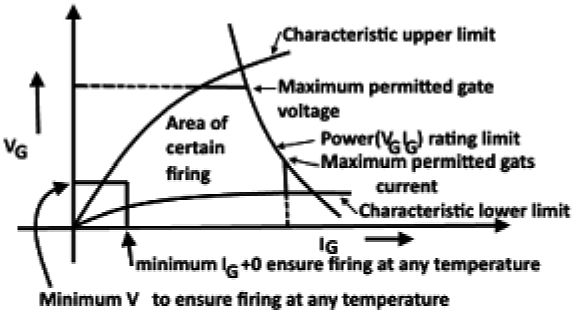
For equal sharing of current, SCRs must have the same **V-I** characteristics during forward conduction.V_T across them must be the same. For the same VT,**SCR_1** shares **I_1** and **SCR_2** shares **I_2**. If **I_1** is the rated current **$I2 < I_1$** The total current **$I_1 + I_2$** and not rated current **$2I_1$**.Type equation here.

Thus string efficiency ,

$\eta = (V_1+V_2)/2V_1$

- Middle conductor will have more inductance as compared to the other two nearby conductors. As a result less current flows through the middle conductor. Another method is by magnetic coupling.

Thyristor Gate Characteristics



- **V_g** = +ve gate to cathode voltage. I_g= +ve gate to cathode current. As the gate cathode characteristic of a thyristor is a p-n junction.
- Curve 1 the lowest voltage values that must be applied to turn on the SCR.
- Curve 2 highest possible voltage values that can be safely applied to get the circuit.
- **V_{gm}**= Maximum limit for gate voltage ;
- **I_{gm}**= Maximum limit for gate current.
- **P_{gav}** = Rated gate power dissipation for each SCR.
- These limits should not be crossed in order to avoid the permanent damage of the device junction **J_3.**
- OY = Minimum limit of gate voltage to turn ON . OX = minimum limit of gate current to turn ON.
- If **V_{gm}, I_{gm},P_{gav}** are exceeded the thyristor will be damaged so the preferred gate drive area of SCR is bcdefghb.
- **oa** = The non triggering gate voltage , If firing circuit generates +ve gate signal prior to the desired instant of triggering the SCR.It should be ensured that this unwanted signal should be less than the non–triggering voltage **oa**.

- **$E_s = V_g + I_g R_s$** Gate Source Voltage; **V_g** = Gate Cathode Voltage.
- **Rs = Gate source resistance**
- If I_{gmn} **, V_{gmn}** are the minimum gate current and gate voltage to turn ON the SCR.

$E_s = (I_{gmn} + V_{gmn}/R_1)R_s + V_{gmn}$.

Thanks!

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