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ENGINEERS ACADEMY

RPSC - A.En.

Assistant Engineering

ELECTRICAL

Rajasthan Public Service Commission (RPSC)

Volume - 6

Power Electronics

SIERRA INNOVATIONS

1
POWER ELECTRONICS DEVICES

THEORY

1.1 Introduction

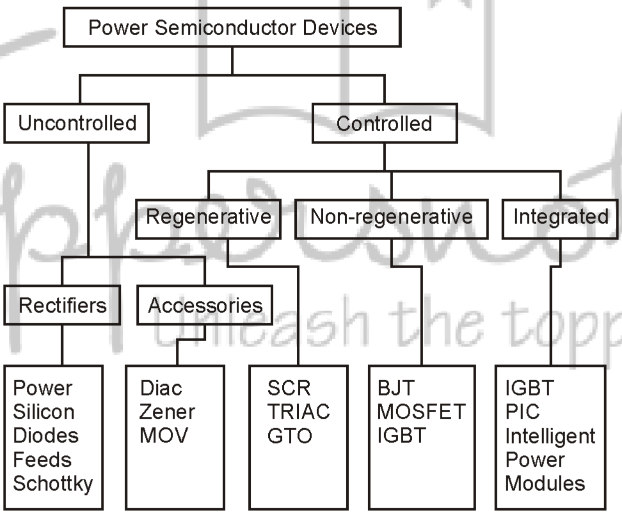
Power semiconductor devices can be categorized into three types based on their control input requirements:

(a) Current-driven devices: BJTs, GTOs.

(b) Voltage-driven devices: MOSFETs, IGBTs, MCTs.

(c) Pulse-driven devices: SCRs, TRIACs.

1.1.1 Power Semiconductor Device Variety



1.2 Power Transistors

1. BJT
2. MOSFET
3. IGBT
4. GTO

1.2.1 BJT

- Bipolar device i.e. holes & electrons.
- Current controlled device.

- Low input impedance.
- Low ON-state voltage drop and lower conduction loss.
- Higher switching power losses.
- Secondary breakdown occur.
- Negative temperature coefficient Because of negative temperature coefficient BJT are not advisable for parallel operation.
- Low conduction losses.
- Lower operating frequency (10 kHz).
- ON-state in saturation region.
- Controlled turn-on & turn-off device.
- Turn-on & Turn-off time depend on junction capacitances.
- Control signal requirement continuously.
- Ratings : 1400V, 400A, 10 kHz
- Switching period, $t_s = 50\mu$ sec-100μsec

1.2.2 MOSFET

- Unipolar device i.e. majority carrier device.
- Voltage controlled device.
- High input impedance.
- High-ON state voltage drop and higher conduction losses.
- Lower-switching power losses.
- Free from secondary breakdown.
- Positive temperature coefficient.
- Because of positive temperature coefficient, MOSFET are advisable for parallel operation.
- Higher conduction losses.
- Higher operating frequency (100 kHz).
- ON-operating in ohmic region.
- Control turn-on & turn-off device.
- Smaller turn-off time because it does not have minority carrier storage.
- Control signal requirement continuously.
- Ratings : 1000V; 50A, 100 kHz
- Switching period,

$$t_s = 1\mu \text{ sec}$$

1.2.3 IGBT

- Bipolar device.
- Voltage controlled device.

- Three terminal device : Emitter, collector and gate.
- Low forward voltage drop.
- Low on-state power loss than MOSFET.
- Low conduction loss than MOSFET.
- Having characteristics of BJT & MOSFET.
- Controlled turned-on & turned-off devices.
- Control signal requirement continuously.
- High input impedances.
- Positive temperature coefficient.
- Secondary breakdown not occur.
- Used for parallel operation.
- Ratings : 1200V, 500A, 50 kHz.
- Switching period, $t_s = 20\mu$ sec.
- Two terminal, three layer device : power diode, DIAC.
- Majority carrier device : MOSFET, SIT.
- Bipolar device : Diode, BJT, IGBT, MCT.
- Unidirectional device : Diode, SCR, LASCR.
- Bidirectional device : TRIAC, DIAC, BJT.
- Negative pulse turn-on device : MCT.
- Negative pulse turn-off device : GTO.
- Controlled turn-on & off device : BJT, MOSFET, IGBT, SIT MCT.
- Continuous control signal : BJT, MOSFET, IGBT, SITH.
- Uncontrolled device : Diode, DIAC.
- Bistable switch : SCR.
- Bidirectional current device : TRIAC, RCT.
- Unidirectional current device : Diode, SCR, GTO, BJT, MOSFET, IGBT, SITH and MCT.

1.2.4 Gate Turn Off (GTO)

Basic Structure

- The Gate turn off thyristor (GTO) is a four layer PNPN power semiconductor switching device that can be turned on by a short pulse of gate current and can be turned off by a reverse gate pulse.
- A GTO is a current controlled minority carrier device.
- The anode shorts of a GTO improves the turn-off performance but degrades the turn on performance.
- The reverse voltage blocking capacity of a GTO is small due to the presence-of anode shorts.

1.3 THYRISTOR

- Thyristor denotes a family of semiconductor devices used power control in DC and AC systems.
- Thyristor means devices function same as that of thyraton tube and construction wise similar to transistor.
- The most widely used member of thyristor family, called silicon controlled rectifier (SCR) we will use SCR and thyristor as synonyms.

1.3.1 Silicon Controlled Rectifier (SCR)

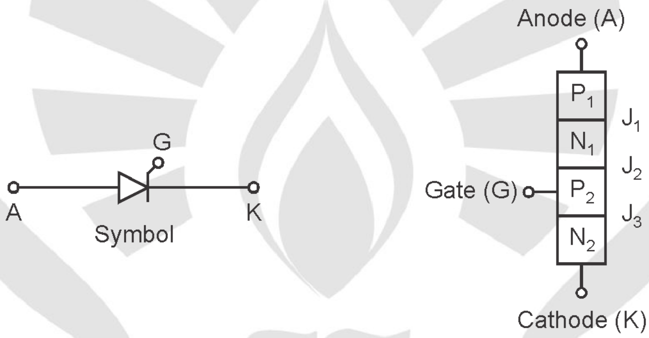
Introduction

- It has four layer, three junction, three terminal semiconductor device the terminals namely:

  Anode (A)

  Cathode (K)

  Gate (G)



Approximate level of doping of layers outer layers P_1 & N_2 is $10^{19}/cm^3$ i.e. high doped, inner p-layer i.e. P_2 is $10^{17}/cm^3$ & inner N-layer i.e. N_1 has 10^{13} to 5×10^{14} / cm^3 (i.e. very lightly doped).

- Inner two layers of SCR are lightly doped so that the strength of junction J, is more than the strength of junction J_1 and J_3 because as level of doping increases, width of depletion region decreases.

1.3.2 Working

- When anode is made positive with respect to cathode then SCR is forward biased.
- A small positive voltage is applied between gate and cathode to turn-ON the SCR. Now current flows from anode to cathode in the SCR.
- When a thyristor is in a conduction mode, the forward voltage drop is very small typically 0.5 to 2 volts. Once the SCR turned ON, the gate has no control over the SCR. Even if the gate is removed, SCR does not turn-OFF.
- A conducting thyristor can be turned-OFF, by making the potential of the anode equal or less than the cathode potential.

Advantages

1. Very small amount of gate drive is required.
2. SCR's with high voltage and current ratings are available.
3. ON-state losses in SCRs are reduced.

Disadvantages

1. Gate has no control once the SCR is turned-ON.
2. External circuits are required to turn-OFF the SCR.
3. Operating frequencies are very low generally upto 1 kHz.
4. Snubber (RC circuits) are required for $\frac{dv}{dt}$ protection.

1.3.3 Applications

SCR are best suited for:

1. Controlled rectifiers.
2. AC regulators, and heating applications.
3. DC motor drives, large power supplies and electronic circuits breaker.

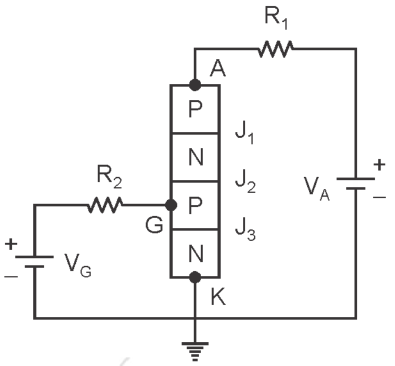
Important Facts

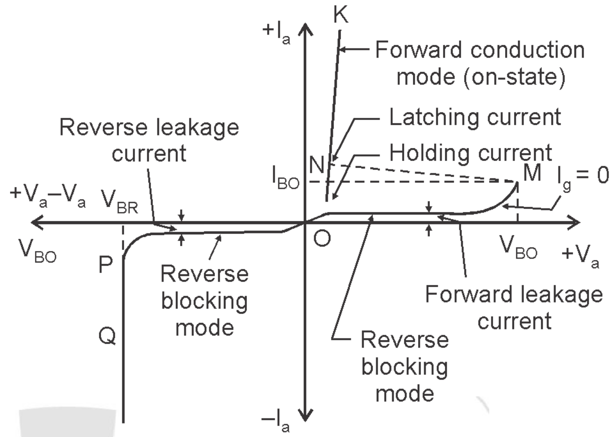
- SCR has two stable states, an ON-state and an OFF-state and can change its state from one to another so it is called bistable switch.
- An SCR is specified on the basis of the voltage blocking capability and continuous current capability as well as speed with which it is able to achieve turn-off.
- SCR has highest voltage rating (10 kV) and highest current rating (3 kA) and power handling capacity of 30 MW are available after this we are using a fuse for over current protection.
- A device of such a high rating can be switched on by a low voltage supply on gate of about 1 Amp & 10 watts which gives us an idea of the tremendous power amplification of this device (3×10^6).
- An SCR is considered to be a semicontrolled device because it conducts only during one half-cycle of an alternating current wave i.e. SCR can be fired only when it is forward biased means only in positive half cycle of alternating voltage.

Remember Points

- Pulse driven device.
- Unidirectional device/Unilateral device.
- Triggered/Latching device.
- Charge controlled device.
- Controlled DC switch.
- Bistables switch.
- Turn on by Regeneration.
- Negative temperature coefficient.

1.3.4 Static V-I Characteristics of Thyristor





V_{BO} = Forward breakover voltage

V_{BR} = Reverse breakover voltage

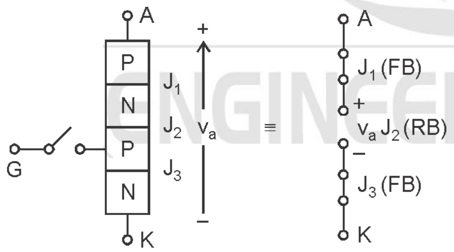
I_g = Gate current

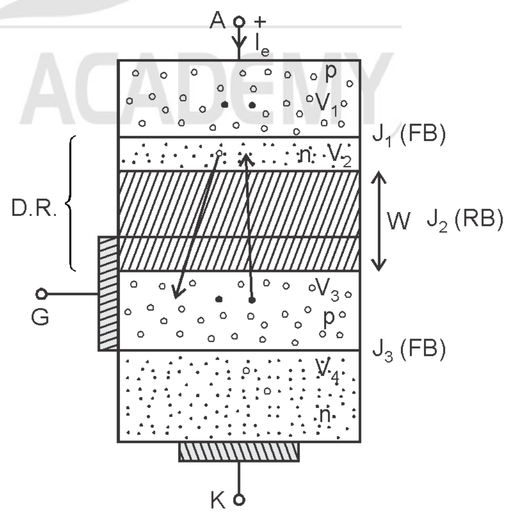
1.4 Operating Region of SCR

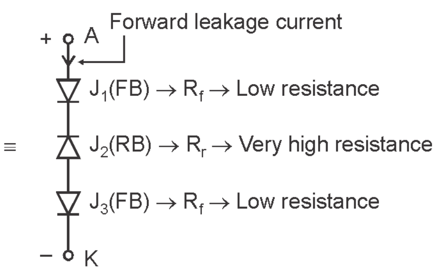
1. Forward blocking mode - off state
2. Forward conduction mode - on state
3. Reverse blocking mode - off state

1.4.1 Forward Blocking Mode

- When the anode voltage is made positive with respect to the cathode, with gate circuit open the junction J_1 & J_3 are forward bias. The junction J_2 is reverse bias. Hence forward voltage is to be hold by junction J_2.
- A very small current flows from anode to cathode due to minority charge carriers around junction J_2. This current is called as forward leakage current. The thyristor is then said to be in forward blocking mode. i.e. off state.
- The device remains in off state until the anode voltage reaches a critical value called forward break over voltage (V_{BO}).







As $V_1 > V_2 > V_3 > V_4$

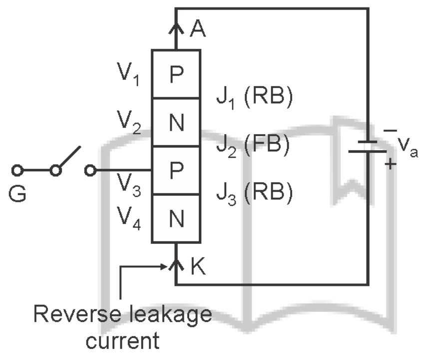
So J_2 is reverse biased & depletion region exists there, most of the width of D.R. is lying in n-layer as it is very lightly doped in comparison to inner p-layer.

- If (v_a) is Increased at a particular value V_{BO} (i.e. forward breakover voltage) junction J_2 breakdown & large number of charge carriers are generated in the depletion region so SCR starts conducting the forward current, so SCR jumps into forward conduction mode.
- The thyristor is treated as an open switch is forward blocking mode.

1.4.2 Forward Conduction Mode

- When the anode voltage is greater than forward breakover voltage i.e. $v_a > V_{BO}$ then avalanche breakdown occurs at junction J_2 and device start conducting.
- In conduction mode the anode current is mainly decided by load impedance along as voltage drop across SCR is quite small. This ON-state voltage drop (between 1 to 1.5 V) across the device is due to ohmic drop in ON condition and behaves as a closed switch.

1.4.3 Reverse Blocking Mode



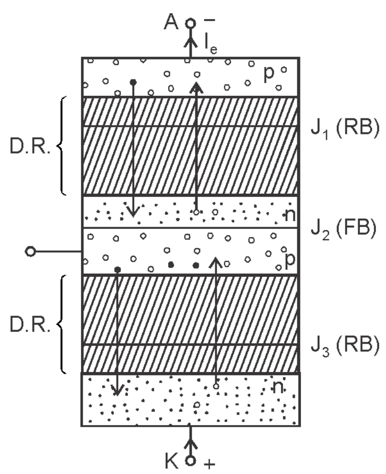
As K is at higher potential than A, the voltage decreases progressively from K to A i.e. $V_4 > V_3 > V_2 > V_1$.

For junction J_1, $V_2 > V_1$ so it is reversed biased

For junction J_2, $V_3 > V_2$ so it is forward biased

For junction J_3, $V_4 > V_3$ so it is reversed biased.

The depletion regions exists around junctions J_1 & J_3.



- Holes & electron (majority & minority charge carriers).

  It can be observed that only minority charge carriers are able to cross the junctions J_1 & J_3 hence small reverse leakage current flows only due to minority charge carriers.
- When anode voltage is made negative with respect to cathode, the junction J_1 & J_3 are in reverse bias and J_2 is in forward bias.
- As reverse voltage i.e. $(-v_a)$ is increased further a particular value say reverse breakdown i.e. negative V_{BR}, reverse biased junction J_1 & J_3 breaks down and large number of charge carriers are generated in the D.R. so reverse current increases sharply and the device gets damaged due to higher power dissipation.
- A very small current flows from cathode to anode is called reverse leakage current and this mode is called reverse blocking mode.
- At reverse breakdown, the high voltage is present across the thyristor and heavy current flows through it. Hence large power dissipation takes place in the thyristor. Due to this dissipation the thyristor will be damaged.

Breakover Voltage (V_{BO})

- When gate is open and if anode to cathode voltage exceeds forward breakover voltage "V_{BO}" the SCR is driven into forward conduction.

Latching Currents

- Latching current is the minimum forward current that flows through the thyristor to keep it in forward conduction mode (i.e. ON-state) at the time of triggering.

  It is defined as the minimum value of anode current which it must attains during turn-ON process to maintain conduction when gate signal removed.
- If the forward current is less than latching current thyristor does not turn-ON i.e. $I_a < I_L$.
- Latching current equal to two to three times the holding current.

Holding Current

- Holding current is minimum forward current that flows through the thyristor to keep it in forward conduction mode when forward current reduces below holding current turns-OFF.
- The value of anode current below which it must fall for SCR to regain its blocking capacity i.e. to turn-OFF SCR.

1.4.4 Comparison Between Holding and Latching Current

1. Latching current is effective at the time of turning-ON where as holding current is effective at the time of turning-OFF the thyristor.
2. Latching current is the maximum current that should flow at the time of triggering to turn- ON the thyristor.

   Where as once the thyristor is already in ON-state its current should not reduce below holding current otherwise it turn-OFF.
3. Latching current related to turning- ON process where as holding current related to turning- OFF process.
4. $I_{Latching} > I_{holding}$ i.e. latching current is greater than holding current even though their magnitude are much related.

Zener Breakdown

- If electric field is very high the holes and the electron in covalent bond is so high as electron may break the covalent bond so large number of charge carrier are generated. This type of breakdown is called Zener breakdown or direct rupturing of covalent bond.
- It depends on voltage and doping level, both layer must be highly doped, small voltage required for breakdown. It is electrostatic breakdown.

Avalanche Breakdown

- It occurs due to thermal effect or temperature. It occurs more common in lightly doped semiconductor junctions.
- Avalanche breakdown mean cumulative process of collision.

1.5 Thyristor Turn-On Methods

With anode positive with respect to cathode, a thyristor can be turned On by one of the following techniques.

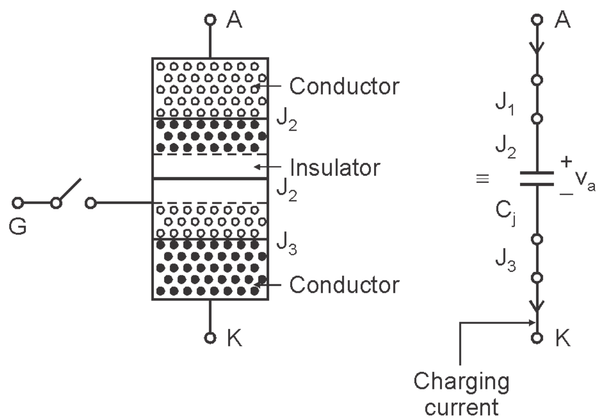
1. Forward voltage triggering/High voltage triggering.
2. $\frac{dv}{dt}$ triggering.
3. Temperature triggering/Thermals triggering.
4. Light triggering.
5. Gate triggering.

1.5.1 Forward Voltage Triggering

- When forward voltage is applied between anode and cathode with gate circuit open junction J_2 is Reverse bias where as whole of anode voltage appears across the Reverse bias junction J_2.
- If forward voltage i.e. V_a across anode-cathode is gradually increased, a stage (i.e. $V_a > V_{BO}$) comes then avalanche breakdown occurs in J_2. Hence SCR conducting.
- Losses in the device are maximum during transition from off state to on-state at V_{BO} is never employed as it may destroy the device and after avalanche breakdown, junction J_2 losses its reverse blocking capability. Hence this method of triggering is not preferred.

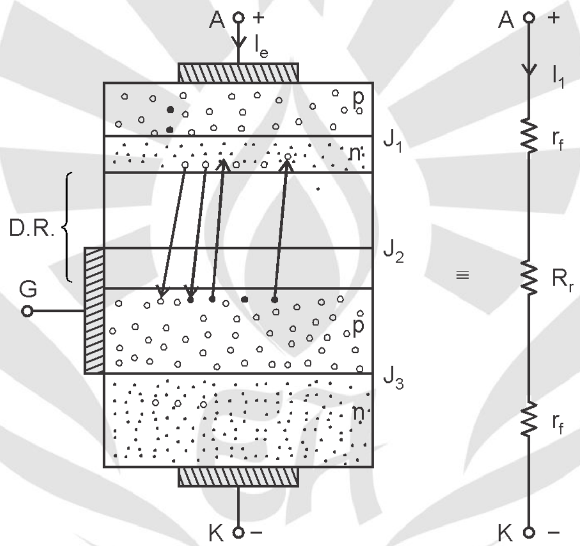
1.5.2 $\frac{dv}{dt}$ Triggering

- When forward voltage across the anode and cathode of a thyristor the junction J_1 & J_3 are forward biased, but junction J_2 is reversed bias. Junction J_2 has the characteristics of a capacitor due to charges existing across the junction J_2 i.e. space charges exist in the depletion region as shown in figure.



- If forward voltage is suddenly applied, a charging current through junction capacitance C_j may turn of the SCR. Suddenly entire V_a appears across J_2, the high value of charging current, i_c of capacitance junction may be sufficient enough to turn-ON the thyristor, even through gate signal is zero.
- Charging current in capacitor $i_c = C_i \frac{dv_a}{dt}$
- A high value of charging current may damage the thyristor & device must be protected against higher value of $\frac{dv}{dt}$.
- Voltage transient during supply is switched-ON in the circuit may causes false triggering of the device.
- This false triggering can be avoided by using a circuit called snubber circuit.

1.5.3 Temperature Triggering



In forward blocking mode, the forward leakage current I_l is flowing due to minority charge carriers. As reverse biased J_2 offers high resistance R_r(≈ MΩ) so power loss $I_l^2 R_r$ occurs mainly across J_2. To avoid thermal runaway (i.e. temperature triggering) the heat developed across J_2 is continuously removed using A_1 heat sink.

- During forward blocking mode, forward voltage appears across reverse biased junction J_2.
- In reverse biased junction J_2, reverse leakage current flow which rises by the junction temperature current 10% per °C rise in temperature.
- With increases in temperature, width of depletion layer decreases. This further leads to more leakage current and therefore, more junction temperature.
- With the cumulative process, at some high temperature, avalanche breakdown in junction J_2 and device gets turned ON.
- This type of turn-ON may cause thermal runaway and it normally avoided.

1.5.4 Light Triggering

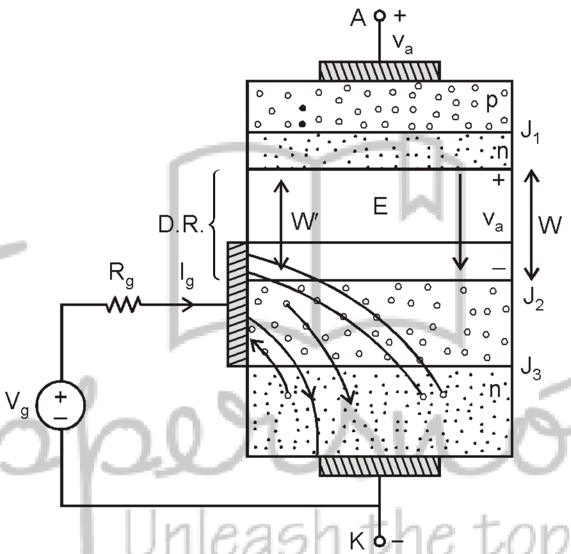
- For light-triggered SCRs, a recess (or niche) is mode in the inner p-layer.
- When a pulses of light of appropriate wavelength and of sufficient intensity, is allowed to strike the gate to cathode junction, the electron-hole pairs are generated in inner p-layer thus width of depletion region in inner p-layer gets reduced, hence avalanche breakover may occur which may turn-on SCR.
- Light triggering SCR has the advantage of electrical isolation between power circuit and control circuits.

  The SCR employing light triggering are called LASCR (Light activated SCR) used in HVDC transmission system.

1.5.5 Gate Triggering

- It is simple, reliable, efficient and most commonly used method of turn-ON of SCR.

  If a thyristor is forward biased, the injection of gate current by applying positive gate voltage between the gate and cathode terminal and turn-ON the thyristor.



In forward biased condition, the D.R. around J_2 behaves as open circuit so total voltage v_a appears across it hence electric field in D.R.

$$E = \frac{v_a}{W} \quad \text{where W is the width of D.R.}$$

Due to the positive gate current from G to K i.e. holes flow from G to K & electrons from K to G.

$$I_g = I_{gn} + I_{gp}$$

Gate Current due to electrons $\quad I_{gn} = neAv_n$

Gate current due to holes $\quad I_{gp} = peAv_p$

A is the area & v_n, v_p are the drift velocities of charge carriers.

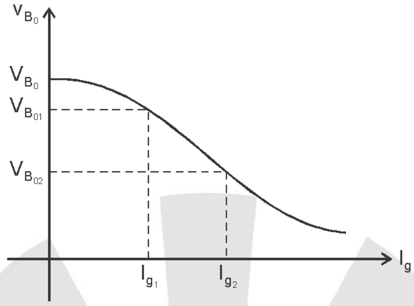
As outer n-layer is highly doped in comparison to inner p-layer the gate current flows mainly due to electrons

$$n >> p \Rightarrow I_{gn} >> I_{gp}$$

$\Rightarrow \quad I_g \simeq I_{gn} = neAv_n$

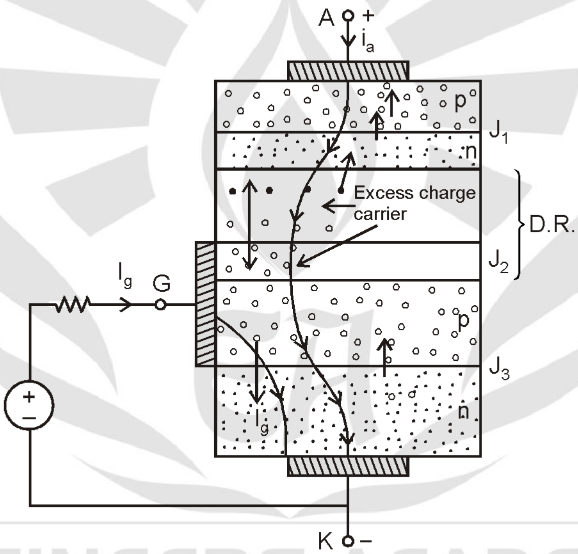
When electrons are moving from K to G, some of the electrons enter the D.R. of p-layer so there is reduction in the width of D.R. in p-layer W′ < W so electric field in D.R. increases E′ > E for same voltage v_a hence electrons are able to break the covalent bonds due to cumulative process of collision & breakdown occurs at a voltage (less than V_{BO}) so the role of I_g is to inject the charge carriers in D.R.

If gate current is increased, more number of charge carriers (i.e. electrons) enter the D.R. and there is more reduction in the width of D.R. so there is further less voltage required for breakdown



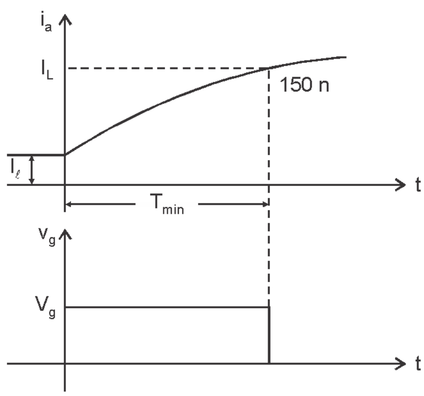
As $I_{g2} > I_{g1} \Rightarrow V_{B02} < V_{B01}$

Once SCR is conducting the anode current, the charge carriers are crossing the D.R., these charge carriers will maintain further breakdown of J_2 so gate signal can be removed.



The anode current $i_a = n_e Av_n + p_e Av_p$

Where n & p are the number of electrons & holes crossing J_2 due to i_a



At t = 0, SCR is fired, i_a starts increasing from leakage current I_l so number of charge carriers crossing J_2 increases.

Let minimum number of charge carriers required to cross J_2 to sustain the breakdown is 100n where n is some constant.

So if charge carriers crossing J_2 are less than 100n, J_2 will be blocked again and SCR will be turned-off.

After time T, i_a rises upto I_L i.e. corresponding to 150n charge carriers (significantly more than 100n) so gate signal can be removed.

Hence minimum gate pulse width required = T

T = Time taken by i_a to rise upto I_L

I_L = 0.1 A to 0.5 A

When SCR is conducting the large anode current, large number of charge carriers are crossing J_2. For turning off SCR, i_a must be reduced below a particular value, holding current I_H, the number of charge carriers crossing J_2 are reduced say upto 60n (significantly below 100 n) the junction J_2 will be blocked again so SCR can be turned off (or commutated)

$I_L = 150n,\ I_H = 60n$

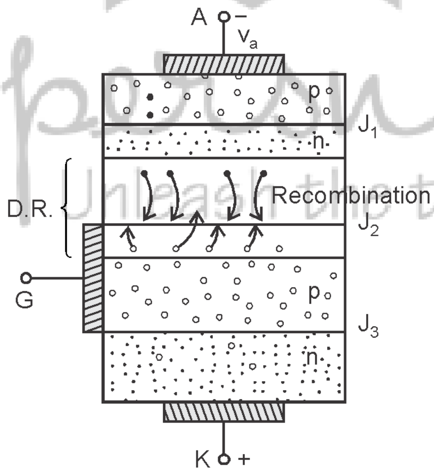
Surely $I_L > I_H$

In general I_L is upto 2 to 3 times of I_H.

In general, $I_H \simeq 10$ mA

Let $I_H \simeq 0$

Even after reducing $i_a \simeq 0$ (i.e. below I_H) the excess charge carriers remain present due to which SCR may conduct as soon as it is forward biased even without gate signal.



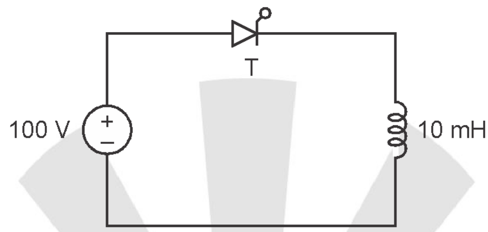
So to remove excess charge carriers around J_2 it should be reverse biased for short duration. The excess charge carriers will be lost by recombination. So to commutate (or to turn-off) SCR i_a should be reduced below I_H & then it should be kept reversed for time t_q.

$t_q \rightarrow$ Turn-off time of SCR

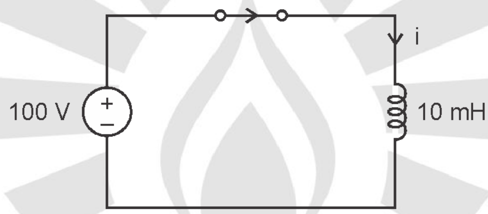
- As the gate current is increased, the forward breakover voltage is decreased.
- Gate current magnitudes are of the order of 20 to 200 mA.
- Figure explains the chemistry of turning-on of SCR by gate triggering.

- When a positive gate pulse is applied, gate current flows due to which electrons from outer n-layer are injected into inner p-layer as a result of which width of depletion layer around reverse biased junction J_2 reduces.
- This causes the junction J_2 to breakdown at an applied Voltage lower than forward breakdown voltage, V_{BO}.
- If the magnitude of gate current is increased more numbers of electrons reached junction J_2 reduces to zero very fast and thus SCR will get turn-on at reduced forward voltage.

Example 1 : If the latching current of SCR is 40 mA. Determine minimum gate pulse width.



Solution: Let T is fired at t = 0



At $t = 0,\ i = 0$

& $$V_s = L\frac{di}{dt}$$

$\Rightarrow$ $$\int di = \frac{V_s}{L}\int dt$$

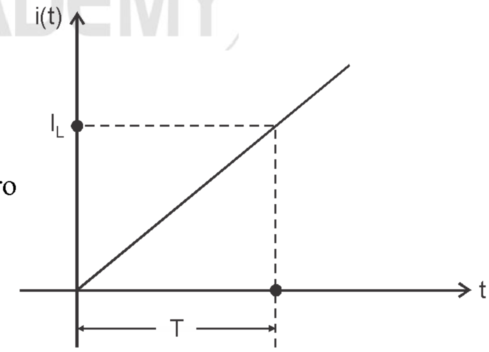
$$i(t) = \frac{V_s}{L}t + A \quad \ldots(1)$$

Where A is an arbitrary constant

At $t = 0,\ i = 0$

$$0 = 0 + A$$

$A = 0$ i.e. constant is zero



So $$i(t) = \frac{V_s}{L}t$$

$$i(t) = \frac{100}{0.01}t$$

$$i(t) = 10^4\ t$$

At $t = T,\ i = I_L = 40\ \text{mA} = 0.04\ \text{A}$

$$i(t) = 10^4\,t$$

$$0.04 = 10^4 \times T$$

$$T = 4 \times 10^{-6} = 4\ \mu\text{ sec}$$

$$T = 4\ \mu\text{ sec}$$

Minimum gate pulse width = time required by i_a to rise up to I_L.

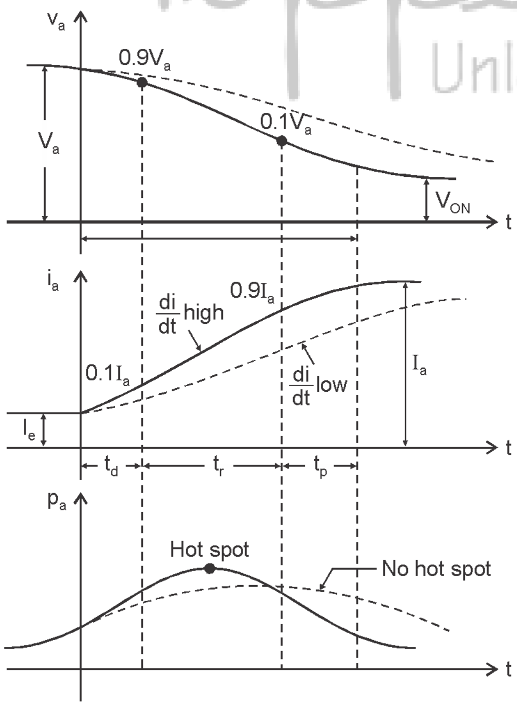
$\Rightarrow$ Pulse width = T = 4 μ sec

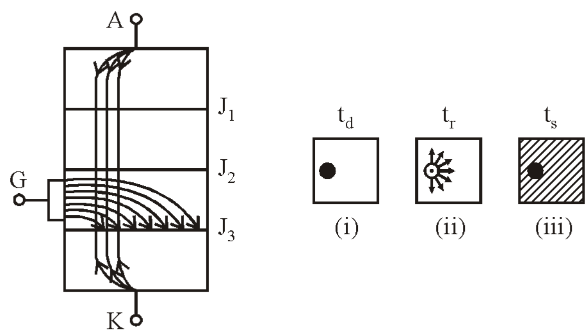
1.6 Switching, Dynamic or Transient Characteristic of SCR

- A transient time from forward-OFF state to forward-ON state, called thyristor turn-ON time.
- The turn-ON time 't_{ON}' of the SCR is subdivided into three distinct periods.
  - (i) Delay time "t_d"
  - (ii) Rise time "t_r"
  - (iii) Spread time "t_s"

(i) Delay Time

- This is the time between the instant at which the gate current reaches to 90% of its final value (from 0 to 90% I_a) & the instant at which the anode current reaches 10% of its final value (i.e. 10 I_a)
- It can also be defined as the time during which anode voltage fall from 100% of V_a to 90% of V_a as shown in figure.
- During delay time gate current flows from gate to cathode has non-uniform distribution, more current density near gate but decreases rapidly as the distance from the gate increases hence anode current flows in a narrow region near gate as shown in figure.





- The delay time can be decreased by applying high gate current and more forward voltage between anode to cathode. The delay time is fraction of a microsecond.

(ii) Rise Time

- This is the time required for anode current to rise from 10 to 90% of its final value.
- It is also defined as the time during which anode voltage, V_a falls from 90% of V_a to 10% of V_a.
- The rise time is inversely proportional to the magnitude of gate current and its build up rate i.e. $\frac{di_g}{dt}$, its depends on the nature of anode circuit.
- Rise time(t_r) can be reduced if high and speed current pulses are applied to gate.
- During rise time anode current flows in narrow conducting area as turn-on losses in the thyristor are the highest due to high anode voltage and large anode current, occurring together in the thyristor.
- As these losses occur only over a small conducting region, local hot spots may be formed and the device may be damaged.

  i.e. $P = V_a I_a$

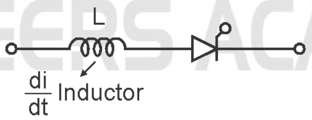
  This power dissipation is called switching losses of thyristor.

(iii) Spread Time

- The spread time is the time required for the anode voltage, V_a to fall from 10% V_a to the ON-state voltage drop (1V to 1.5V).
- After spread time, anode Current attains steady state values & the voltage drop across the SCR is equal to the ON-state Voltage drop of the order of 1 V to 1.5 V.
- During spread time the conduction spreads whole at cathode surface.

NOTE: When the amplitude of gate pulse is larger than the minimum gate current (i.e $i_g >> i_{g\,min}$) required for turning-ON the SCR, the device is called hard driven or over driven which reduces the t_{ON} & thus enhance $\frac{di}{dt}$ capability.

Due to maximum power loss during t_r there are hot spots formation as these losses are confined to the narrow conducting region. To avoid hot spots formation i.e. to reduce peak power loss during t_r, rate of rise of i_a should be reduced by connecting an inductor in series with SCR



The specified values of $\frac{di}{dt}$ for SCR varies from 20 A/μs to 500 A/μs practically.

1.7 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 i.e. from conduction state to forward blocking state is called turn-OFF process.
- The thyristor can be turned-OFF by reducing the anode current below holding current i.e. $I_a < I_H$, still the device will not be able to block this forward voltage as the carriers (hole and electrons) in the four layers are favorable for conduction.

- Turn-OFF time is divided into :
  (i) Reverse recovery time 't_{rr}'
  (ii) Gate recovery time 't_{gr}'

1.7.1 *Reverse Recovery Time 't_{rr}'*

- Once anode current is zero, the device start to turn-OFF but not immediately and it will take some to turn-OFF.
- The time taken by the minority carriers present in the PN-junction to recombine with opposite charges and to be neutralized. This time is called reverse recovery time 't_{rr}'

1.7.2 *Gate Recovery Time 't_{gr}'*

- The time taken by charges for the recombination when reverse voltage is maintained across the thyristor.
- The time taken by the thyristor to change state from ON-state to OFF-state is called turn-OFF state.
- Turn-OFF time is the sum of t_{rr} & t_{gr}.

  $t_{OFF} = t_{rr} + t_{gr}$
- Turn-OFF time is the time taken by the SCR to regain its forward blocking capability after the anode current is reduced to zero.

  The turn-OFF time 't' of SCR:
- The time between the instant anode current becomes zero & the instant SCR regains forward blocking capability.

Circuit Turn-OFF Time "t":

- The time between the instant anode current becomes zero & the instant reverse voltage due to practical circuit reaches to zero.
- The turn-OFF time provided to the SCR by the practical circuit is called circuit turn-OFF time, t_c.

NOTE: For reliable operation of SCR the circuit turn-OFF time must be greater than the thyristor turn-OFF time i.e. $t_c > t_q$.

Important Facts

During Turn-ON

- Total turn on time = $t_r + t_d + t_p$
- Turn-ON time can be reduced by using higher values of gate currents.
- $|I_g|$ = 3 to 5($I_{g\,min}$) i.e. hard fired or overdriven.
- The magnitudes of gate current is equal to 3 to 5 times the minimum gate current required to trigger an SCR.
- Hard-firing or overdriving of a thyristor reduces its turn-ON time & enhance its di/dt capability.
- Turn-ON time depends upon the anode circuit parameters and gate signal waveshapes.

During Turn-OFF

- From conduction state to forward blocking state called commutation process or turn-OFF process.
- SCR can be turned-OFF by reducing the anode current below holding current.

- The thyristor turn-OFF time t_q is in the range of 3 to 100 μsec .
- Turn-OFF time decreases with an increase in the magnitude of reverse voltage (0 to 50 V).
- Circuit turn-OFF time 't_c' must be greater than 't_q' for reliable turn-OFF SCR.

Define turn-OFF time of thyristor and mention any two factors that affect it.

1. Inverter Grade Thyristor

- The thyristor with fast turn-OFF time i.e. 3 to 50 μ sec are called inverter grade SCR's.
- Inverter grade thyristors are costlier and are used in INVERTERS and CHOPPERS.

2. Converter Grade Thyristors

- Thyristor with SLOW turn-OFF time i.e. 50 to 100 μ sec are called converter grade thyristor.
- These are cheaper and are used in phase- controlled rectifiers, ac voltage controllers, cyclo-converters etc.

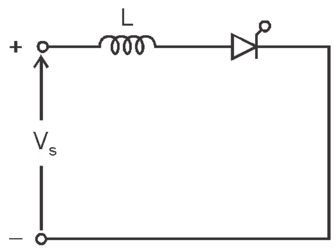
1.8 Thyristor Protection

- For reliable operation of SCR, it should be operate with the specific ratings.
- SCRs must be protected against abnormal operating conditions. Various protection of SCR are.

1. di/dt protection
2. dv/dt protection
3. Over voltage protection
4. Over current protection
5. Gate protection

1.8.1 di/dt Protection

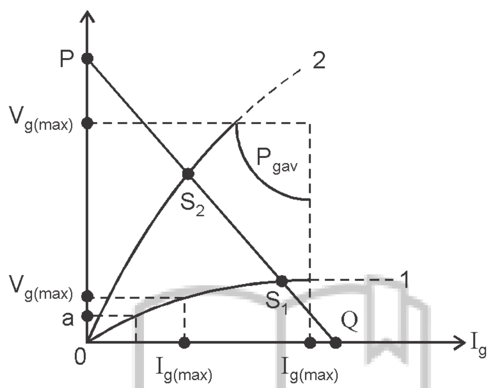
- di/dt is the rated of change of current in a device.
- When SCR is forward biased and is turned-ON by the gate signal, the anode current starts flowing in the narrow conducting channel near gate.
- The anode current requires some time to spread inside the device i.e. spreading of charge carriers.
- But if the rate of rise of anode current (di/dt) is greater than the spread velocity of charge carriers than local hot spot is created near gate due to increased current density. This localized heating may damage the device.
- Local hot spot heating is avoided by ensuring that the conduction spreads to the whole area very rapidly. 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' oppose the high di/dt variations.
- When current variation is high, the inductor 'L' smooth it and protects the SCR from damage.
- To limit di/dt with in safe limit is 20-500 A/μ sec.

Thyristor Gate Characteristics

- Figure shows the gate characteristics of a thyristor. Here positive gate cathode voltage V_g and positive gate to cathode current I_g represents dc values.
- For a particular type of SCRs $V_g - I_g$ characteristics has spread between curves 1 and 2 as shown in figure. This spread or scatter of characteristics is due to difference in low doping levels of P and N layers.



- Curve-1 represents the lowest voltages values that must be applied to turn-ON the SCR & curve-2 gives the highest possible voltage values that can be safely applied to gate circuit.
- Each thyristor has maximum limits as $V_{g(max)}$ for voltage $I_{g(max)}$ for gate current, there is also a limit on the maximum gate power dissipation.

  $P_{g(max)} = V_g I_g$

  These limits should not be exceed in order to avoid permanent damage of junction J_z.
- There are also minimum limits for V_g & I_g for reliable turn-ON, these are represented by $V_{g\ min}$ & $I_{g\ min}$ as shown in figure.
- If $V_{g\ max}$, $I_{g\ max}$ & $P_{g\ avg}$ are exceeded, the thyristor can be destroyed.

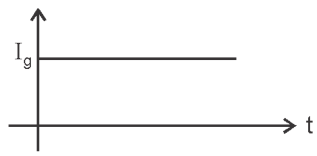
There are Three Important Regions

1. The first region '0 to a' is defined by maximum gate voltage that will not trigger any device.
2. The second region is the minimum value of gate-voltage & current required to trigger the SCR.
3. The third region is the largest limits on the gate- signals for reliable firing. For applications where fast turn-ON is required, a hard firing signal is needed.

Gate Triggering Method

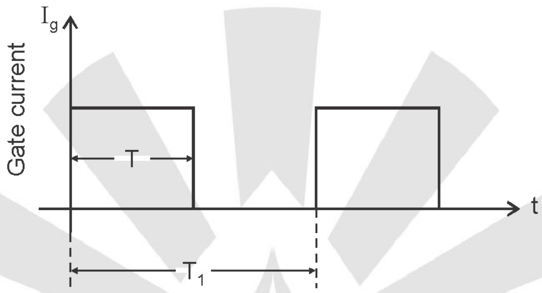
1. Continuous gate triggering
2. Pulse triggering
3. High frequency gate triggering

1. Continuous Gate Triggering



- Not an efficient method because of continuous gate power loss.
- When a thyristor gets turn-ON, the gate drive should be removed to avoid increased loss and higher junction temperature.

2. Pulse Triggering



Where T_1 is periodicity and T_1 is pulse width.

- In pulse triggering, average power dissipation should be less than peak instantaneous gate power dissipation.

$$P_{gav} < P_{gm}$$

- Gate pulse width T is equal or greater than, SCR turn-ON (t_{on}) time i.e. $T > T_{ON}$
- Frequency of firing obtained by

$$\frac{P_{gm}T}{T_1} \geq P_{gav} \text{ or } P_{gm} . T . f \geq P_{gav}$$

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

where $f = \frac{1}{T_1}$ = frequency of firing

T = pulse width in sec.

$$\frac{P_{gav}}{fT} = P_{gm} \text{ or } f = \frac{P_{gav}}{T.P_{gm}}$$

- A duty cycle is defined as the ratio of pulse-ON period to periodic time of pulse, i.e. T to T_1 duty cycle

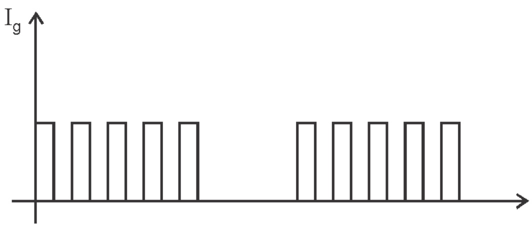
$$\delta = \frac{T}{T_1} = fT$$

Hence $\frac{P_{gave}}{\delta} = P_{gm}$

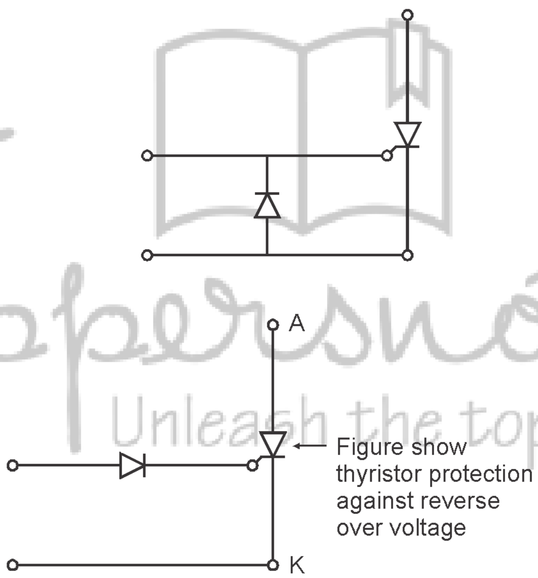
- The turn-ON time of thyristor can be reduced by Increasing the amplitude of gate current and power dissipation can be reduced by reducing the period of gate pulse in pulse triggering.
- The magnitude of gate voltage and gate current for triggering an SCR is inversely, proportional to junction temperature.

3. High Frequency Gate Triggering

- The advantages offered by this method of firing the SCRs are lower rating, reduced dimensions and therefore an overall economical design of the pulse transformer needed for isolating the low power circuit from the main power circuit.



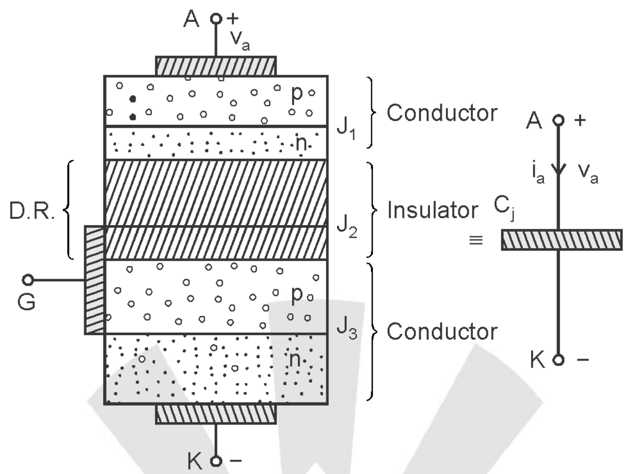
- It should be ensured that (pulse voltage amplitude) (pulse current amplitude) < P_{gm}



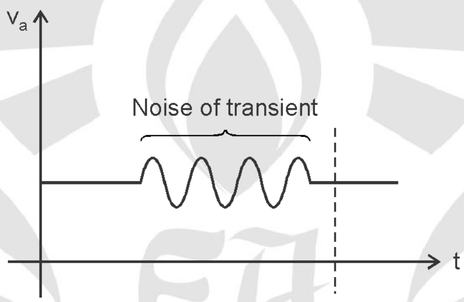
- There is a peak reverse voltage (gate negative with respect to cathode) that can be applied across gate-cathode terminals.
- Any interference or any voltage signal given by trigger circuit, if exceed 5 to 20 V may damage gate circuit.
- For preventing the occurrence of such hazards, a diode is connect either series with gate circuit or across, the gate-cathode terminals as shown figure.
- Diode across the gate-cathode terminals, called clamping diode, prevents the gate cathode voltage from becoming more than about 1 volt.
- Diode in series with gate circuit prevents the flow of negative gate current from becoming more than small reverse leakage current.

1.8.2 dv / dt Protection

During forward blocking mode, Thyristor is acting like a capacitor i.e. junction capacitance C_j (it is similar to the transition capacitance or space charge capacitance of pn junction)



Due to higher charging current, large number of charge carriers crosses the J_2 which may create breakdown of D.R. & SCR may turn-ON even without gate signal, it is said to be $\frac{dv_a}{dt}$ triggering.



Let the noise signal be sinusoidal $v = V_n \sin \omega_n t$

$$\Rightarrow \quad \frac{dv}{dt} = \omega_n V_n \cos\omega_n t$$

$$\Rightarrow \quad \frac{dv_n}{dt} = \omega_n V_n = 2\pi f_n V_n$$

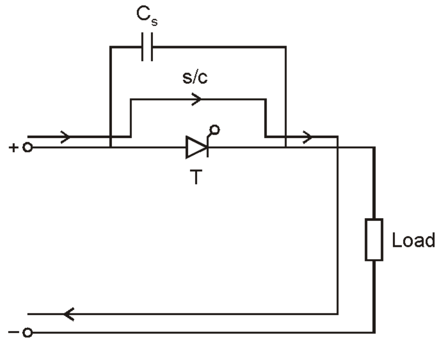
For high frequency noise/transient i.e. f_n high, $\frac{dv}{dt}$ high.

For $\frac{dv}{dt}$ triggering, let a capacitor C_s is connected across the SCR.

$$X_c = \frac{1}{\omega_n C_s} = \frac{1}{2\pi f_n C_s}$$

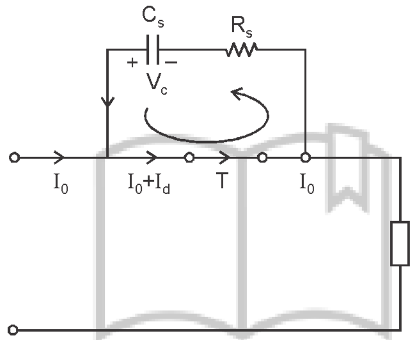
If f_n – high $\Rightarrow X_c$ – low

i.e. $X_c \to 0$ i.e. short-circuit.



As thyristor acts as open circuited (forward blocking mode) & C_s as short circuited so transient is bypassed from the thyristor thus protecting the thyristor. Once transient/noise is over C_s gets charged say upto voltage V_c. Whenever T is fired C_s will discharge through T (i.e. forward Conduction mode & low resistance path).

To limit the discharging current I_d a resistance R_s is also connected.

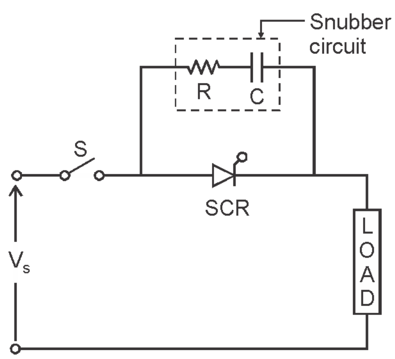


Peak Discharging current, $I_d = \frac{V_c}{R_s}$

Peak Thyristor current, $I_{TP} = I_0 + I_d$

- We know that $i_c = C\frac{dv}{dt}$ i.e. when $\frac{dv}{dt}$ is high, i_c is high and low impedance offered by capacitor.
- This high current (i_c) may turn-ON SCR even when gate current is zero. This 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

Snubber Circuit



- The capacitor 'C' is used to limit the dv/dt across the SCR.
- The resistor 'R' is used to limit high discharging current through the SCR.
- When switch S is closed, the capacitor 'C' behaves as a short-circuit and therefore voltage across SCR is zero.
- As time increases, voltage across 'C' increases at a slow rate. Therefore dv/dt across 'C' and SCR is less than maximum dv/dt rating of the device.
- The capacitor charges to full voltage V_S, after which the gate is triggered and SCR is turned ON and high current flows through in SCR.
- As di/dt is high, it may damage the SCR. To avoid this, the resistor 'R' is series with 'C'.

1.8.3 Overvoltage Protection

- Overvoltage may result in false turn-ON of the device (or) damage the device.
- SCR is subjected to internal and external over voltage.

Internal Overvoltage

- The reverse recovery current of SCR decays at a very fast rate i.e. high di/dt.
- So a voltage surface is produced whose magnitude is L(di/ dt).
- As this internal overvoltage may be several times the breakover voltage of the device, the thyristor maybe destroyed permanently.

External Overvoltage

- These are caused by the interruption of current flow in the inductive circuit and also due to lightning strokes on the lines feeding the SCR systems.
- The effect of overvoltage is reduced: by using snubber circuits and Non-Linear resistors called voltage clamping devices.

Voltage Clamping Device

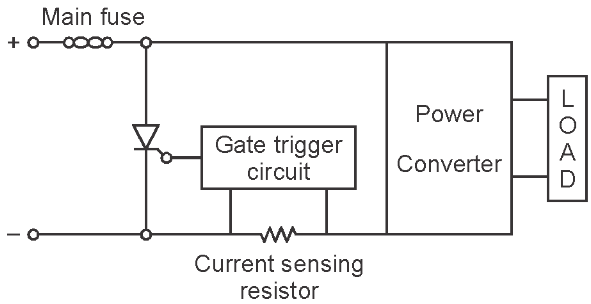
- It is a non-linear resistor called as VARISTOR (variable resistor) connected across the SCR.
- The resistance of varistor will decreases with increase in voltage.
- During normal operation, varistor has high resistance and draws only small leakage current.
- When high voltage appears, it operates in low resistance region and surge energy is dissipated across the resistance by producing a virtual short-circuit across the SCR.

1.8.4 Overcurrent Protection

- The overcurrent can flow through the device either due to short circuited due to overloading.
- The protection against overloading is provided using circuit breaker (CB) and protection against short circuit can be provided by HRC fuse.
- In an SCR due to over-current, the junction temperature exceeds the rated value and the device gets damaged.
- Overcurrent is interrupted by conventional fuses and circuit breakers.
- The fault current must be interrupted before the SCR gets damaged and only faulty branches of the network should be isolated.

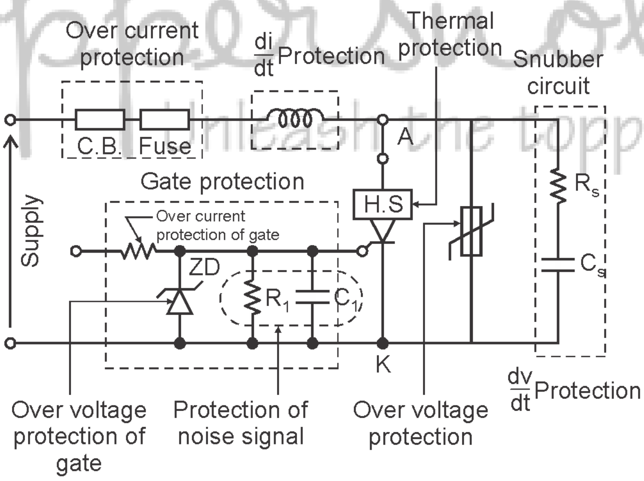
- Circuit breaker has long tripping time. So it is used for protecting SCR against continuous over loads (or) against surge currents of long duration.
- Fast acting current limiting fuse is used to protect SCR against large surge current of very short duration.

Electronics Crowbar Protection



- SCR has high surge current ability.
- SCR is used in electronic crowbar circuit for overcurrent protection of power converter.
- In this protection, an additional SCR is connected across the supply which is known as "Crowbar SCR'.
- Current series resistor detects the value of converter current.
- If it exceeds preset value, then gate trigger circuits turn-ON the crowbar SCR.
- So the input terminals are short circuit by SCR and thus it bypass the converter over current.
- After some time the main fuse interrupts the fault current.

1.8.5 Gate Protection

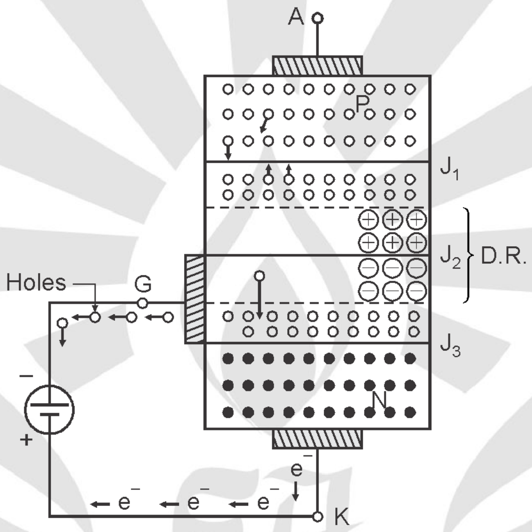


- Heat Sink (H.S) are provided for SCRs for thermal protection.
- Protection against overvoltage is achieved by connecting a zener diode (ZD) across the gate circuit.
- Protection against overcurrent is achieved by connecting a resistor R_2 in series with gate circuit.
- Protection against noise signal is achieved by connecting a resistance R_1 and capacitance C_1 across gate circuit.

- A capacitor C_1 and resistor R_1 is connected across gate to cathode to by pass the noise signals.
- A resistor R_1 is connected across gate-cathode terminal to bypass a part of thermally generated leakage current across junction J_2 (forward blocking mode) improves thermal stability of SCR, its dv/dt rating, holding current, and noise immunity of SCR.
- Stabilized gate voltage is obtained using ZD, while R_1 & C_1 are used as a filter.
- The flux linkage to the load circuit with the gate circuit of different SCR can result in false triggering due to induced voltage. It can be avoided by locating SCR symmetrical on heat sink. The heat sink are mode up of aluminium.

1.9 Operating Principle of a GTO

- GTO being monolithic p-n-p-n structure just like a thyristor its basic operating principle can be explained in a manner similar to that of a thyristor.



- It is identical to SCR except that it can be turn- off applying negative gate current.
- When thyristor carrier significant current during ON condition large number of charge carrier are crossing junction J_2 due to anode current which consist of equilibrium concentration charge carrier and excess charge carrier due to breakdown of junction J_2.
- If negative gate current is supplied in this condition holes are moving outside from gate terminals and electrons outside from cathode terminals.
- Hence recombination takes place so excess charge carrier are removed by negative gate pulse.
- In SCR, gate current is very small of the order of mA while anode current is very large of the order of kA. So there is no significant effect of negative gate current.
- However if negative gate current is very high upto 20% to 30% of anode current, there is significant reduction in the availability of charge carrier for anode current.
- So in G.T.O gate circuit should be design to carrier very large current.

  In GTO junction J_2 is design in such a manner as minimum number of charge carrier crossing it are very large as compare to SCR. Hence latching current and holding current is very large in G.T.O as compare to SCR.

- So due to negative gate current, anode current may reduce below holding current hence G.T.O can be turn-off.
- The available rating of G.T.O is less as compare to SCR because if anode current ratio of GTO higher, gate circuit also should be design for very large current that is not economic.

NOTE: The static V-I characteristic of GTO is similar to SCR.

1.10 Comparison Between GTO and Thyristor

A GTO has the following disadvantages as compared to a conventional thyristor.

(i) Magnitude of latching and holding currents is more in a GTO.

(ii) On state voltage drop and the associated loss is more in a GTO.

(iii) Due to the multicathode structure of GTO, triggering gate current is higher than that required for a conventional SCR.

(iv) Gate drive circuit losses are more.

(v) Its reverse-voltage blocking capability is less than its forward-voltage blocking capability. But this is no disadvantage so far as inverter and chopper circuit are concerned.

In spite of all these demerits, GTO has the following advantages over an SCR:

(i) GTO has faster switching speed.

(ii) Its surge current capability is comparable with an SCR.

(iii) It has more di/dt rating at turn-on.

(iv) GTO circuit configuration has lower size and weight as compared to thyristor circuit unit.

(v) GTO unit has higher efficiency because an increase in gate-drive power loss and on-state loss is more than compensated by the: elimination of forced-commutation losses.

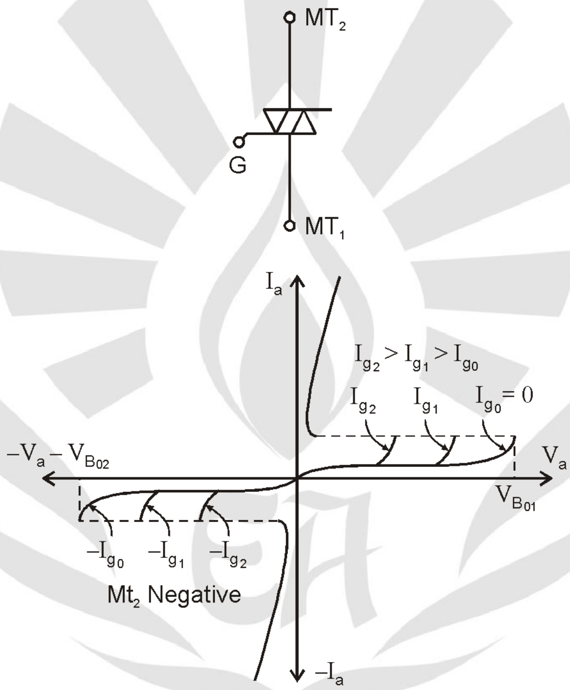
(vi) GTO unit has reduced acoustical and electromagnetic noise due to elimination of commutation chokes.

Remember Points

- GTO is a four layer, three terminal current controlled minority carrier device.
- A GTO can be turned on by applying a positive gate current pulse when it is forward biased and turned off by applying a negative gate current.
- A GTO has a "shorted anode" and highly inter-digitized gate cathode structure to improve the gate turn-off performance.
- The forward i-v characteristics of a GTO is similar to that of a thyristor. However, they have relatively larger holding current and gate trigger current.
- The turn-on di/dt capability of a GTO is significantly enhanced by using higher peak gate current and large rate of rise of the gate current.
- Due to relatively larger holding current of a GTO a continuous low value gate current (called the back, porch current) should be injected throughout the on period of the GTO.
- GTOs have relatively low turn off current gain.
- The GTO gate drive unit should be capable of injecting large positive and negative gate currents with large rate of rise for satisfactory switching of the device.

- A GTO can block rated forward voltage only when the gate cathode junction is reverse biased.
- A GTO can operate safely in the "reverse avalanche" region for a short time provided the gate cathode junction is reverse biased.
- Latching current of GTO, I_L = 2 Amp and Latching current of SCR, I_L = 100 to 500 mA.
- Self turn-off capability of GTO makes it the most suitable device for inverter and chopper applications.
- The GTO has gate controlled turn-off capability unlike a conventional thyristor.
- Due to its special structure, the GTO has i.e. low limited reverse blocking-capability as compared to a conventional thyristor.
- There is no need for an external commutation circuit to turn it off. So inverter circuits built by this device are compact and low-cost.

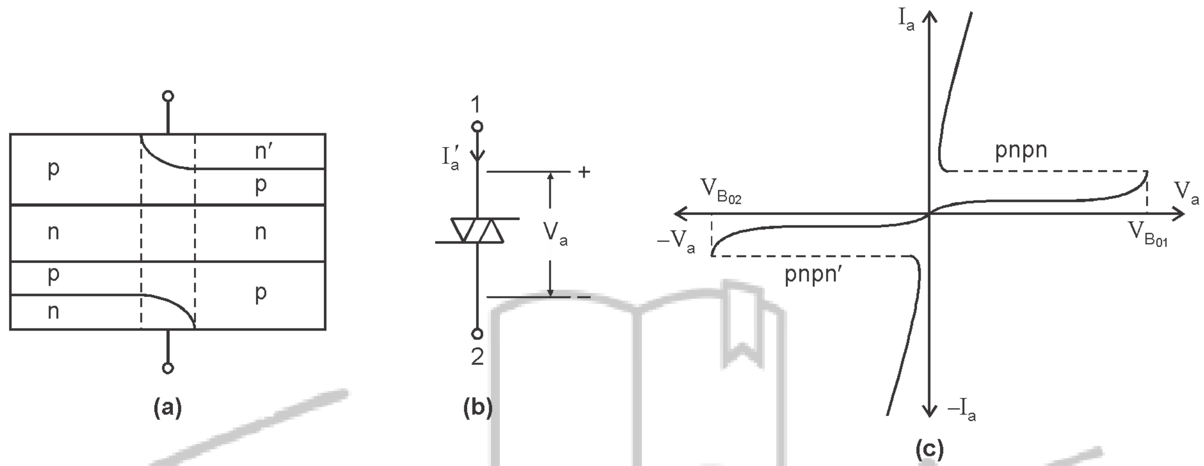
1.11 TRIAC



- Triac is the word derived by combining the capital letters from the words Triode and AC. A triac is equivalent to two SCRs connected in antiparallel.
- A TRIAC is a bidirectional thyristor with three terminals and five layers. It can conduct from anode to cathode and from cathode to anode.
- TRIAC is operating in four modes so it can be used as AC switch.
- Most suitable when supply voltage is low frequency ac. It is only preferred for low and medium power applications.
- TRIAC requires more current for turn-on than SCR at a particular voltage.
- Sensitivity of the triac is greatest in the I^{st} quadrant when turn-on with positive gate current and also in the third quadrant when turned on with negative gate current.
- Sensitivity of the triac is low in the I^{st} quadrant when turned-on with negative gate current and also in third quadrant when turned on with positive gate current.

- Thus the triac is rarely operated in Ist quadrant with negative gate current and in the third quadrant with positive gate current.
- A TRIAC may sometimes operate in the rectifier mode rather than in the bidirectional mode.
- An additional lateral region serves as control gate.
- TRIAC is only used for resistive loads and low inductive loads in ac voltage controller. It is not preferred for high inductive loads with high time constant.
- Triacs are used extensively in residential lamp dimmers, heat control and for the speed control of small single-phase series and induction motors.

1.12 The Diac (Bidirectional Thyristor Diode)



- Diode that Can work on AC i.e. DIAC.
- Two terminals device.
- Three layer device.
- Bidirectional switch.
- Uncontrolled device.
- Diac has symmetrical breakdown characteristics.
- Its turn-on voltage is about 30 volt.
- When conducting, it acts like a low resistance with 3 volt drop across it.
- When it is not conducting, it acts like an open switch.
- A diac is sometimes called a gateless triac.
- Diac operate in four modes and acts as ac switch.
- Diac is used in TRIAC firing circuit.

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