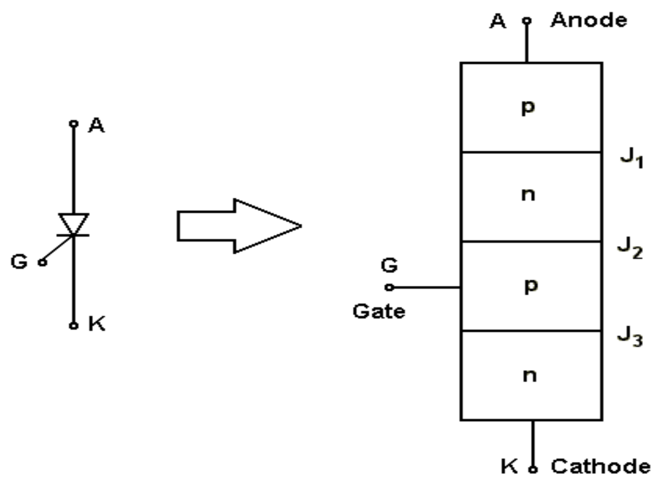
SHIVAJI UNIVERSITY, KOLHAPUR
B.Sc. (Part III) Semester -V
Electronics (Paper-XII)
Power Electronic Devices and Applications

Unit 2:- Thyristors (6 Marks)

Thyristors are a family of power semiconductor devices. They are operated as bistable switches, operating from non-conducting state to conducting state. Compared to transistors, thyristors have lower on-state conduction losses and higher power handling capability.

Structure:-

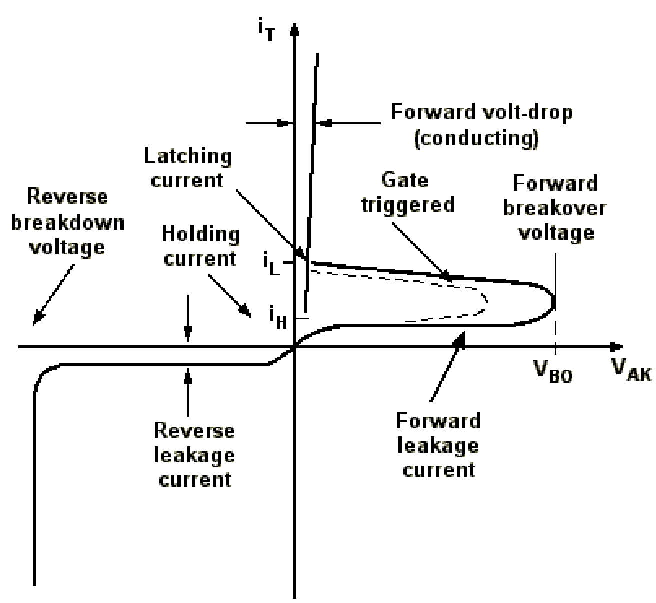
- A thyristor is a four layer pnpn semiconductor device
- It consists of three pn junctions namely J_1, J_2, and J3.
- It has three terminals: an anode a cathode and a gate.
- Thyristors are manufactured by diffusion.
- Figure below shows the thyristor symbol and a sectional view of the three pn junctions.



Thyristor Symbol & pn Junctions

I-V Characteristics:-

Figure below shows the I-V characteristics of thyristor.



Forward biasing:-

When the anode voltage is made positive with respect to the cathode, junctions $\mathbf{J_1}$ and $\mathbf{J_3}$ are forward biased and junction $\mathbf{J_2}$ is reverse biased. The thyristor is said to be in the *forward blocking* or *off-state condition*.

A small leakage current flows from anode to cathode and is called the *off-state current*.

If the anode voltage $\mathbf{V_{AK}}$ is increased to a sufficiently large value, the reverse biased junction $\mathbf{J_2}$ would breakdown. This is known as *avalanche breakdown* and the corresponding voltage is called the *forward breakdown voltage* $\mathbf{V_{BO}}$. Since the other two junctions $\mathbf{J_1}$ and $\mathbf{J_3}$ are already forward biased, there will be free movement of carriers across all three junctions. This results in a large forward current. The device is now said to be in a *conducting* or *on-state*. The voltage drop across the device in the on-state is due to the ohmic drop in the four layers and is very small.

Reverse biasing:-

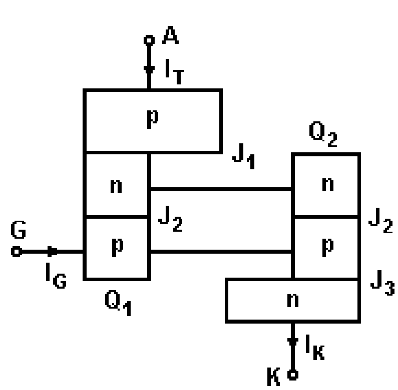
When the anode voltage is made negative with respect to the cathode, Junctions J_1 and J_3 are reverse biased whereas the junction J_2 is forward biased. The behavior of the thyristor here is similar to that of two diodes are connected in series with reverse voltage applied across them. As a result only a small leakage current of the order of a few μAmps flows. The device is now said to be in the *reverse blocking mode* or the *off-state*.

If the reverse voltage is now increased, then at a particular voltage, known as the *critical breakdown voltage* V_{BR}, junctions J_1 and J_3 breaks down and the reverse current increases rapidly. A large current associated with V_{BR} gives rise to more losses in the thyristor, which results in heating. This may lead to thyristor damage as the junction temperature may exceed its permissible temperature rise.

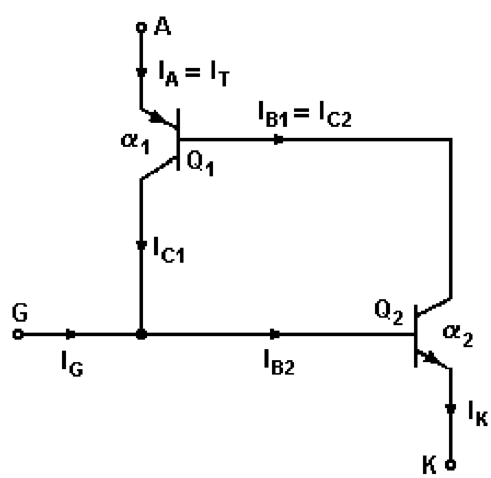
The important points on this characteristic are:

- **Latching Current $\mathbf{I_L}$:-** This is the minimum anode current required to maintain the thyristor in the on-state immediately after a thyristor has been turned on and the gate signal has been removed.
- **Holding Current $\mathbf{I_H}$: -** This is the minimum anode current required to maintain the thyristor in the on-state.
- **Reverse Current $\mathbf{I_R}$: -** When the cathode voltage is positive with respect to the anode, the junction J2 is forward biased but junctions $\mathbf{J_1}$ and $\mathbf{J_3}$ are reverse biased. The thyristor is said to be in the *reverse blocking state* and a reverse leakage current known as reverse current $\mathbf{I_R}$ will flow through the device.
- **Forward Breakover Voltage $\mathbf{V_{BO}}$: -** If the forward voltage $\mathbf{V_{AK}}$ is increased beyond $\mathbf{V_{BO}}$, the thyristor can be turned on. But such a turn-on could be destructive. In practice the forward voltage is maintained below $\mathbf{V_{BO}}$ and the thyristor is turned on by applying a positive gate signal between gate and cathode.

Two transistor analogy:-



(a) Basic structure



(b) Equivalent circuit

This model is used to demonstrate the regenerative or latching action due to positive feedback in the thyristor. A thyristor can be considered as two complementary transistors. One being pnp and the other npn. The two-transistor model is shown in figure above.

The collector current $\mathbf{I}_C$ of a transistor is related to the emitter current $\mathbf{I}_E$ and the leakage current of the collector base junction $\mathbf{I}_{CBO}$ as

$$I_C = \alpha I_E + I_{CBO} \qquad \text{............(1)}$$

The emitter current of transistor $\mathbf{Q}_1$ is the anode current $\mathbf{I}_A$ of the thyristor and collector current $\mathbf{I}_{C1}$ is given by

$$I_{C1} = \alpha_1 I_A + I_{CBO1} \qquad \text{............(2)}$$

Where, α_1 and $\mathbf{I}_{CBO1}$ are the current gain and leakage current respectively for transistor $\mathbf{Q}_1$.

Similarly, the collector current for transistor $\mathbf{Q}_2$ is $\mathbf{I}_{C2}$ where

$$I_{C2} = \alpha_2 I_k + I_{CBO2} \qquad \text{............(3)}$$

Where, α_2 and $\mathbf{I}_{CBO2}$ are the current gain and leakage current respectively for transistor $\mathbf{Q}_2$.

Combining the two collector currents $\mathbf{I}_{C1}$ and $\mathbf{I}_{C2}$ yields

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

$$I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \qquad \text{............(4)}$$

When a gate current $\mathbf{I}_G$ is applied to the thyristor

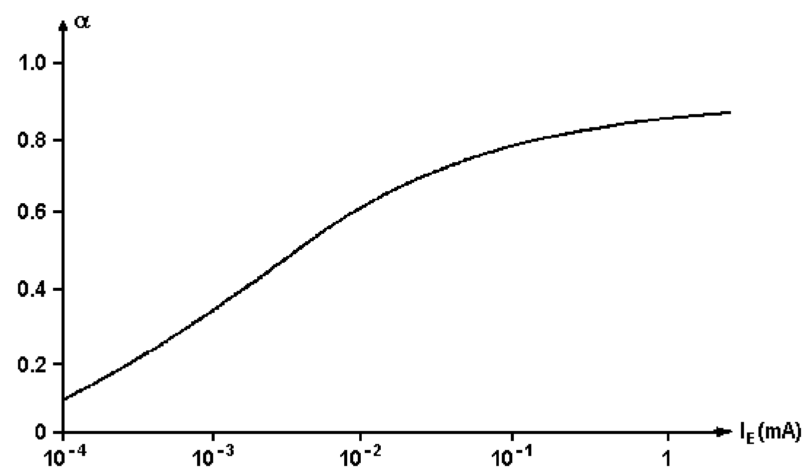
$$I_k = I_A + I_G \qquad \text{............(5)}$$

Solving for anode current $\mathbf{I}_A$ in equation 5 yields

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \qquad \text{............(6)}$$

The current gain α_1 varies with emitter current $\mathbf{I}_{E1}$ which is equal to $\mathbf{I}_A$; and α_2 varies with emitter current $\mathbf{I}_{E2}$ which is equal to $\mathbf{I}_k$.

A typical variation of current gain α with emitter current $\mathbf{I}_E$ is shown in figure below.



If the gate current I_G is increased from zero to some positive value, this will increase the anode current I_A as shown by equation 6. An increase of I_A which is an increase of I_{E1} would increase α_1 as shown in figure above and also α_2 since $I_{E2} = I_k = I_A + I_G$. The increase in values of both α_1 and α_2 would further increase the value of anode current I_A which is a *regenerative* or *positive feedback effect*.

If a1 and a2 approach unity, the denominator of equation 6 approaches zero and a large value of anode current is produced causing the thyristor to turn on as a result of the application of a small gate current.

Turn ON and turn OFF process:-

Thyristor turn ON:-

A thyristor is turned on by increasing the anode current,. This can be accomplished in one of the following ways.

1. **Thermal: -**

- When the anode terminal is positive with respect to cathode, Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- The width of depletion layer across junction J2 decreases with increase in junction temperature.
- By increasing the junction temperature the reverse biased junction J2 collapses thus the device starts to conduct.

2. **Light: -**

- When the anode terminal is positive with respect to cathode, Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- If light is allowed to strike on the junction J2 of a thyristor, the electron-hole pairs increase; and the thyristor may be turned on.
- These types of thyristors are called as LASCR.

3. **High voltage: -**

- When the anode terminal is positive with respect to cathode, Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- No current flows due to depletion region in J2 (except leakage current).
- As V_{AK} is further increased, at a voltage V_{BO} (Forward Break Over Voltage) the junction J2 undergoes avalanche breakdown and so a current flows and the device tends to turn ON.

4. **dv/dt method:-**

- When the device is forward biased, J1 and J3 are forward biased, J2 is reverse biased.
- Junction J2 behaves as a capacitor, due to the charges existing across the junction.
- If voltage across the device is V, the charge by Q and capacitance by C then,

  $ic = dQ/dt$

  $ic = d(CV) / dt$…………………($Q = CV$)

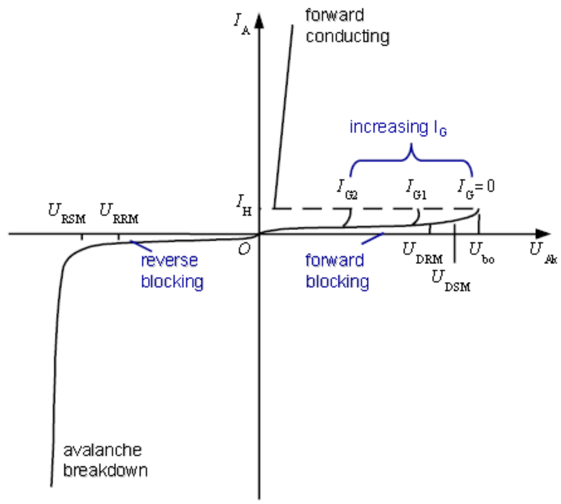
  $ic = C.\ dV/dt + V.\ dC/dt$

  as $dC/dt = 0$, $ic = C.dV/dt$

- 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.

5. **Gate current:**-

- This is most widely used Thyristor triggering method.
- When the anode terminal is positive with respect to cathode, Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- No current flows due to depletion region in J2 (except leakage current).
- 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 i.e. V_{BO} decreases.



Thyristor turn OFF:-

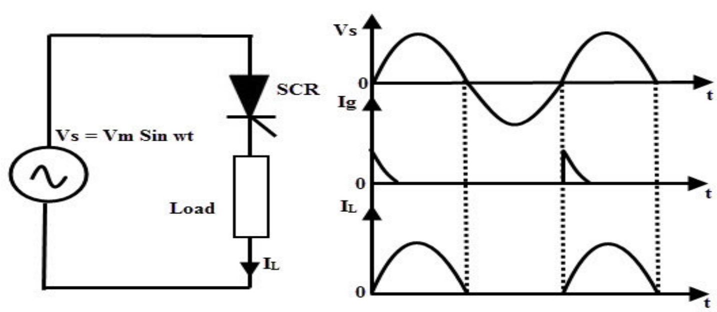
The turn OFF process of a thyristor is called **commutation**. The term commutation means the transfer of currents from one path to another. To turn OFF the conducting thyristor the below conditions must be satisfied.

- The anode or forward current of thyristor must be reduced to zero or below the level of holding current and then,
- A sufficient reverse voltage must be applied across the thyristor to regain its forward blocking state.

The commutation methods are classified into two major types.

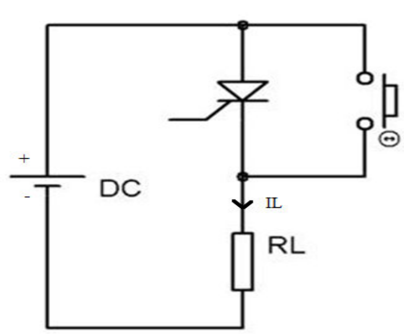
1. Natural Commutation:-

In natural commutation, the source of commutation voltage is the supply source itself. If the thyristor is connected to an AC supply, at every end of the positive half cycle the anode current goes through the natural current zero and also immediately a reverse voltage is applied across the thyristor. These are the conditions to turn OFF the thyristor. Therefore thyristor turns off.



2. Forced Commutation:-

In case of DC circuits, there is no natural current zero to turn OFF the thyristor. In such circuits, forward current must be forced to zero with an external circuit to commutate the thyristor hence named as forced commutation.



In above circuit, the thyristor is on then the forward current flows through it. When switch is pressed, the load current flows through the switch increases because of low resistance of switch. This decreases the forward current flowing through the thyristor below holding current and thyristor will turn off.

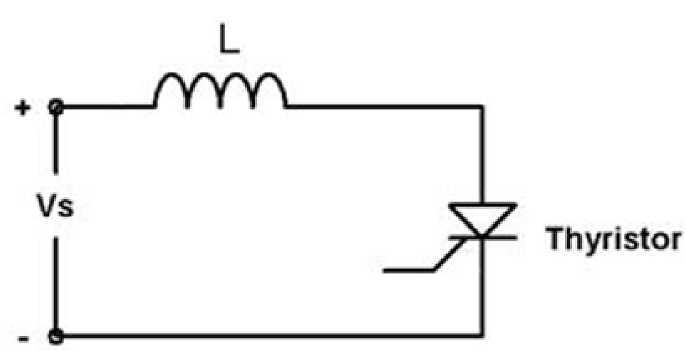
Thyristor rating:-

1. **Latching Current (I_L):** Latching current I_L is the minimum anode current required to maintain thyristor in ON state immediately after thyristor has been Turn ON and the gate signal has been removed
2. **Holding Current (I_H):** Minimum anode current below which device stop conducting and return to its off state usually this value is very small in mA.
3. **Forward Breakdown Voltage (V_{BO}):** If anode to cathode voltage VAK is increase to sufficient large value, the reverse bias junction J2 breaks this is known as Avalanche Breakdown and corresponding voltage is called as forward breakdown voltage V_{BO}.
4. **Reverse Breakdown Voltage (V_{BR}):** If reverse voltage is increased during reverse blocking and if Ig =0 then only reverse saturation current (Is) flows until the reverse voltage reaches reverse break down voltage (V_{BR}). At this point current starts rising sharply. Large reverse voltage and current generates excessive heat and destroys the device.
5. **dv/dt:** dv/dt rating of thyristor indicates maximum rate of rise of anode voltage that will not trigger the device without any gate signal.
6. **di/dt:** di/dt rating of thyristor indicates maximum rate of rise of anode to cathode current.
7. **Gate current to trigger (I_{GT}):** Minimum value of the gate current below which reliable turn on of the thyristor cannot be guaranteed. Usually specified at a given forward break over voltage.
8. **Gate voltage to trigger (V_{GT}):** Minimum value of the gate cathode forward voltage below which reliable turn on of the thyristor cannot be guaranteed. It is specified at the same break over voltage as IGT.

Concept of di/dt and dv/dt:-

di/dt Protection:-

- di/dt is the rate of change of current in a device.
- When thyristor 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 is created near the gate due to increased current density. This localized 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.

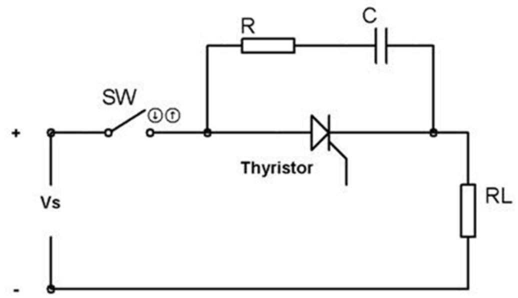


- The inductance L opposes the high di/dt variations.
- When the current variation is high, the inductor smoothes it and protects the thyristor from damage. (Though di/dt variation is high, the inductor 'L' smoothes it because it takes some time to charge).
  $L \geq [Vs / (di/dt)]$.

dv/dt Protection:-

- dv/dt is the rate of change of voltage in thyristor.
- We know that i_C=C.dv/dt. ie, when dv/dt is high, i_C is high.
- This high current(i_C) may turn ON thyristor even when gate current is zero. This is called as dv/dt turn ON or false turn ON of thyristor.
- To protect the thyristor against false turn ON or against high dv/dt a "Snubber Circuit" is used.

Snubber circuit:-

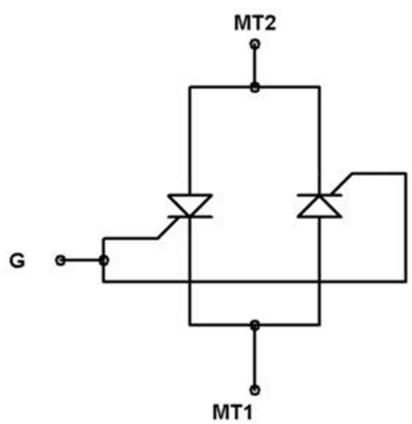


- The snubber circuit is a series combination of resistor 'R' and capacitor 'C'.
- They are connected across the thyristor to be protected.
- The capacitor 'C' is used to limit the dv/dt across the thyristor.
- The resistor 'R' is used to limit high discharging current through the thyristor.
- When switch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

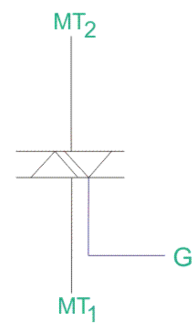
Triac:-

Introduction:-

Two thyristors are connected in inverse parallel with gate terminal as common. Gate terminals is connected to both the N and P regions due to which gate signal may be applied which is irrespective of the polarity of the signal. Here, we do not have anode and cathode since it works for both the polarities which means that device is bilateral. It consists of three terminals namely, main terminal 1(MT_1), main terminal 2(MT_2), and gate terminal G.



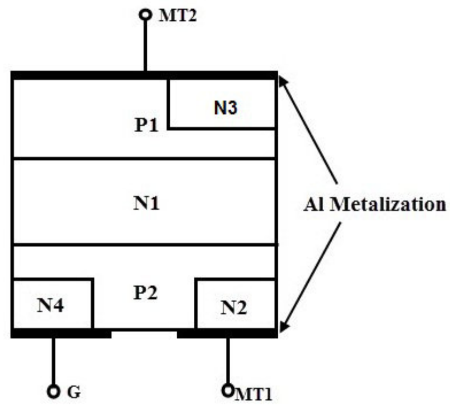
Two Thyristor Analogy



Symbol

Construction of Triac:-

A triac is a five layer, three terminal semiconductor device. The terminals are marked as MT1, MT2 as anode and cathode terminals in case of SCR. And the gate is represented as G similar to the thyristor. The gate terminal is connected to both N4 and P2 regions by a metallic contact and it is near to the MT1 terminal. The terminal MT1 is connected to both N2 and P2 regions, while MT2 is connected to both N3 and P1 regions. Hence, the terminals MT1 and MT2 connected to both P and N regions of the device and thus the polarity of applied voltage between these two terminals decides the current flow through the layers of the device.



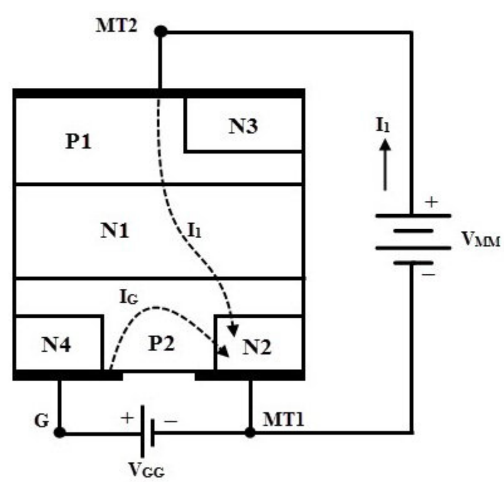
Operation of Triac:-

It is possible to connect various combinations of negative and positive voltages to the triac terminals because it is a bidirectional device. The four possible electrode potential combinations which make the triac to operate four different operating quadrants or modes are given as.

1. MT2 is positive with respect to MT1 with a gate polarity positive with respect to MT1.
2. MT2 is positive with respect to MT1 with a gate polarity negative with respect to MT1.
3. MT2 is negative with respect to MT1 with a gate polarity negative with respect to MT1.
4. MT2 is negative with respect to MT1 with a gate polarity positive with respect to MT1.

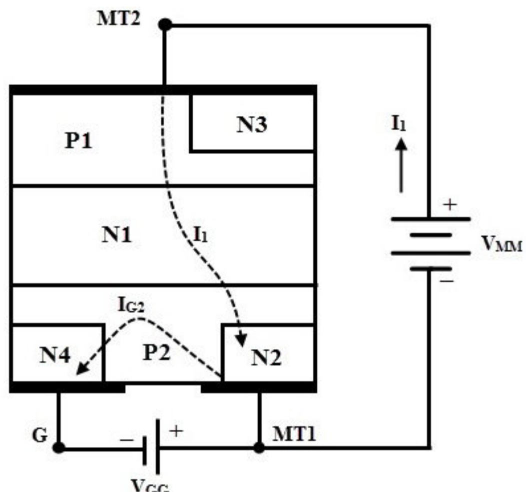
Mode 1: MT2 is Positive, Positive Gate Current:-

When the gate terminal is made positive with respect to MT1, gate current flows through the P2 and N2 junction. When this current flows, the P2 layer is flooded with electrons and further these electrons are diffused to the edge of junction J2 (or P2-N1 junction). These electrons collected by the N1 layer builds a space charge on the N1 layer. Therefore, more holes from the P1 region are diffused into the N1 region to neutralize the negative space charges. These holes arrive at the junction J2 and produce the positive space charge in the P2 region, which causes more electrons to inject into P2 from N2. This results a positive regeneration and finally the main current flows from MT2 to MT1 through the regions P1- N1 – P2 – N2.



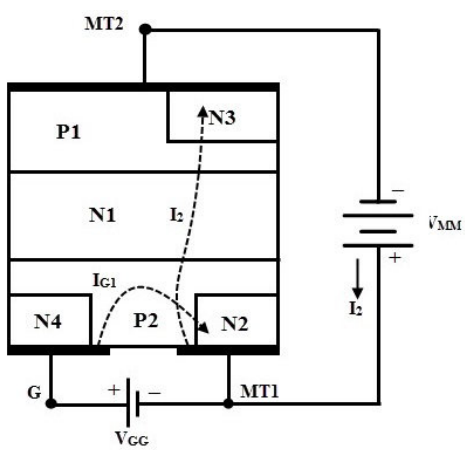
Mode 2: MT2 is Positive, Negative Gate Current:-

When MT2 is positive and the gate terminal is negative with respect to MT1, gate current flows through the P2-N4 junction. This gate current forward biases the P2-N4 junction for auxiliary P1N1P2N4 structure. This results the triac to conduct initially through the P1N1P2N4 layers. This further raises the potential between P2N2 towards the potential of MT2. This causes the current to establish from left to right in the P2 layer which forward biases the junction P2N2. And hence the main structure P1N1P2N2 begins to conduct. Initially conducted auxiliary structure P1N1P2N4 is considered as a pilot SCR while later conducted structure P1N1P2N2 is considered as main SCR. Hence the anode current of pilot SCR serves as gate current to the main SCR. The sensitivity to gate current is less in this mode and hence more gate current is required to turn the triac.



Mode 3: MT2 is Negative, Positive Gate Current:-

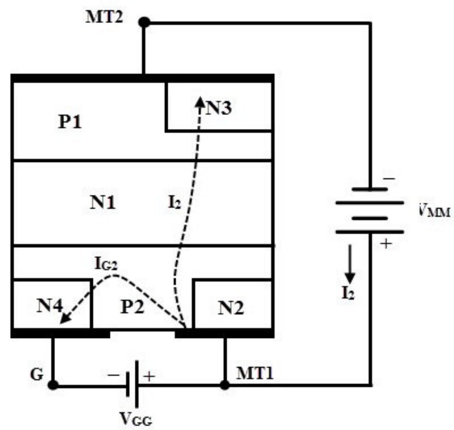
In this mode, MT2 is made negative with respect to MT1 and the device is turned ON by applying a positive voltage between the gate and MT1 terminal. The turn ON is initiated by N2 which acts as a remote gate control and the structure leads to turn ON the triac is P2N1P1N3. The external gate current forward biases the junction P2-N2. N2 layer injects the electrons into the P2 layer which are then collected by junction P2N1. This result to increases the current flow through P2N1 junction.



The holes injected from layer P2 diffuse through the N1 region. This builds a positive space charge in the P region. Therefore, more electrons from N3 are diffused into P1 to neutralize the positive space charges. Hence, these electrons arrive at junction J2 and produce a negative space charge in the N1region which results to inject more holes from the P2 into the region N1. This regenerative process continues till the structure P2N1P1N3 turns ON the triac and conducts the external current. As the triac is turned ON by the remote gate N2, the device is less sensitive to the positive gate current in this mode.

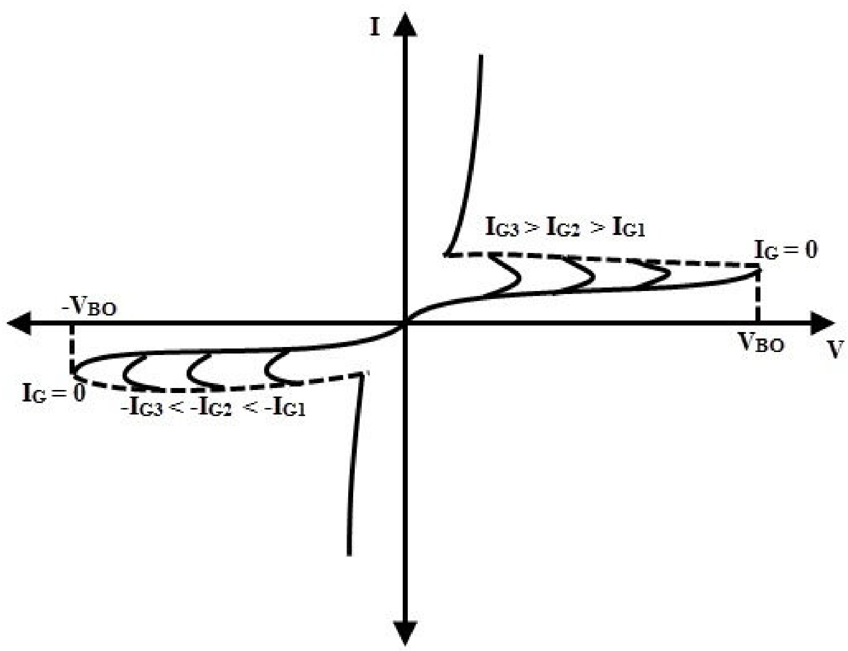
Mode 4: MT2 is Negative, Negative Gate Current

In this mode N4 acts as a remote gate and injects the electrons into the P2 region. The external gate current forward biases the junction P2N4. The electrons from the N4 region are collected by the P2N1 junction increase the current across P1N1 junction. Hence the structure P2N1P1N3 turns ON by the regenerative action. The triac is more sensitive in this mode compared with positive gate current in mode 3.



Characteristics of a Triac:-

The traic function like a two thyristors connected in anti-parallel and hence the VI characteristics of triac in the 1st and 3rd quadrants will be similar to the VI characteristics of a thyristors. When the terminal MT2 is positive with respect to MT1 terminal, the traic is said to be in forward blocking mode. A small leakage current flows through the device provided that voltage across the device is lower than the breakover voltage. Once the breakover voltage of the device is reached, then the triac turns ON as shown in below figure. However, it is also possible to turn ON the triac below the V_{BO} by applying a gate pulse in such that the current through the device should be more than the latching current of the triac.



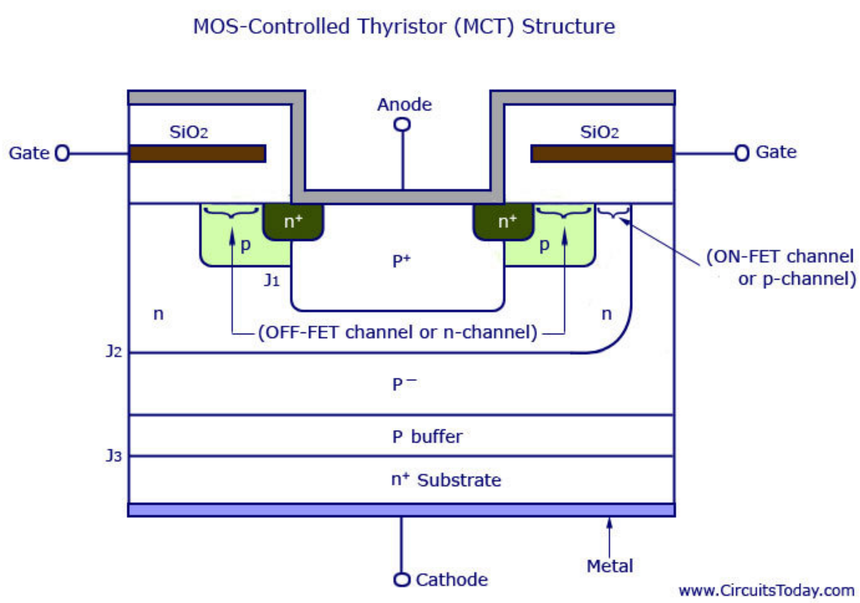
Similarly, when the terminal MT2 is made negative with respect to MT1, the traic is in reverse blocking mode. A small leakage current flows through the device until it is triggered by breakover voltage or gate triggering method. Hence the positive or negative pulse to the gate triggers the triac in both directions. The supply voltage at which the triac starts conducting depends on the gate current. If the gate is current is being greater, lesser will be the supply voltage at which the triac is turned ON. Above discussed mode -1 triggering is used in the first quadrant whereas mode-3 triggering is used in 3rd quadrant.

Triac rating:-

1. **Latching Current (I_L):** Latching current I_L is the minimum forward current required to maintain Triac in ON state immediately after Triac has been Turn ON and the gate signal has been removed
2. **Holding Current (I_H):** Minimum anode current below which device stop conducting and return to its off state usually this value is very small in mA.
3. **Forward Breakdown Voltage (V_{BO}):** If voltage across Triac is increase to sufficient large value, the reverse bias junction breaks this is known as Avalanche Breakdown and corresponding voltage is called as forward breakdown voltage V_{BO}.
4. **dv/dt:** dv/dt rating of Triac indicates maximum rate of rise of voltage that will not trigger the device without any gate signal.
5. **di/dt:** di/dt rating of Triac indicates maximum rate of rise of current through Triac.
6. **Gate current to trigger (I_{GT}):** Minimum value of the gate current below which reliable turn on of the Triac cannot be guaranteed. Usually specified at a given break over voltage.
7. **Gate voltage to trigger (V_{GT}):** Minimum value of the gate voltage below which reliable turn on of the thyristor cannot be guaranteed. It is specified at the same break over voltage as I_{GT}.

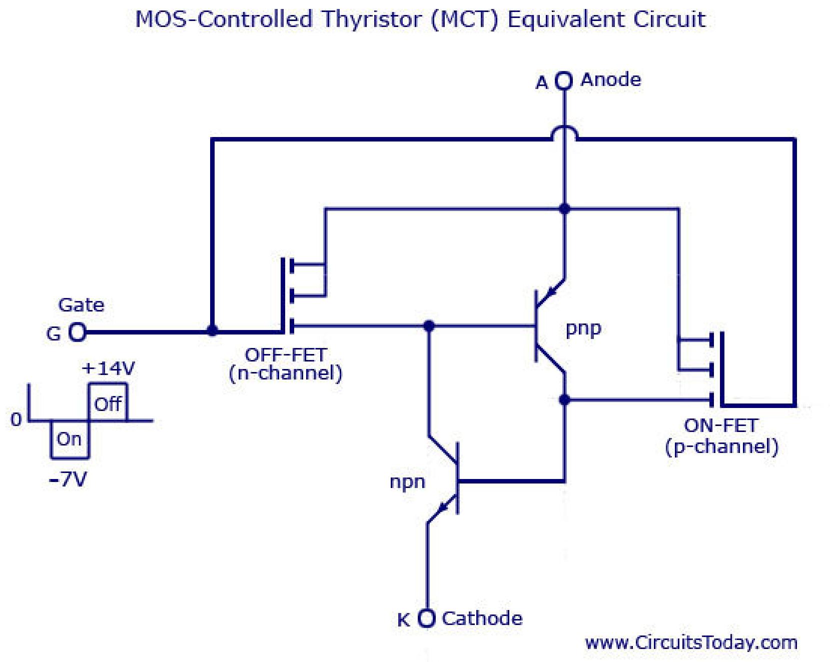
MOS controlled Thyristor (MCT):-

The device is basically a thyristor with two MOSFET's built into the gate structure. A MOSFET is used for turning ON the MCT and another one is used for turning it OFF. The device is mostly used for switching applications and has other characteristics like high frequency, high power, and low conduction drop and so on. An MCT combines the feature of both conventional four layer thyristor having regenerative action and MOS- gate structure. In this device, all the gate signals are applied with respect to anode, which is kept as the reference. In a normally used SCR, cathode is kept as the reference terminal for gate signals.
The basic structure of an MCT cell is shown in the figure below.

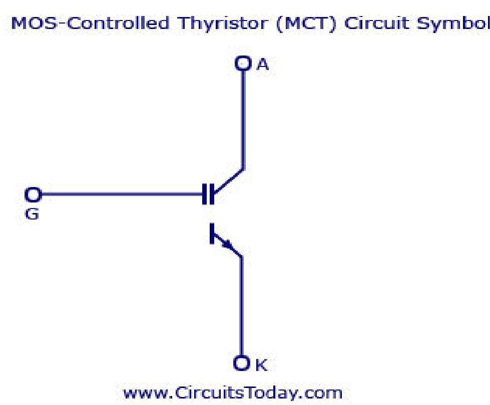


MOS Controlled Thyristor (MCT) Structure

In practice, a MCT will include thousands of these basic cells connected in parallel, just like a PMOSFET. This helps in obtaining a high current carrying capacity for the device. The equivalent circuit of the MCT is shown in the figure below.



It consists of an ON-FET, an OFF-FET and two transistors. The MOS structure of the MCT is represented in the equivalent circuit. It consists of one ON-FET, a p-channel MOSFET, and an OFF-FET. Both n-p-n and p-n-p transistors are joined together to represent the n-p-n-p structure of MCT. An n-channel MOSFET is represented by drawing the arrow towards the gate terminal. A p-channel MOSFET is indicated by drawing the arrow away from the gate terminal. The two transistors in the equivalent circuit indicate that there is regenerative feedback in the MCT just as it is an ordinary thyristor. The circuit symbol of MCT is shown below.



Turning ON Process:-

The device is turned ON by a negative voltage pulse at the gate with respect to the anode. For turning ON MCT, gate is made negative with respect to anode by the voltage pulse between gate and anode. So, MCT must be initially forward biased, and then only a negative voltage be applied. With the application of this negative voltage pulse, ON-FET gets turned ON whereas OFF-FET is already OFF. With ON-FET ON, current begins to flow from anode A, through ON-FET and then as the base current and emitter of n-p-n transistor and then to cathode K. This turns on n-p-n transistor. This causes the collector current to flow in n-p-n transistor. As OFF FET is OFF, this collector current of npn transistor acts as the base current of p-n-p transistor. Subsequently, p-n-p transistor is also turned ON. If both the transistors are ON, regenerative action of the connection scheme takes place and the MCT is turned ON.

Turning OFF process:-

The device is turned OFF by applying a positive voltage pulse at the gate. The positive voltage pulse causes the OFF-FET to turn ON and ON-FET to turn OFF. After OFF-FET is turned ON, emitter based terminals of p-n-p transistor are short circuited by OFF-FET. So, now anode current begins to flow through OFF-FET and thus base current of p-n-p transistor begins to decrease. The device has the disadvantage of reverse voltage blocking capability.

Advantages of MCT:-

1. Low forward conduction drop
2. Fast TURN-ON and then OFF times
3. Low switching losses
4. High gate input impedance