1.9 Commutation Circuit for SCR

To turn on a Thyristor, there are various triggering methods in which a trigger pulse is applied at its Gate terminal. Similarly, there are various techniques to turn Off a Thyristor, these techniques are called Thyristor Commutation Techniques. It can be done bybringing the Thyristor back into the forward blocking state from the forward conduction state. To bring the Thyristor into forward blocking state, forward current is reduced below the holding current level. For the purpose of power conditioning and power controla conducting Thyristor must be commutated properly.

There are mainly two techniques for Thyristor Commutation:

Natural Commutation- in ac circuits:

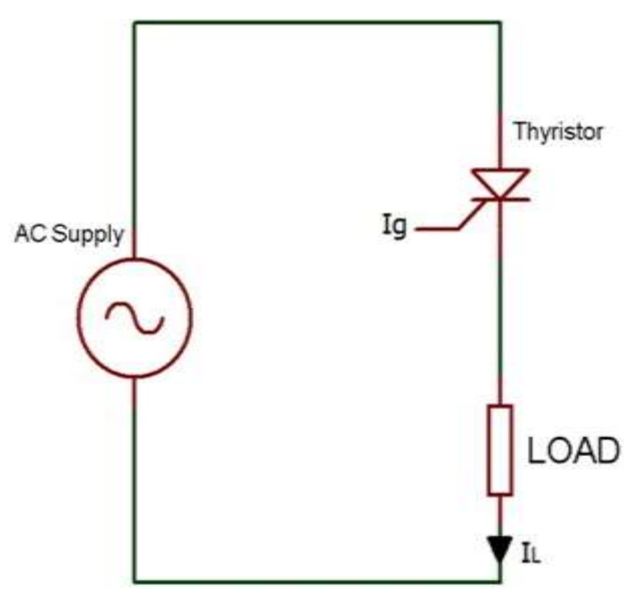


Figure 1.9.1 Natural Commutation

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 160]*

Natural Commutation

Natural Commutation occurs only in AC circuits, and it is named so because it occurs naturally and doesn't require any external circuit. When a positive cycle reaches to zero and the anode current is zero, immediately a reverse voltage (negative cycle) is applied across the Thyristor which causes the Thyristor to turn OFF.A Natural Commutation occurs in AC Voltage Controllers, Cycloconverters, and Phase Controlled Rectifiers.

Forced Commutation- in dc circuits

Forced commutation is classified into 5 types based on the commutation voltage generated as

1. Class A: Self or Load Commutation
2. Class B: Resonant-Pulse Commutation
3. Class C: Complementary Commutation
4. Class D: Impulse Commutation
5. Class E: External Pulse Commutation

Forced Commutation

As we know there is no natural zero current in DC Circuits like as natural commutation. So, Forced Commutation is used in DC circuits and it is also called as DC commutation. It requires commutating elements like inductance and capacitance to forcefully reduce the anode current of the Thyristor below the holding current value, that's why it is called as Forced Commutation. Mainly forced commutation is used in Chopper and Inverters circuits. Forced commutation is divided into six categories, which are explained below:

Class A: Self or Load Commutation

Class A is also called as "Self-Commutation" and it is one of the most used technique among all Thyristor commutation technique. In the below circuit, the inductor, capacitor and resistor form a second order under damp circuit.

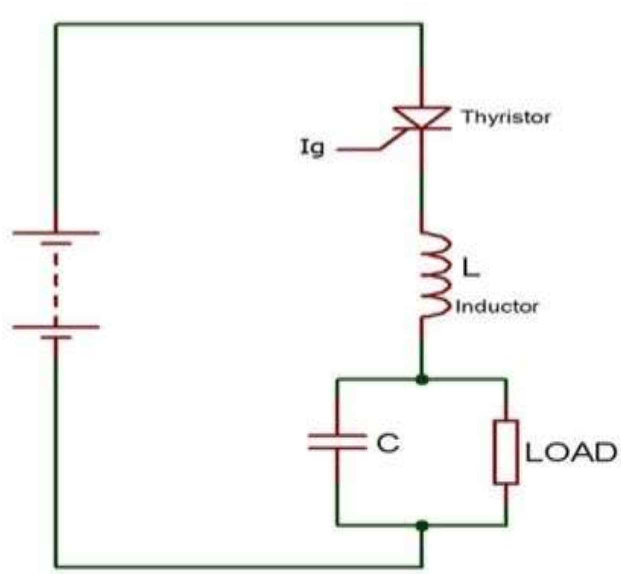


Figure 1.9.2 Class A: Self or Load Commutation

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 161]*

When we start supplying the input voltage to the circuit the Thyristor will not turn ON,as it requires a gate pulse to turn ON. Now when the Thyristor turns ON or forward biased, the current will flow through the inductor and charges the capacitor to its peakvalue or equal to the input voltage. Now, as the capacitor gets fully charged, inductor polarity gets reversed and inductor starts opposing the flow of current. Due to this, the output current starts to decrease and reach to zero. At this moment the current is below the holding current of the Thyristor, so the Thyristor turns OFF.

Class B: Resonant-Pulse Commutation:

Class B commutation is also called as Resonant-Pulse Commutation. There is only a small change between Class B and Class A circuit. In class B LC resonant circuit is connected in parallel while in Class A it's in series.

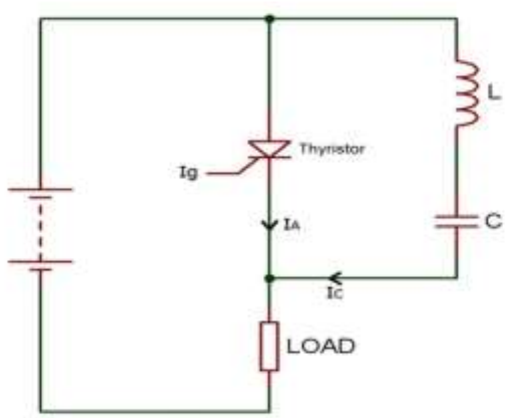


Figure 1.9.3 Class B: Resonant-Pulse Commutation

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 162]*

Now, as we apply the input voltage, the capacitor starts charging up to the input voltage (Vs) and Thyristor remains reversed biased until the gate pulse is applied. When we apply the gate pulse, the Thyristor turns ON and now the current start flowing from both the ways. But, then the constant load current flows through the resistance and inductance connected in series, due to its large reactance.

Then a sinusoidal current flow through the LC resonant circuit to charge the capacitor with the reverse polarity. Hence, a reverse voltage appears across the Thyristor, which causes the current Ic (commutating current) to oppose the flow of the anode current IA. Therefore, due to this opposing commutating current, when the anode current is getting lesser than the holding current, Thyristor turns OFF.

1.10 Introduction to Snubber and Driver Circuits

A snubber circuit limits or stops (snubs) switching voltage amplitude and its rate of rise, therefore reducing power dissipation. In its simplest form, a snubber circuit basically consists of a resistor and capacitor connected across the thyristor.

MOSFET DRIVE CIRCUIT

A driver circuit need to turn on the semiconducting devices. A MOSFET usually needs a gate driver to do the on/off operation at the desired frequency. For high frequencies, MOSFETs require a gate drive circuit to translate the on/off signals from an analog or digital controller into the power signals necessary to control the MOSFET. Since the MOSFET is a voltage-driven device, no DC current flows into the gate.In order to turn on a MOSFET, a voltage higher than the rated gate threshold voltage Vth must be applied to the gate. While in a steady on or off state, the MOSFET gate drive basically consumes no power. The gate-source capacitance of a MOSFET seenby the driver output varies with its internal state.MOSFETs are often used as switching devices at frequencies ranging from several kHz to more than several hundreds of kHz. The low power consumption needed for gate drive is an advantage of a MOSFET as a switching device. MOSFETs designed for low-voltage drive are alsoavailable.

The basic requirements for a MOSFET drive circuit include an ability to apply a voltage sufficiently higher than Vth to the gate and a drive capability to sufficiently charge the input capacitance. This section describes an example of a drive circuit for an N-channel MOSFET.

The below figure shows a basic MOSFET drive circuit. In practice, the capacitance of a MOSFET to be driven and its usage conditions must be considered in designing a drive circuit.

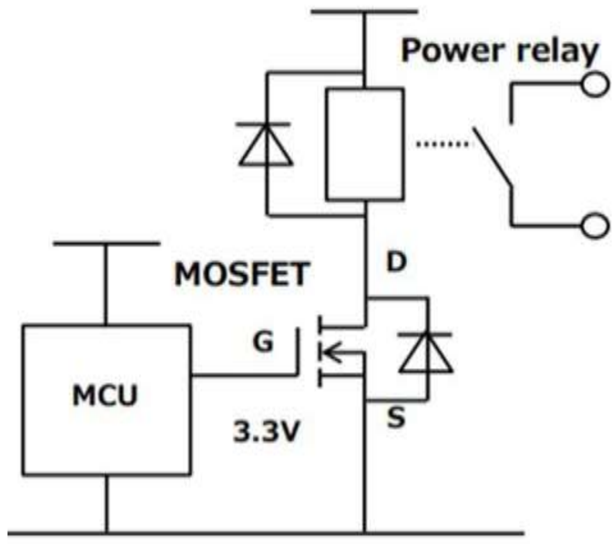


Figure 1.10.1 MOSFET drive circuit

[Source:"Power Electronics" byP.S.Bimbra,Khanna Publishers Page:23]

There is a growing need for MOSFETs for switching applications (load switches) to provide a conducting path in a circuit only when it is operated, and thereby reduce the power consumption of electronic devices. At present, MOSFETs are directly driven by a logic circuit or a microcontroller in many applications. Figure 2.2 shows an example of acircuit for turning on and off a power relay. Since turn-on and turn-off times may be as slow as a few seconds for load switches, the MOSFET gate can be driven with a small current.There are other ways of triggering MOSFET are using a high-voltage device and a bootstrap circuit, Pulse transformer drive (insulated switching) ,using a photo coupler and a floating power supply.

1.5 BIPOLAR JUNCTION TRANSISTOR

BJT is a 3-layer, 2-junction, 3-terminal npn or pnp semiconductor device. Bipolar= 2 polarities of charge carriers constitute the current flow in the device. There are 2 types, NPN and PNP. NPN type is widely used as they are easy to manufacture and cheaper.

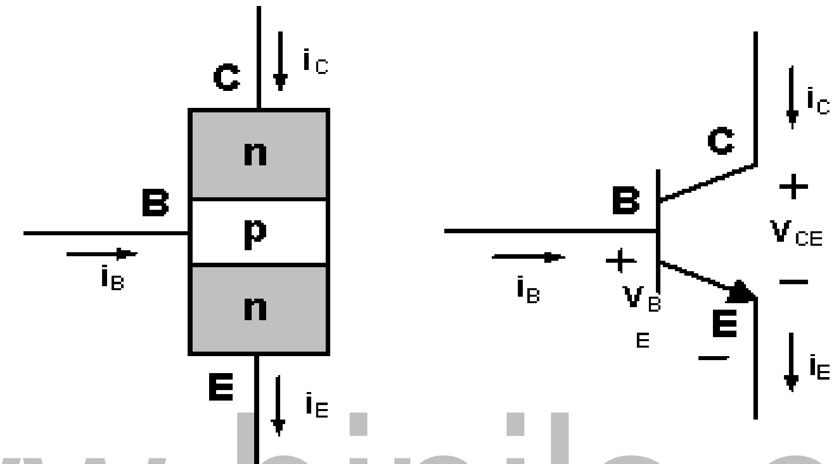


Figure 1.5.1 Symbol

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 11]*

CONSTRUCTION

A power transistor is a vertically oriented four-layer structure of alternating p-type and n-type. It helps in maximizing the cross-section area and results in higher current rating of BJT, minimize the on-state resistance, and thus reduce the power losses.

- It has an extra lightly doped (n-) region called as collector drift region in addition toNPN layers
- The n-layer increases the voltage blocking capacity of transistor which is needed isfast switching application in efficient power control
- The characteristics of the device is determined by the doping level in each of the layers and the thickness of the layers.

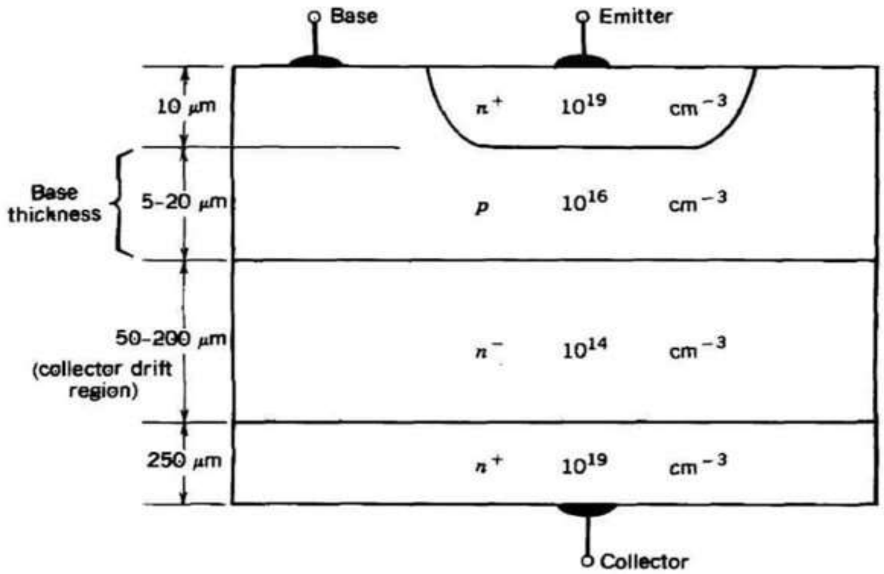


Figure 1.5.2 Structure of BJT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 11]*

The thickness of the drift region determines the breakdown voltage of the Powertransistor. The base thickness is made as small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised.

POWER BJT – VI CHARACTERISTICS

The VI characteristics of the Power BJT is different from signal level transistor. The major differences are Quasi saturation region & secondary breakdown region. The Quasi saturation region is available only in Power transistor characteristic not in signal transistors. It is because of the lightly doped collector drift region present in Power BJT. The primary breakdown is similar to the signal transistor's avalanche breakdown. Operation of device at primary and secondary breakdown regions should be avoided as it will lead to the catastrophic failure of the device.

Input characteristics

A graph between base current IB and base emitter voltage VBE is called as input characteristics. The base emitter region is a diode and hence the input characteristics resembles the V-I characteristics of a PN junction diode. Base current decreases as collector emitter voltage increases for the same base emitter voltage.

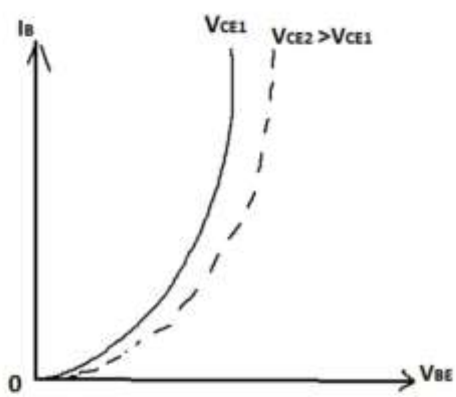


Figure 1.5.3 Input characteristics of BJT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 11]*

Output characteristics

A graph between collector current IC and collector emitter voltage VCE is called as output characteristics, Power BJT operates in four regions

- *Cutoff region-Both BE and CE junction must be reversed biased.*
- Active region-BE junction must be forward biased and CB reverse biased
- *Quasi-saturation region-Both forward biased.*
- Hard-saturation region-Both forward biased.

Quasi-saturation region

- Quasi saturation region is a new region in Power BJT due to lightly doped (n-) drift region. If the BJT is to be operated in high switching frequency, they operate in this region. It provides low resistance to voltage in on state than active region. Since it does not get into deep saturation we can turn on and off power BJT very quickly.

- In power handling and control purposes power BJT are generally used in cutoff for off state and quasi-saturation for on state to act as a switch.

Cut-off Region

- When the base current (IB) is zero, the collector current (IC) is insignificant and the transistor is driven into the cutoff region. The transistor is now in the OFF state.

- The collector–base and base–emitter junctions are reverse biased in the cutoff regionor OFF state, the transistor behaves as an open switch.

- In this region:IC= 0 and the collector–emitter voltage VCE is equal to the supply voltage VCC

Saturation Region

When the base current is sufficient to drive the transistor into saturation.During saturation, both junctions are forward-biased and the transistor acts like a closed switch.In the quasi saturation and hard saturation, the base drive is applied and transistor issaid to be on.

In this region: I(C)=VCC/RC and VCE=0.

Active Region

In the active region, the collector–base junction is reversed-biased and the base–emitter junction is forward-biased.

The active region of the transistor is mainly used for amplifier applications and shouldbe avoided for switching operation.

The power BJT is never operated in the active region (i.e. as an amplifier) it is alwaysoperated between cut-off and saturation.

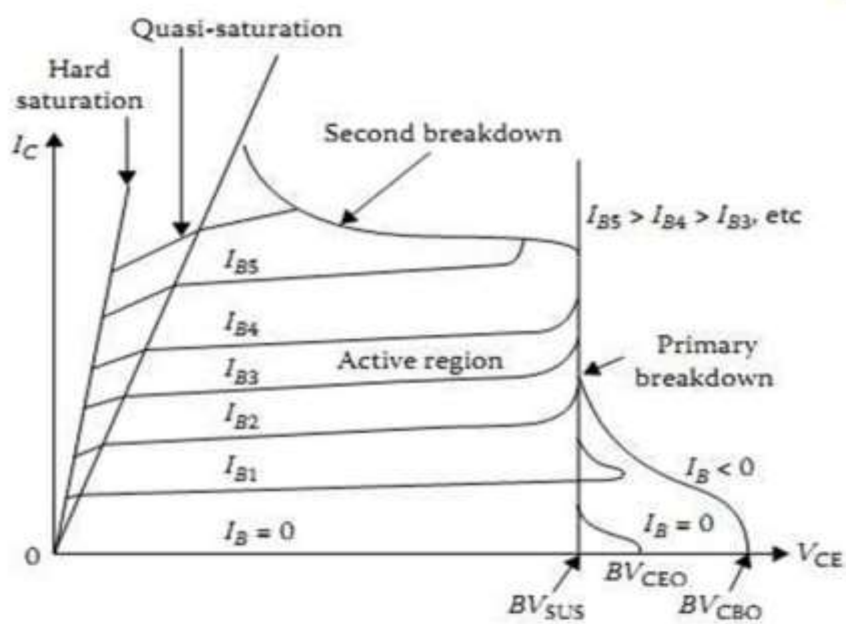


Fig 1.5.4 output characteristics of BJT

SWITCHING CHARACTERISTICS OF POWER BJT

Switching characteristics of power BJT is shown in Fig. As the positive base voltage is applied, base current starts to flow but there is no collector current for some time. This time is known as the delay time (td) required to charge the junction capacitance of the base to emitter to 0.7 V approx. (known as forward-bias voltage). For t > td, collector current starts rising and VCE starts to drop with the magnitude of 90% of its peak value. This time is called rise time, required to turn on the transistor. The transistor remains on so long as the collector current is at least of this value.

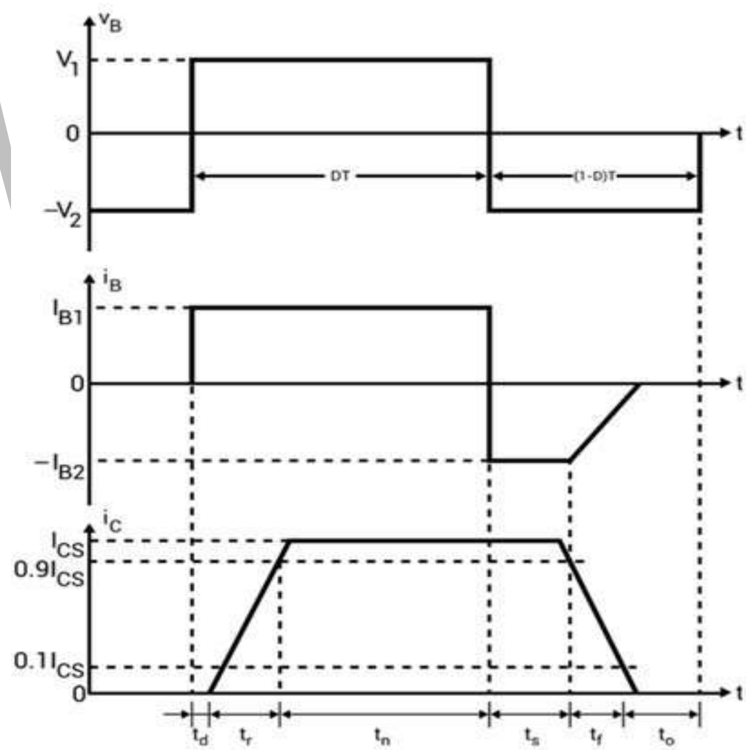


Fig 1.5.5 Switching characteristics of BJT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 15]*

For turning off the BJT, polarity of the base voltage is reversed and thus the base current polarity will also be changed as shown in Fig. The base current required during the steady-state operation is more than that required to saturate the transistor. Thus, excess minority carrier charges are stored in the base region which needs to be removed during the turn-off process. The time required to nullify this charge is the storage time ts. Collector current remains at the same value for this time. After this, collector current starts decreasing and base-to-emitter junction charges to the negative polarity, base current also get reduced.

APPLICATIONS OF POWER BJT

- SMPS (Switch mode power supply) used in computers.
- Final audio amplifier in stereo systems.
- Power amplifiers.
- DC to AC inverters.
- Relay and display drivers.
- AC motor speed controllers.
- control circuits.

1.4 Study of GTO

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.

- This reverse gate current amplitude is dependent on the anode current to be turned off.
- There is no need for an external commutation circuit to turn it off. So inverter circuitsbuilt by this device are compact and low-cost.
- The device is turned on by a positive gate current and it is turned off by a negativegate cathode voltage.

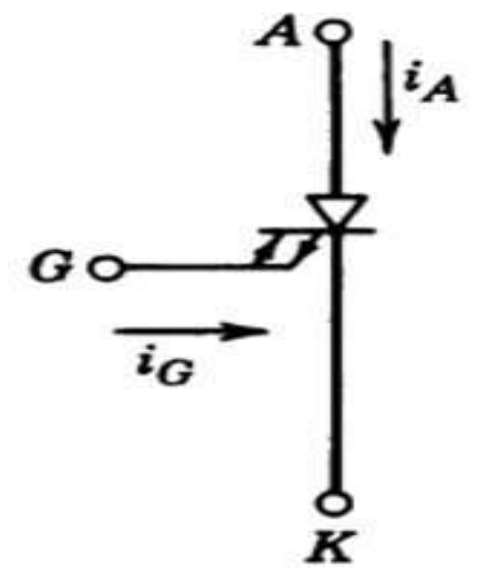


Fig 1.4.1 Symbol of GTO

[Source:“PowerElectronics”byP.S.Bimbra,KhannaPublishersPage:127]

The Symbol has three terminals namely Anode(A), Cathode(K) and Gate(G). The two-way arrow convention on the gate lead distinguishes the GTO from the conventional thyristor.

CONSTRUCTION

Consider the below structure of GTO, which is almost similar to the thyristor. It is alsoa four layer, three junction P-N-P-N device like a standard thyristor. In this, the n+ layer at the cathode end is highly doped to obtain high emitter efficiency. This result the breakdown voltage of the junction J3 is low which is typically in the range of 20 to40 volts.The doping level of the p type gate is highly graded because the doping level should be low to maintain high emitter efficiency, whereas for having a good turn OFF properties, doping of this region should be high. In addition, gate and cathodes should be highly interdigited with various geometric forms to optimize the currentturn off capability.

The junction between the P+ anode and N base is called anode junction. A heavily doped P+ anode region is required to obtain the higher efficiency anode junction so that a good turn ON properties is achieved. However, the turn OFF capabilities are affected with such GTOs. This problem can be solved by introducing heavily doped N+ layers at regular intervals in P+ anode layer as shown in figure. So this N+ layer makes a direct contact with N layer at junction J1. This cause the electrons to travel from base N region directly to anode metal contact without causing hole injection from P+ anode. This is called as a anode shorted GTO structure.Due to these anode shorts, the reverse blocking capacity of the GTO is reduced to thereverse breakdown voltage of junction j3 and hence speeds up the turn OFF mechanism.

However, with a large number of anode shorts, the efficiency of the anode junction reduces and hence the turn ON performance of the GTO degrades. Therefore, careful considerations have to be taken about the density of these anode shorts for a good turn ON and OFF performance.

PRINCIPLE OF OPERATION

The turn ON operation of GTO is similar to a conventional thyristor. When the anode terminal is made positive with respect to cathode by applying a positive gate current, the hole current injection from gate forward bias the cathode p-base junction. This results in the emission of electrons from the cathode towards the anode terminal. This induces the hole injection from the anode terminal into the base region. This injection of holes and electrons continuous till the GTO comes into the conduction state.

In case of thyristor, the conduction starts initially by turning ON the area of cathode adjacent to the gate terminal. And thus, by plasma spreading the remaining area comes into the conduction.

Unlike a thyristor, GTO consists of narrow cathode elements which are heavily inter digitated with gate terminal, thereby initial turned ON area is very large and plasma spreading is small. Hence the GTO comes into the conduction state very quickly.

TWO TRANSISTOR MODEL OF GTO OPERATION

The aspects of the Gate turnoff thyristor, GTO are very similar to that of the ordinary thyristor. In GTO, one PNP and one NPN transistor being connected in a regenerative configuration whereby once turned on the system maintains itself in this state.

When a potential is applied across the gate turn-off thyristor between the anode and cathode, no current will flow because neither device is turned on. Current would only flow if the voltage exceeded the breakdown voltage and current would flow as a result of avalanche action, but this mode would not suggested for normal operation. In this non-conducting state the gate turn-off thyristor is said to be in its forward blocking mode.

To turn the device on it is necessary to inject current into gate circuit of the device. When this is done, it turns on TR2 in the Fig. This pulls the collector of this transistor down towards the emitter voltage and in turn this turns on the other transistor TR1.

The fact that TR1 is now switched on ensures current flows into the base of TR2, and thus this feedback process ensures that once the gate turn-off thyristor like any other thyristor is turned on it remains on.The key capability of the gate turn-off thyristor is its ability to be turned off by the use of the gate electrode on the device.

The device turn off is achieved by applying a negative bias to the gate with respect to the cathode. This extracts current from the base region of TR2. The resulting voltage drop in the base starts to reverse bias the junction and thereby stopping the current flow in this transistor TR2.Which stops the injection into the base region of TR1 and this prevents current flow in this transistor.

When the overall current flow stops and the depletion layers around the junctions grow- the gate turn-off thyristor enters its forward blocking state again.

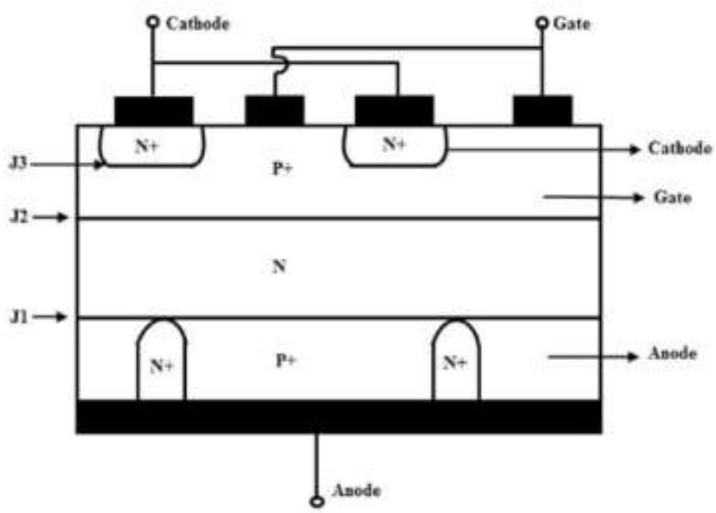


Fig. 1.4.2. Basic structure of GTO

[Source:“PowerElectronics”byP.S.Bimbra,KhannaPublishersPage:127]

Static VI characteristics of GTO

The static I-V characteristics of a GTO is identical with that of a conventional thyristor.If gate current is not able to turn on the GTO,it behaves like a high-voltage, low gain transistor with considerable anode current. This leads to a noticeable power loss under such conditions. In the reverse mode, reverse-voltage blocking capability of GTO is low, typically 20 to 30V, because of (i) anode shorts and (ii) large doping densities on both sides of reverse blocking junction J3

GATE TURN-ON:

The turn-on process in n GTO is similar to that of a conventional thyristor. Gate turn-on time for GTO is made up of delay time, rise time and spread time like a CT. Further, turn- on time in a GTO can be decreased by increasing its forward gate current as in a thyristor. In Fig. 1.15 (b), a steep-fronted gate pulse is applied to tum-on GTO. Gate drive can be removed once anode current exceeds latching current. However, some manufacturers advise that even after GTO is on, a continuous gate current, called back porch current should be applied during the entire on-period of GTO. The aim of this recommendation is to avoid any possibility of unwanted turn-off of the GTO.

GATE TURN-OFF:

The turn-off characteristics of a GTO are different from those of an SCR. Before the initiation of turn-off process, a GTO carries a steady current Ia. Fig. 15(b). This figure shows a typical dynamic turn-off characteristic for a GTO. The total turn-off 'time tq is subdivided into three different periods; namely the storage period (ts), the fall period (tf) and the tail period (tt).

In other words,

$t_q = t_s + t_f + t_t$

Initiation of turn-off process starts as soon as negative gate current begins to flow after t= 0 at instant A. The rate of rise of this gate current depends upon the gate circuit inductance L and the gate voltage applied. During the storage period, anode current Ia and anode voltage (equal to on-state voltage drop) remain constant. Termination of the storage period is indicated by a fall in If and rise in Va . During ts excess charges, i.e. holes, in p base are removed by negative gate current and the centre junction comes out of saturation. In other words, during storage time the negative gate current rises to a particular value and prepares the GTO for turning-off (or commutation) by flushing outthe stored carriers. After ts anode current begins to fall rapidly and anode voltage starts rising The anode current falls to a certain value and then abruptly changes its rate of fall. This interval during which anode current falls rapidly is the fall time tf Fig. 1.15 (b) and is of the order of 1second. The fall period tf is measured from the instant gate current is maximum negative to the instant anode current falls to its tail current.

At the time t = ts + tf there is a spike in voltage due to abrupt change in anode current. After tf anode current ia and anode voltage Va keep moving towards their turn-off valuesfor a time called tail time tt . After tf anode current reaches zero value and Va undergoes a transient overshoot due to the presence of Rs, Cs and then stabilizes to its off-state value equal to the source voltage applied to the anode circuit. Here Rs and Cs are the snubber circuit parameters. The turn-off process is complete when tail current reaches zero. The over shoot voltage and tail current can be decreased by increasing the size of Cs, but a compromise with snubber loss must be made. The duration off, depends upon the device characteristics.

APPLICATION OF GTO:

- GTOs are used in motor drives, static VAR compensators (SVCs) and AC/DC power supplies with high power ratings.

DISADVANTAGES OF GTO

Compared to a conventional SCR, the GTO has the following disadvantages:

1. Magnitude of latching, holding currents is more. The latching current of the GTO is
   several times more as compared to conventional thyristors of the same rating.
2. On state voltage drop and the associated loss is more.
3. Due to multi cathode structure of GTO, triggering gate current is higher than thatrequired for normal SCR.
4. Gate drive circuit losses are more. Its reverse voltage blocking capability is less thanthe forward voltage blocking capability.

ADVANTAGES OF GTO OVER BJT

Compared to BJT the GTO has the following advantages:

1. High blocking voltage capabilities
2. High over current capabilities
3. exhibits low gate currents
4. fast and efficient turn off
5. Better static and dynamic dv/dt capabilities

1.8 Study of IGCT

The Integrated Gate-Commutated Thyristor (IGCT) operates on the principle thatthyristors are ideal conduction devices whereas transistors are ideal turn-off devices. The IGCT therefore converts a thyristor structure to a transistor structure prior to turn- off by fast commutation of the cathode current and keeps it biased off with a 20 V source. This results in a device which dynamically and statically blocks like an IGBT (open-base pnp transistor producing the same turn-off losses) but conducts like a thyristor i.e. with about half the on-state voltage due to the greater plasma density produced by the two emitters. (pnp & npn transistors)

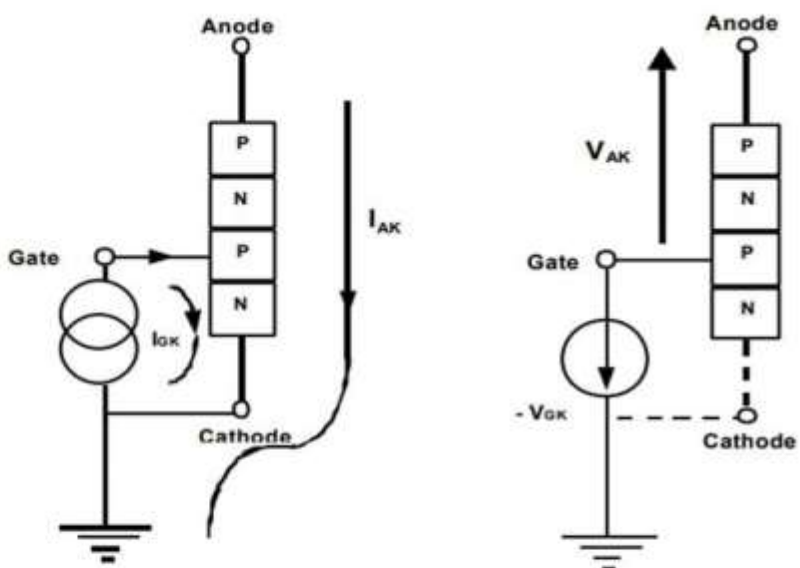


Fig 1.8.1 Symbol of IGCT

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 27]

IGCT is the new member in the power semiconductor family (1997). It was introduced by ABB. It is a special type of GTO thyristor. Similar to GTO, it is a fully controllable power switch. ie, It can be turned-On and turned-Off by applying a gate signal. It has lower conduction losses as compared to GTO thyristors. It withstands higher rates of voltage rise(dv/dt). So snubber circuits are not required for most of the applications.

STATIC AND SWITCHING CHARACTERISTICS OF IGCT

The structure of IGCT is very similar to a GTO thyristor.

In an IGCT, the gate turn-off current is greater than the anode current. This results in shorterturn-off times.The main difference compared with a GTO and thyristor is a reduction in cell size, combined with a much more substantial gate connection, resulting in a much lower inductance in the gate drive circuit and drive circuit connection.The very high gate currents and the fast di/dt rise of the gate current means that regular wires cannot be used to connect the gate drive to the IGCT.

TURN-ON

In the turn-on mode, GCT behaves exactly like a thyristor (or a GTO). This operation principle can be understood by considering the equivalent two-transistor model. The p+n− p and n+ p n− regions represent PNP and NPN transistors respectively. The anode of the GCT is connected to p+ region, which is the emitter of the PNP transistor. The collector of the PNP is connected to the gate of the NPN transistor and vice-versa, because of n− region neighboring the p region. The cathode of the GCT is connected to the n+ region, which is the emitter of the NPN transistor. This two-transistor model has two stable states, ON and OFF, which are determined by the gate control. When a current is supplied to the gate to turn on the GCT, the gate current flows to the cathode.

This turns on the NPN transistor and its collector current will now flow from the anode through the J1junction. The J1junction is the emitter of the PNP transistor; therefore,the collector current of the PNP is then the base current of the NPN.

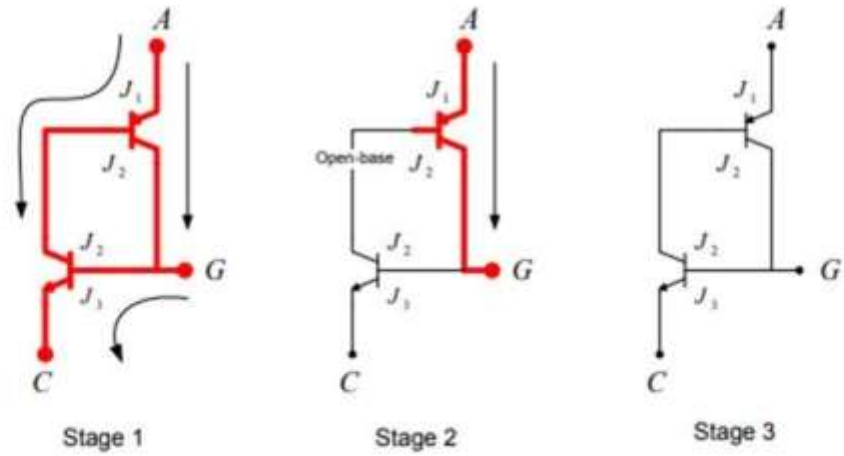


Fig 1.8.2 Turn on stages of IGCT

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 28]

The two transistors are connected in positive feedback allowing for a self-sustaining state called latch-up. This state is reached because the large current flowing between the anode and cathode is able to inject enough carriers into the base regions to keep the transistors saturated without the need of continuous gate current flow. Typical turn-on time for a GCT is about ≈ 10µs.

TYPES OF IGCT

These devices are available either with or without reverse blocking capability.IGCTs capable of blocking reverse voltage are known as symmetrical IGCTs. The typical application of symmetrical IGCTs is in Current Source Inverters (CSI).IGCTs incapable of blocking reverse voltage are known as asymmetrical IGCTs. They typically have a reverse breakdown rating in tens of volts or less. Such IGCTs are used where either a reverse conducting diode is applied in parallel or where reverse voltage would never occur. Asymmetrical IGCT can be fabricated with a reverse-conducting diode in the same package. These are known as reverse conducting (RC) IGCTs.

APPLICATIONS

The main applications of IGCT are in variable frequency inverters, drivers and traction. Multiple IGCTs can be connected in series or in parallel for higher power applications. The device has been applied in power system inter-tie installations (100MVA) and medium-power (up to 5MW) industrial drives.

1.7 INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

- IGBT is a voltage controlled device.
- It has high input impedance like a MOSFET and low on-state conduction losses like aBJT.
- IGBT has three terminals gate (G), collector (C) and emitter (E).
- With collector and gate voltage positive with respect to emitter the device is in forwardblocking mode.
- When gate to emitter voltage becomes greater than the threshold voltage of IGBT, an- channel is formed in the P-region.

Now device is in forward conducting state.

CONSTRUCTION OF IGBT

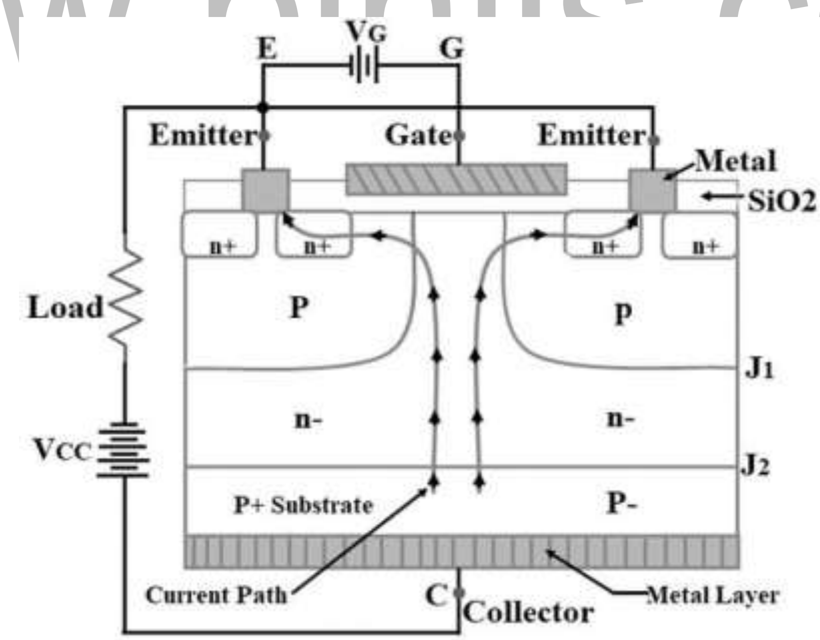


Figure 1.7.1 Structure of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 24]*

The structure of IGBT is very much similar to that of Power MOSFET, except one layer known as injection layer which is p+ unlike n+ substrate in PMOSFET. This p+ injectionlayer is the key to the superior characteristics of IGBT.It injects holes into n- layer. Thickness of n- layer decides the voltage blocking capability. Other layers are called the drift and the body region. The two junctions are labelled J1 and J2.

OPERATION OF IGBT

N-channel IGBT turns ON when the collector is at a positive potential with respect to emitter and gate also at sufficient positive potential (>VGET) with respect to emitter. This condition leads to the formation of an inversion layer just below the gate, leading to a channel formation and a current begins to flow from collector to emitter. This n- channel short circuits the n+ with n- emitter regions. Electrons from emitter n+ region flows to n- drift region through n-channel.

The collector current Ic in IGBT constitutes of two components- Ie and Ih. Ie is the current due to injected electrons flowing from collector to emitter through injection layer, drift layer and finally the channel formed. Ih is the hole current flowing from collector to emitter through Q1 and body resistance Rb.

Characteristics of IGBT

There are two characteristics

1.An output characteristic is a plot of collector current Ic versus collector to emitter voltage VCE for given values of gate to emitter voltage VGE

2.A plot of collector current Ic versus gate-emitter voltage VGE for a given value of VCE gives the transfer characteristic.

Controlling parameter is the gate-emitter voltage VGE in IGBT. If VGE is less than the threshold voltage VT then IGBT is in OFF state. If VGE is greater than the threshold voltage VT then the IGBT is in ON state.

The graph is similar to that of a BJT except that the parameter which is kept constant for a plot is VGE because IGBT is a voltage controlled device unlike BJT which is a current controlled device. When the device is in OFF mode (VCE is positiveand VGE < VGET) the reverse voltage is blocked by J2 and when it is reverse biased,i.e. VCE is negative, J1 blocks the voltage.

Transfer Characteristics of IGBT

Figure below shows the transfer characteristic of IGBT, which is exactly same as PMOSFET. The IGBT is in ON-state only after VGE is greater than threshold value VGET.

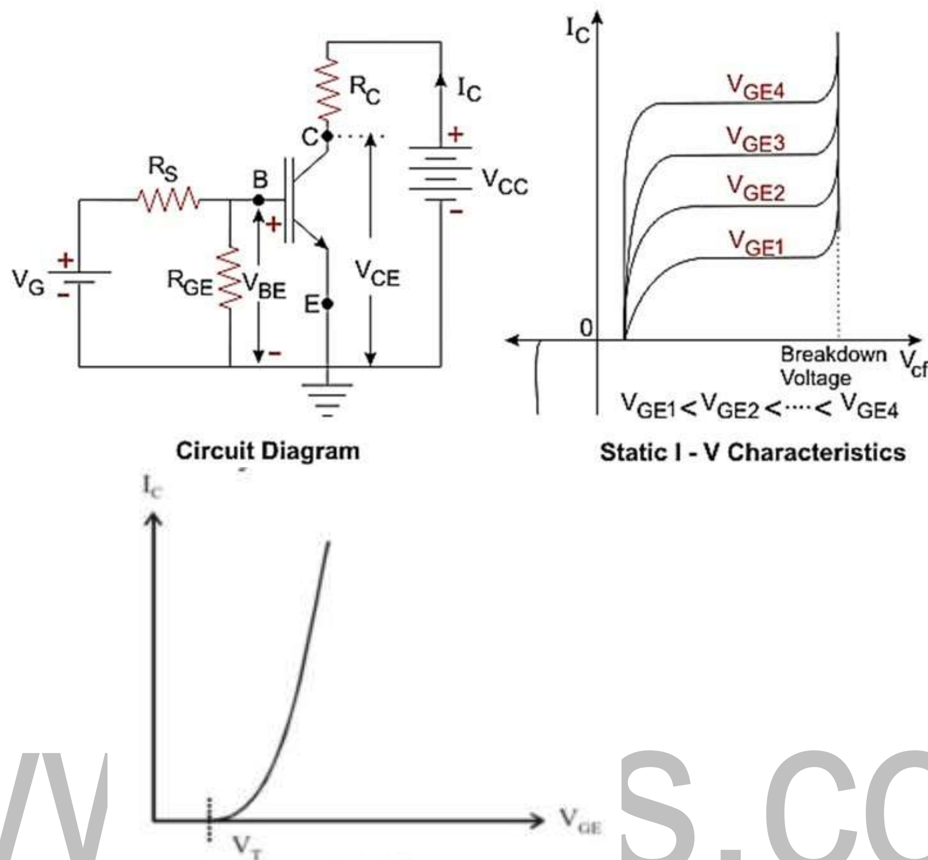


Figure 1.7.2 Characteristics of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra, Khanna Publishers *Page: 25]*

SWITCHING CHARACTERISTICS OF IGBT

After turn-on collector-emitter voltage VCE will be very small during the steady state conduction of the device.

• The turn off time toff consists of three components, delay time (tdf), initial fall time (tf1) and final fall time (tf2). Delay time is defined as time when collector current falls from IC to 0.9 IC and VGE falls to threshold voltage VGET and VCE begins to rise. Initial fall time is the time during which collector current falls from 0.9 IC to 0.2 IC and collector emitter voltage rises

0.1 VCE. The final fall time is defined as time during which collector current falls from 0.2 IC to 0.1 IC. During the turn-off time interval collector-emitter voltage rises to its final value VCE.

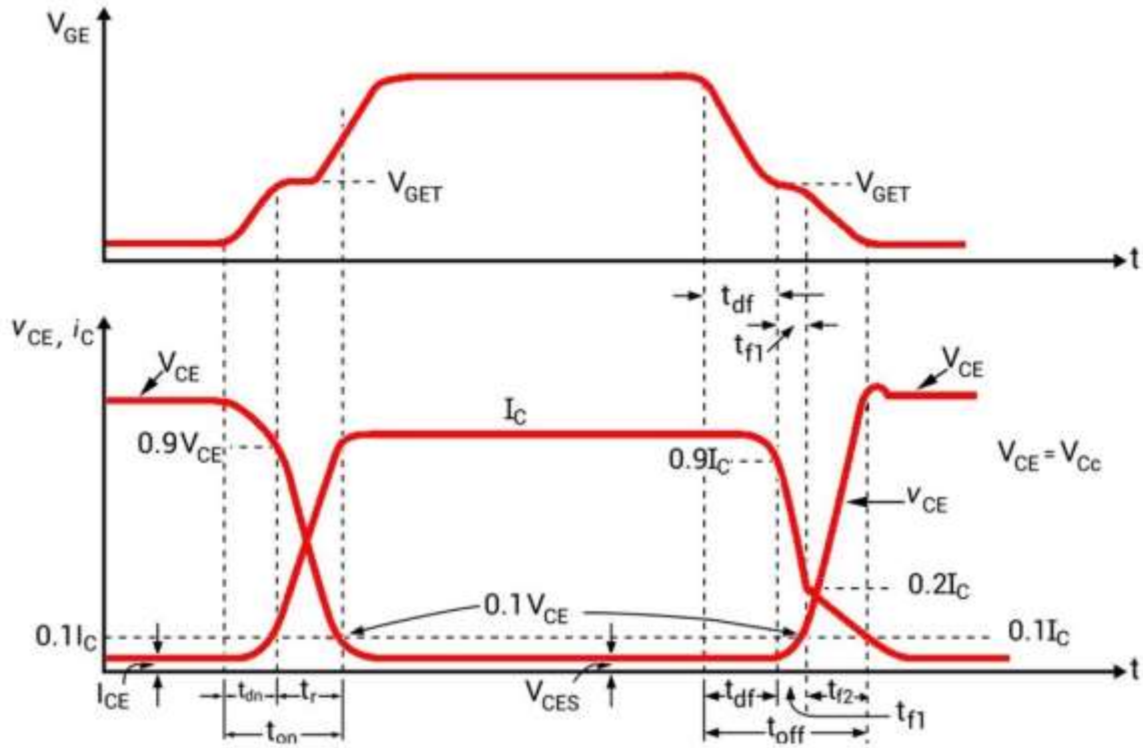


Figure 1.7.3 Switching Characteristics of IGBT

[Source: "Power Electronics" *by* P.S.Bimbra*,* Khanna Publishers *Page: 26]*

The gate drive circuit of an IGBT should ensure fast and reliable switching of the device. In particular, it should.

- Apply maximum permissible VgE during ON period.
- Apply a negative voltage during off period.
- Control dic/dt during turn ON and turn off to avoid excessive Electro magneticinterference (EMI).
- Control dvce dt during switching to avoid IGBT latch up.
- Minimize switching loss.
- Provide protection against short circuit fault.

IGBT APPLICATIONS

IGBT finds its use in Medium power applications like

1. DC and AC motor drives,
2. medium power supplies,
3. solid state relays and contractors,
4. general purpose inverters,
5. UPS,
6. welder equipments,
7. servo controls,
8. robotics,
9. cutting tools

1.6 Study of MOSFET

- MOSFET is metal oxide semiconductor field effect transistor.
- MOSFET is a three terminal device. The three terminals are gate (G), drain (D) andsource (S)
- MOSFET is a unipolar device as its operation depends on flow of majority charge carriersonly.
- It is a voltage controlled device requiring a small input gate voltage.
- It has high input impedance.
- MOSFET is operated in two states viz., ON STATE and OFF STATE.

A power MOSFET is a special type of metal oxide semiconductor field effect transistor. Itis specially designed to handle high-level powers. The power MOSFET's are constructed ina V configuration. Therefore, it is also called as V-MOSFET, VFET

Power MOSFETs are of two types

1. n- channel Enhancement MOSFETs
2. p- channel Enhancement MOSFETs

n-channel enhancement MOSFET is commonly used due to the higher mobility of electrons.

MOSFET CONSTRUCTION

Power MOSFETs are based on vertical structure, the doping and the thickness of the epitaxial layer decide the voltage rating while the channel width decides its current rating. This is the reason because of which they can sustain high blocking voltage and high current, making them suitable for low power switching applications.

The figure shows the planar diffused MOSFET structure for n-channel.

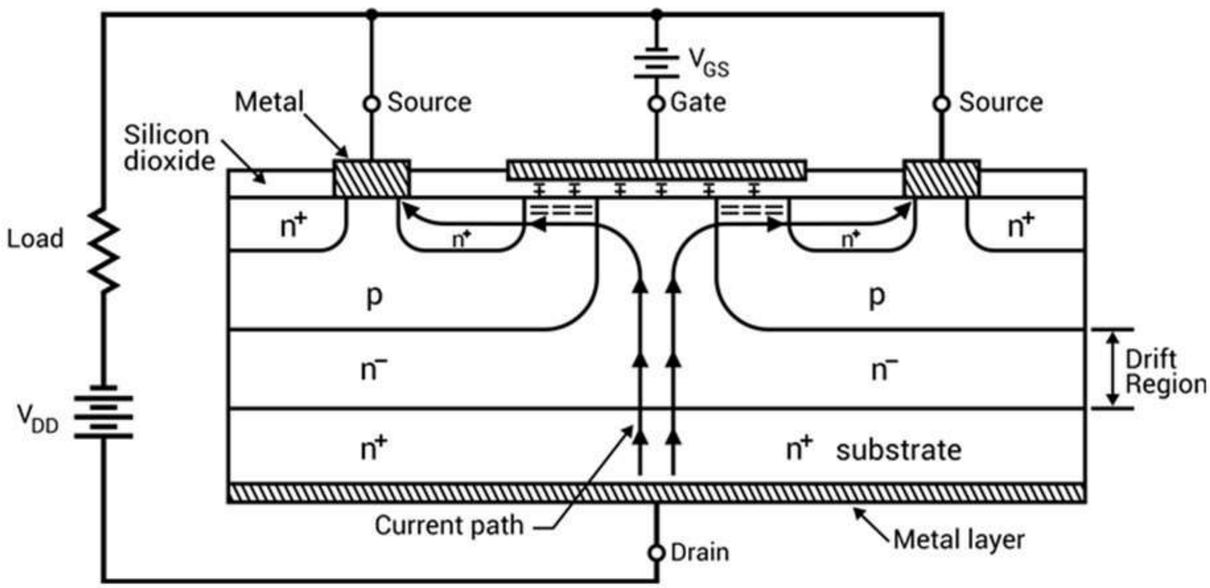


Fig 1.6.1 Structure of MOSFET

[Source: “Power Electronics” by P.S.Bimbra, Khanna Publishers Page: 21]

On n+ substrate, high resistivity n- layer is epitaxial grown. The thickness of n- layer decides the voltage blocking capability of the power Mosfets. The lightly doped n-type semiconductor forms the main body of the device. Two heavily doped p-type regions are there in the body separated by a certain distance L. Now there is a thin layer of silicon dioxide (SiO2) on the top of the substrate which behaves as a dielectric. There is an aluminum plate fitted on the top of this SiO2 dielectric layer.

Most importantly, here, the Source (S) terminal is placed over the Drain (D) terminal forming a vertical structure. As a result, in VDMOS the current flows beneath the gate area vertically between the source and the drain terminals through numerous n+ sources conducting in-parallel. As a result, the resistance offered by the device during its ON state RDS(ON) is much lower than that in the case of normal MOSFETs which enablethem to handle high currents.

OPERATION OF MOSFET

When gate circuit voltage is zero, and VDD is present, n- -p- junction is reverse biased and no current flows from drain to source. When gate terminal is made positive with respect to source, an electric field is established and electrons form an n channel. With gate voltage increased, drain current also increases.The length of n channel can be controlled.

If we apply a positive voltage at gate (G). This will create positive static potential at the aluminum plate of the capacitor. Due to capacitive action, electrons gets accumulated just below the dielectric layer Now if we further increase the positive voltage at thegate terminal, after a certain voltage called threshold voltage, due to the electrostatic force, covalent bonds of the crystal just below the SiO2 layer start breaking. Consequently, electron-hole pairs get generated there. By applying the positive voltage at gate, we can control the drain current.

VI CHARACTERISTICS OF MOSFET

MOSFET can be in any of the in three operating regions viz.,

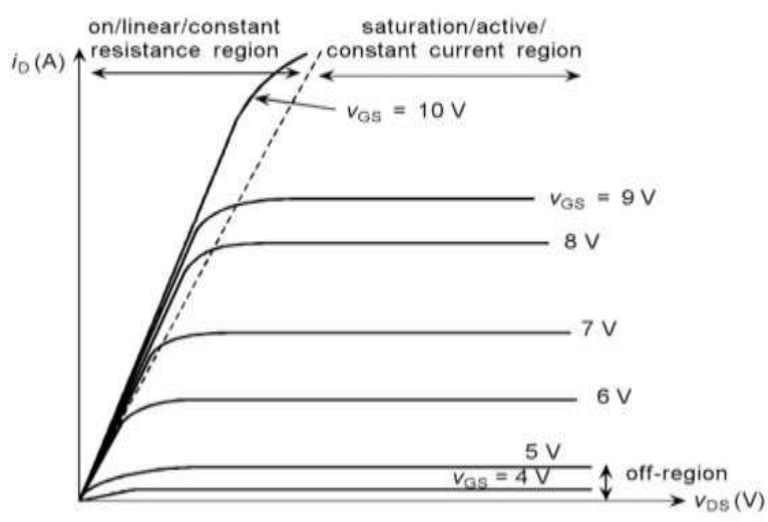


Fig 1.6.2 Characteristics of MOSFET

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 23]

Cut-Off Region

Cut-off region is a region in which the MOSFET will be OFF as there will be no current flow through it. In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.

Ohmic or Linear Region

Ohmic or linear region is a region where in the current IDS increases with an increase in the value of VDS. When MOSFETs are made to operate in this region, theycan be used as amplifiers.

Saturation Region

In saturation region, the MOSFETs have their IDS constant inspite of an increase in VDS and occurs once VDS exceeds the value of pinch-off voltage VP. Under this condition, the device will act like a closed switch through which a saturated value of IDS flows. As a result, this operating region is chosen whenever MOSFETs are required to perform switching operations.

From the transfer characteristics (drain-to-source current IDS versus gate-to-source voltage VGS), itis evident that the current through the device will be zero until the VGS exceeds the value of threshold voltage VT. This is because under this state, the device will be void of channel which will be connecting the drain and the source terminals. Under this condition, even an increase in VDS will result in no current flow as indicated by the corresponding output characteristics (IDS versus VDS). As a result this state represents nothing but the cut-off region of MOSFET's operation.

Next, once VGS crosses VT, the current through the device increases with an increasein IDS initially (Ohmic region) and then saturates to a value as determined by the VGS (saturation region of operation) i.e. as VGS increases, even the saturation current flowing through the device also increases. This is evident by Figure 1b where IDSS2 is greater than IDSS1 as VGS2> VGS1, IDSS3 is greater than IDSS2 as VGS3 >VGS2, so on and so forth. Further, Figure 1b also shows the locus of pinch-off voltage(black discontinuous curve), from which VP is seen to increase with an increase in VGS.

SWITCHING CHARACTERISTICS OF POWER MOSFET

The switching characteristics or the turn-on & turn-off times of the MOSFET are decidedby its internal capacitance and the internal impedance of the gate drive circuit. Turn on time is defined as the sum of turn on delay time and rise time of the device. Turn off time is the sum of turn off delay time and fall time

Turn ON Process:

A positive voltage is applied to the gate of MOSFET to turn e it on. When the gate voltage is applied, the gate to source capacitance CGS starts charging. When the voltage across CGS reached certain voltage level called Threshold voltage(VGST), the drain current ID starts rising.The time required to charge CGS to the threshold voltage level is known as turn ondelay time (td).The time required for charging CGS from threshold voltage to full gate voltage (VGSP). is called rise time (tr).During this period, the drain current rises to its full value, ie ID. Thus the MOSFET is fully turned ON.

The total turn-on time of MOSFET is

TON = tdon+ tr

The turn-on time can be reduced by using low-impedance gate drive source.

Turn OFF Process:

- To turn off the MOSFET, the gate voltage is made negative or zero.
- Due to this, the gate to source voltage then reduces from VI to VGSP.
- As MOSFET is a majority carrier device, turn-off process is initiated soon after removal of gate voltage at time t1.
- That is, CGS discharges from gate voltage V1 to VGSP. The time required for thisdischarge is called turn-off delay time (td(off))
- During this period, the drain current also starts reducing.
- The CGS keeps on discharging and its voltage becomes equal to threshold voltage(VGST).

- The time required to discharge CGS from VGSP to VGST is called fall time (tf). The drain current becomes zero when VGS < VGST. The MOSFET is then said to be have turned-off.
- Thus the total turn-off time of MOSFET is $T_{OFF} = t_{(d(off))} + t_f$

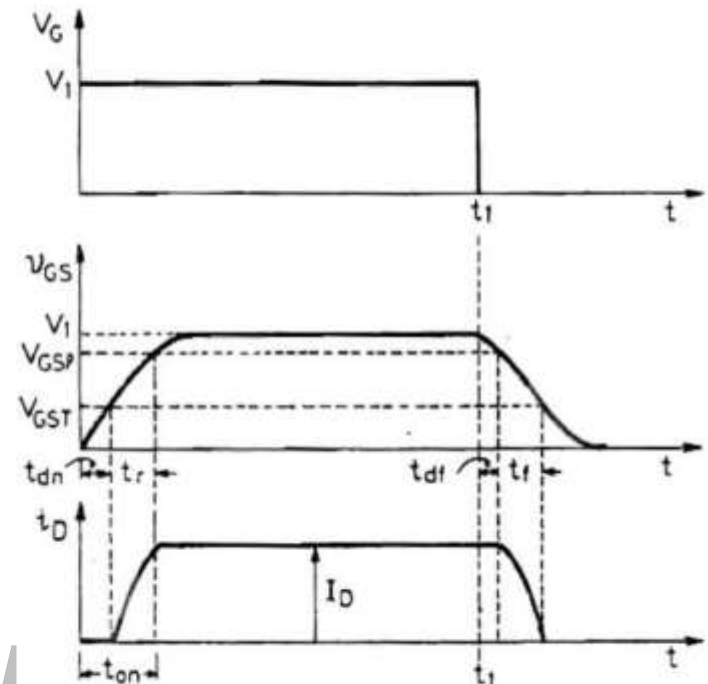


Fig.1.6.3 turn on and off characteristics of MOSFET

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 23]

Applications of POWER MOSFET

Power MOSEFET technology is applicable to many types of circuit.

1. Linear power supplies
2. Switching power supplies
3. DC-DC converters
4. Low voltage motor control

1.2 Study of SCR (Thyristor)

The name 'thyristor ', is derived by a combination of the capital letters from **THYRatr on** and **transistor.** SCRs are solid state devices, they are compact, possess high reliability and have low loss. Because of these useful features, SCR is almost universally employed these days for all high power-controlled devices. Thyristor is a four layer, three-junction, p -n-p –n semiconductor switching device. It has three terminals; anode, cathode and

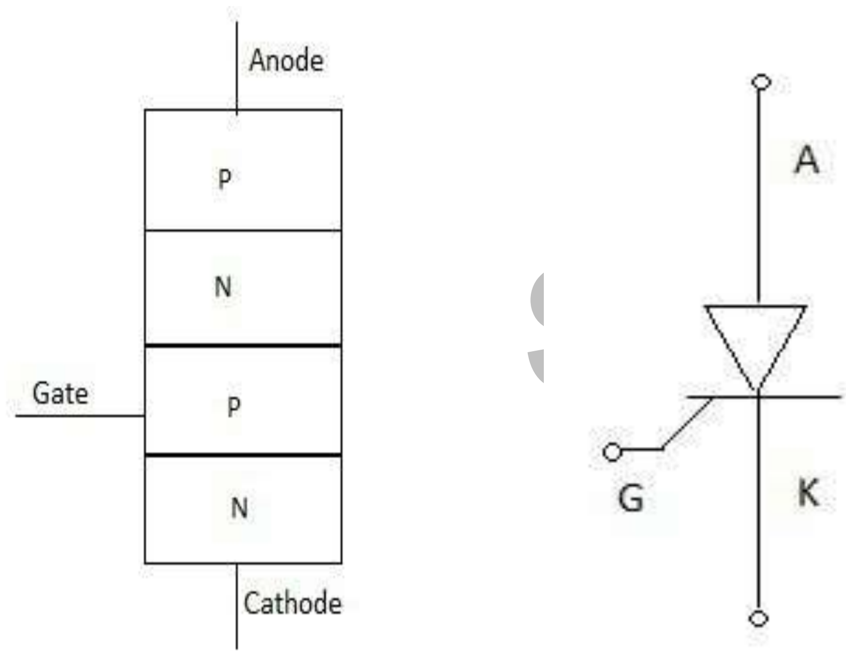


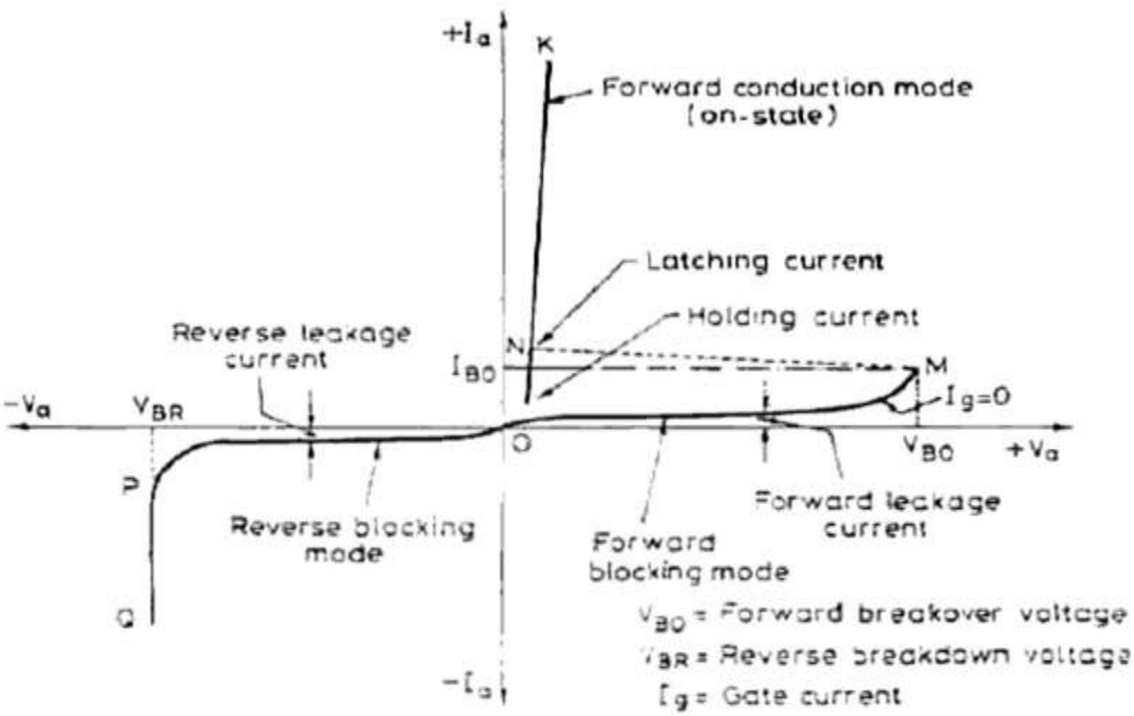
Fig 1.2.1 (a) Layer Structure (b) Symbol

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 63]

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.

Static V-I characteristics of a Thyristor:

The circuit diagram for obtaining static V-I characteristics is as shown. Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source ES.A typical SCR V-I characteristic is as shown below:



V_{BO}=Anode voltage across the thyristor terminal A,K.

Ig =Gate current

Va =Anode voltage across the thyristor terminal A,K.

Ia =Anode current

SCR have 3 modes of operation:

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

Reverse Blocking Mode

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased.junctions J1 and J2 are reverse biased where junction j2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.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 J1 and J3.and the reverse current increases rapidly. As a large current 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.

2. Forward Blocking Mode

When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased.Thus junction J1 and J3 are forward biased and J2 is reverse biased. As the forward voltage is increases junction J2 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.

3. Forward Conduction Mode

Here 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:

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

During forward conduction mode of operation thyristor is in on state and behave 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.

Different turn ON methods for SCR

1. Forward voltage triggering
2. Gate triggering
3.dv/dt triggering
4. Light triggering
5. Temperature triggering

1.Forward voltage triggering

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

- Junction J1 and J3 is forward biased.
- Juntion J2 is reverse biased.
- As the anode to cathode voltage is increased breakdown of the reverse biased junction J2 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 Ia will not go below I_h. Where I_h is the holding current for the thyristor.

2. 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 final voltage rating of the device during the design of SCR application. First step is to choose a thyristor with forward breakover voltage (say 800V) higher than the normal working voltage.

The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with 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 that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n- layer. Now the thyristor is forward biased, so some of these electron reach junction J2.

As a result width of J2 breaks down or conduction at J2 occur at a voltage less than V_{BO} .As Ig increases V_{BO} reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that 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.

3.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 J1 and J3 are forward biased and junction J2 is reversed biased so it behaves as if an insulator is place between two conducting plate. Here J1 and J3 acts as a conducting plate and J2 acts as an insulator. J2 is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction J2 breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from high dv/dt.

$$q = cv$$

$$I_a = c\frac{dv}{dt}$$

$$I_a \, \alpha \, \frac{dv}{dt}$$

4. Temperature triggering

During forward biased, J2 is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat decipitation of junction J2 occurs. When this heat reaches a sufficient value J2 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.

5. 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).

1.1 Study of Switching Device

It is one of the contemporary subjects of electrical engineering which has seen a lot of advancements in recent times and has impacted human life in almost every sphere. We use many power electronic applications in our daily life, without even realizing it. Now the question in front of us is, “what is power electronics?”

Introduction about Power electronics

Power electronics can be defined as the hybrid of power engineering, analogue electronics. We derive the fundamentals of each subject and apply it in an amalgamated way so as to get a regulated form of electrical energy. Electrical energy in itself is not usable until it is converted into a tangible form of energy such as motion, light, sound, heat etc. In order to regulate these forms of energy, an effective way is to regulate the electrical energy itselfand this forms the content of the subject power electronics. We can trace the overwhelming advancement in the subject back to the development of commercial thyristors or silicon controlled rectifiers (SCR) by General Electric Co. in 1958. Before this the control of electrical energy was mainly done using thyratrons and mercury arc rectifiers which works on the principle of physical phenomena in gases and vapors.

After SCR, many power electronic devices have emerged like GTO, IGBT, SIT, MCT, TRIAC, DIAC, IEGT, IGCT and so on. These devices are rated for several hundreds of volt and ampere unlike the signal level devices which work at few volts and mill amperes.

In order to achieve the purpose of power electronics, the devices are made to work as nothing more than a switch. All the power electronic devices act as a switch and have two modes, i.e. ON and OFF.

For example, a BJT (Bipolar Junction Transistor) has three regions of operation in its output characteristics cut-off, active and saturation. In analogue electronics where the BJT is supposed to work as an amplifier, the circuit is so designed to bias it in active region of operation. However in power electronics BJT will work in cutoff region when it is OFF and in saturation region when it is ON.

Now that the devices are required to work as a switch, they must follow the basic characteristic of a switch, i.e. when the switch is ON, it has zero voltage drop

Figure 1.1.1 Ideal switch

[Source:"PowerElectronicsCircuits,DevicesandApplications"byM.H.Rashid,Page:4]

across it and carries full current through it, and when it is in OFF condition, it has full voltage drop across it and zero current flowing through it. The figure below depicts the above statement.

Now since in both the mode either of the quantity V or I is zero, the switch power also turns out to be zero always. This characteristic is easy to visualize in a mechanical switch and the same has to be followed in power electronic switch also.

However practically there always exists a leakage current through the devices when in OFF condition, i.e I leakage ≠ 0 and there is always a forward voltage drop in ON condition, i.e Von ≠ 0. However the magnitude of Von or I leakage is very less and hence the power across the device is also very less, in order of few mill watts. This power is dissipated in the device and hence proper heat evacuation from the device is an important aspect. Apart from this ON state and OFF state losses, there are switching losses also in power electronic devices. This is mainly while the switch toggles from one mode to another and V and I across the device changes.

In power electronics both the losses are important parametersof any device and essential in determining its voltage and current ratings. The power electronic devices alone are not that useful in practical applications and hence require to be designed with a circuit along with other supporting components. These supporting components are like the decision making part which controls the power electronic switches in order to achieve the desired output. This includes the firing circuit and the feedback circuit. The block diagram below depicts a simple power electronic system.

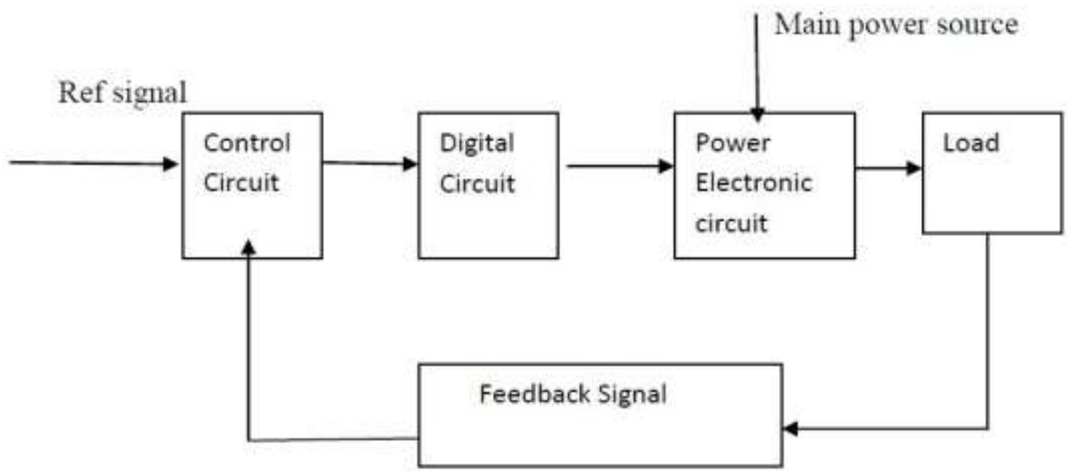


Figure 1.1.2 Power Electronic system

[Source:"Power Electronics" byP.S.Bimbra,Khanna Publishers Page:3]

Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices have been improved tremendously.

The Control Unit takes the output feedback from sensors and compares it with references and accordingly gives input to the firing circuit. Firing circuit is basically a pulse generating circuit which gives pulse output in a fashion so as to control the power electronic switchesin the main circuit block.

The net result is that the load receives the desired electrical power and hence delivers the desired result. A typical example of the above system would be speed control of motors.You can learn more about power electronics by studying our basic electronics questions. Majorly there are five types of power electronic circuits, each having different purposes-

1. Rectifiers – converts fixed AC to variable DC (such as half wave rectifiers or fullwave rectifiers)
2. Choppers – converts fixed DC to variable DC
3. Inverters – converts DC to AC having variable amplitude and variable frequency
4. Voltage Regulators – converts fixed AC to variable AC at same input frequency
5. Cyclo converters – converts fixed AC to AC with variable frequency

Power Semiconductor Devices

The first SCR was developed in late 1957. Power semiconductor devices are broadly categorized into 3 types:

1. Power diodes

2.Transistors

3.Thyristors

1.3 Study of TRIAC

Triacs are electronic components that are widely used in AC power control applications. They are able to switch high voltages and high levels of current, and over both parts of an AC waveform. This makes triac circuits ideal for use in a variety of applications wherepower switching is needed.

An SCR is a unidirectional device as it can conduct from anode to cathode only and not from cathode to anode. A triac can, however, conduct in both the directions. A triac is thus a bidirectional thyristor with three terminals. It is used extensively for the controlof power in ac circuits . Triac is the word derived by combining the capital letters from the words TRIode and AC. When in operation, a triac is equivalent to two SCRs connected in anti parallel.

The triac is a development of the thyristor. While the thyristor can only control current over one half of the cycle, the triac controls it over two halves of an AC waveform.

The triac can be considered as a pair of parallel but opposite thyristors with the two gates connected together and the anode of one device connected to the cathode of the other.

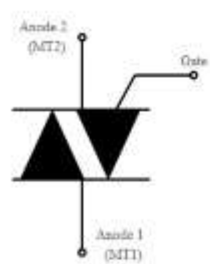


Fig 1.3.1 Symbol of TRIAC

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 123]

As the triac can conduct in both the directions, the terms anode and cathode are not applicable to triac. Its three terminals are usually designated as MTl (main terminal 1), MT2 and the gate by G. The gate G is near terminal MTl. The cross-hatched strip shows that G is connected to N3 as well as P2.Similarly terminal MTI is connected to P2 and N2, terminal MT2 to P1 and N4 . With no signal to gate, the triac will block both half cycles of the applied voltage in case peak value of this voltage is less than the breakover voltage vBDl or VBD2 of the triac, Fig.

The triac can, be turned on in each half cycle of the applied voltage by applying a positive or negative voltage to the gate with respect to terminal MTl. For convenience, terminal MTI is taken as the point for measuring the voltage and current at the gate and MT2 terminals.

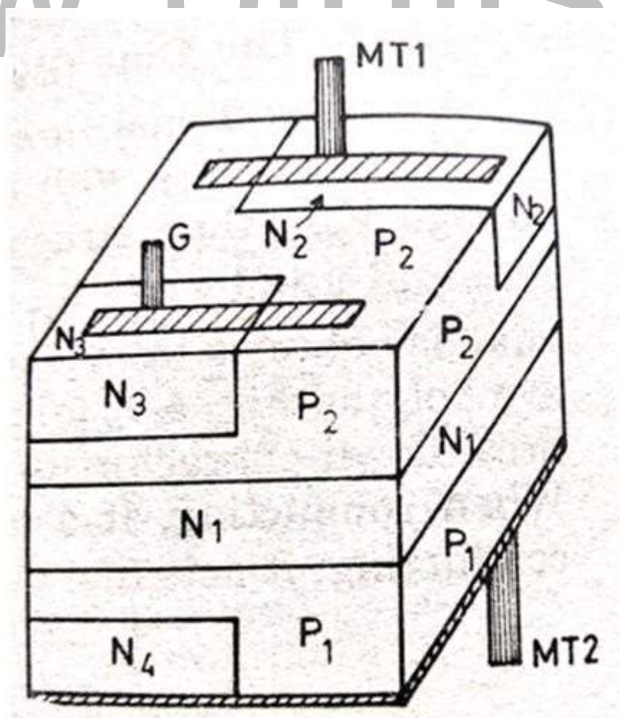


Fig.1.3.2 cross sectional view of TRIAC

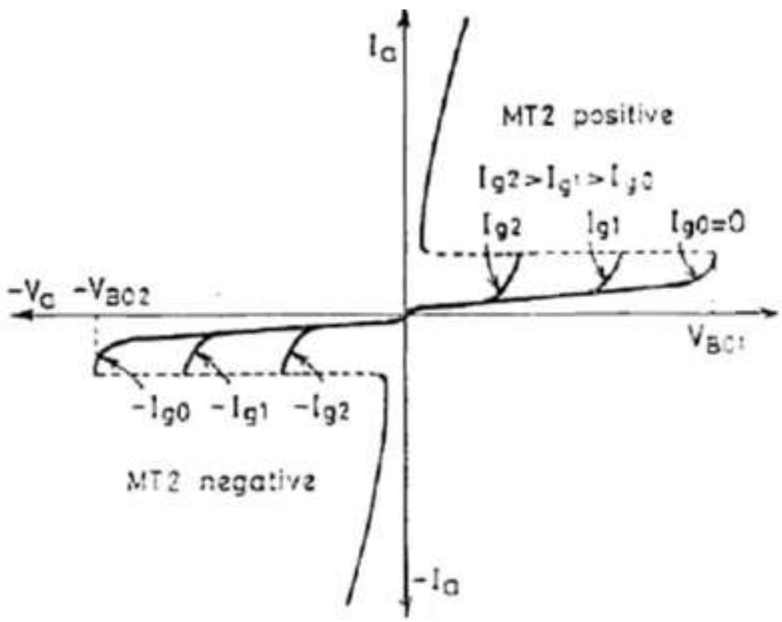


Fig.1.3.3 Static VI characteristics of TRIAC

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 124]

TRIGERRING MODES OF OPERATION OF TRIAC

1.Terminal MT2 and gate are positive with respect to terminal MT1

2.Terminal MT2 is positive but gate is negative with respect to terminal MT1

3.Terminal MT2 and gate are negative with respect to terminal MT1

4.Terminal MT2 is negative but gate is positive with respect to terminal MT1

MT2 is positive and gate current is also positive.

- When MT2 is positive with respect to MTI, junction PI NI, P2 N2 are forward biased but junction NI P2 is reverse biased.
- When gate terminal is positive with respect to MTl, gate current flows mainly through P2 N2 junction like an ordinary SCR.

- When gate current has injected sufficient charge into P2 layer, reverse biased junction NI P2 breaks down just as in a normal SCR.
- Triac starts conducting through PI N I P2 N2 layers.
- Thus when MT2 and gate terminals are positive with respect to MTl, triac turns on like a conventional thyristor. Under this condition, triac operates in the first quadrant of Fig.
- The device is more sensitive in this mode. It is recommended method of triggering if the conduction is desired in the first quadrant.

MT2 is positive but gate current is negative.

- When gate terminal is negative with respect to MTl, gate current flows through P2 N3 junction, Fig, 1.11 (b) and reverse biased junction N1 P2 is forward biased as in a normal thyristor.
- Triac starts conducting through P1 NI P2 N3 layers initially.
- With the conduction of PI N1P2 N 3, the voltage drop across this path falls but potential of layer between P2 N2 rises towards the anode potential of MT2.
- The right hand portion of P2 is clamped at the cathode potential of MTl, a potential gradient exists across layer P2, its left hand region being at higher potential than itsright hand region.
- A current shown dotted is thus established in layer P2 from left to right. This current is similar to conventional gate current of an SCR. As a consequence, right-hand part of triac consisting of main structure PI NI P2 N2 begins to conduct.
- The device structure PI N1 P2 N3 is pilot SCR and the structure PINI P2N2 as the main SCR.

- The anode current of pilot SCR serves as the gate current for the main SCR.
- With the device MT2 positive but gate current negative is less sensitive and therefore, more gate current is required.

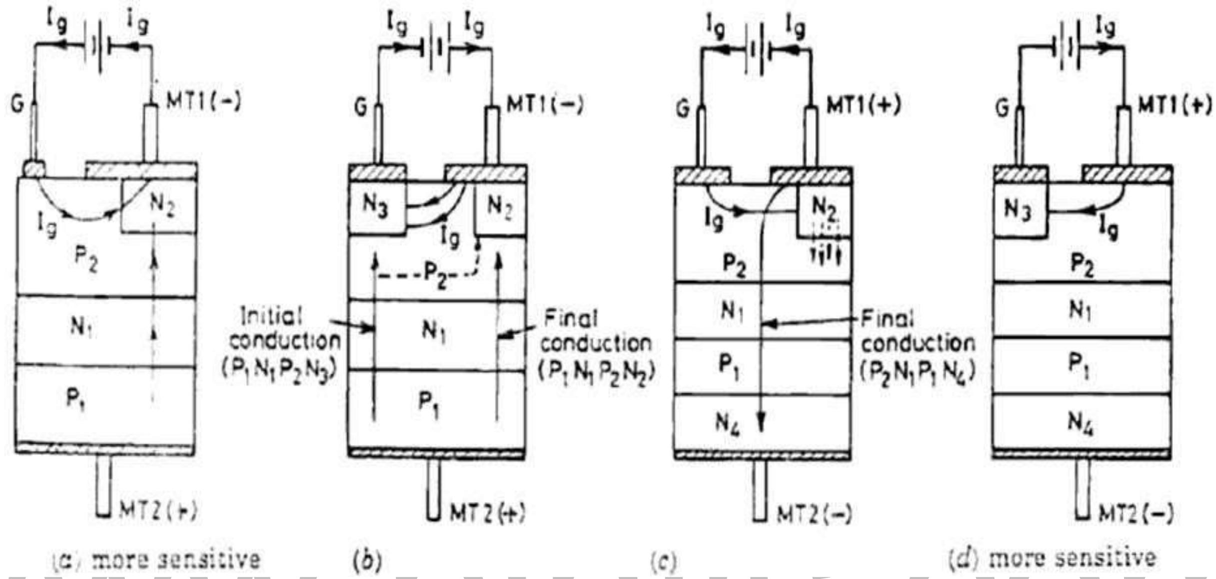


Fig 1.11. Modes of operation of TRIAC

[Source: "Power Electronics" by P.S.Bimbra, Khanna Publishers Page: 124]

MT2 is negative but gate current is positive.

- The gate current Ig forward biases P2 N2 junction
- Layer N2 injects electrons into P2 1ayer as shown by dotted arrows.
- The reverse biased junction N1P 1 breaks down as in a conventional thyristor.
- The structure P2 N1 PI N4 is completely turned on.
- As the triac is' turned on by remote gate N2, the device is less sensitive in the thirdquadrant with positive gate current.

Both MT2 and gate current are negative.

- In this mode, N3 acts as a remote gate,
- The gate current 1g flows from P2 to N3 as in a normal thyristor.
- Reverse-biased junction N1 P1 is broken and finally, the structure P2 N1 Pl N4 is turned oncompletely.
- The triac is turned on by remote gate N3 in third quadrant, yet the device is moresensitive.

ADVANTAGES OF TRIAC

1. It can be triggered with positive or negative polarity gate pulses.
2. It requires only a single heat sink of slightly larger size, whereas for SCR, two heat sinksshould be required of smaller size.
3. It requires single fuse for protection.
4. A safe breakdown in either direction is possible but for SCR protection should be givenwith parallel diode.

APPLICATION OF TRIAC

- They are used in control circuits.
- It is used in AC power control