

POWER ELECTRONICS AND PLC

5TH SEMISTER ELECTRICAL

CHAPTER 01

UNDERSTAND THE CONSTRUCTION AND
WORKING OF POWER ELECTRONICS
DEVICES .

Introduction to power electronics:

Introduction

Power Electronics is a field which combines Power (electric power), Electronics and Control systems.

Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power.

Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power).

Power electronics may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power.

Power electronics deals with the study and design of Thyristorised power controllers for variety of application like Heat control, Light/Illumination control and Motor control - AC/DC motor drives used in industries, High voltage power supplies, Vehicle propulsion systems, High voltage direct current (HVDC) transmission.

Power electronic applications

Commercial applications Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipments, Uninterruptible Power Supplies (UPS), Elevators, and Emergency Lamps

Domestic applications Cooking Equipments, Lighting, Heating, Air Conditioners, Refrigerators & Freezers, Personal Computers, Entertainment Equipments, UPS

Industrial applications Pumps, compressors, blowers and fans Machine tools, arc furnaces, induction furnaces, lighting control circuits, industrial lasers, induction heating, welding equipments

Aerospace applications Space shuttle power supply systems, satellite power systems, aircraft power systems.

Telecommunications Battery chargers, power supplies (DC and UPS), mobile cell phone battery Chargers .

Power semiconductor devices

- i. Power Diodes.
- ii. Power transistors (BJT's
- iii. Power MOSFETS.
- iv. IGBT's.
- v. Thyristors

Thyristors are a family of p-n-p-n structured power semiconductor switching devices

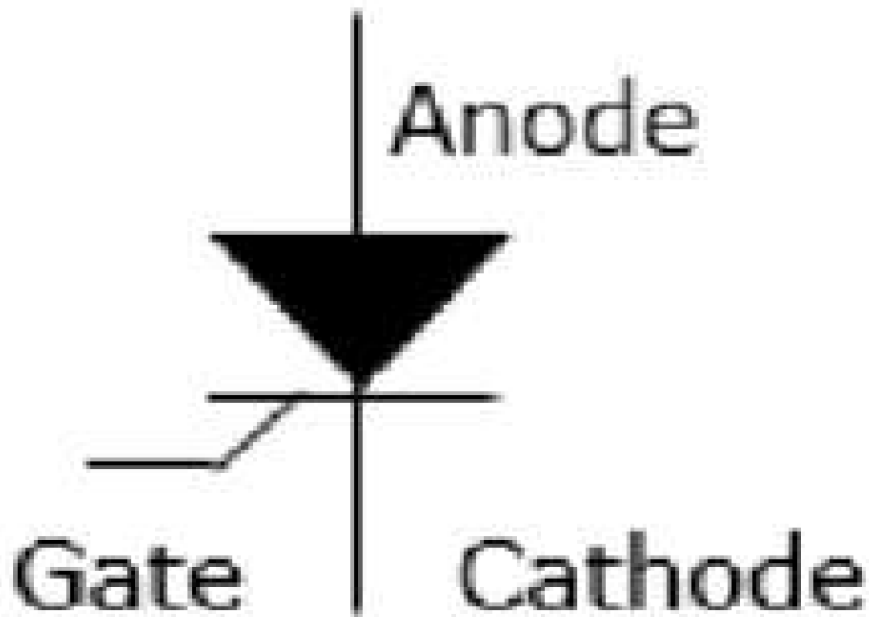
Thyristors are a family of p-n-p-n structured power semiconductor switching devices

Thyristors – Silicon Controlled Rectifiers (SCRs)

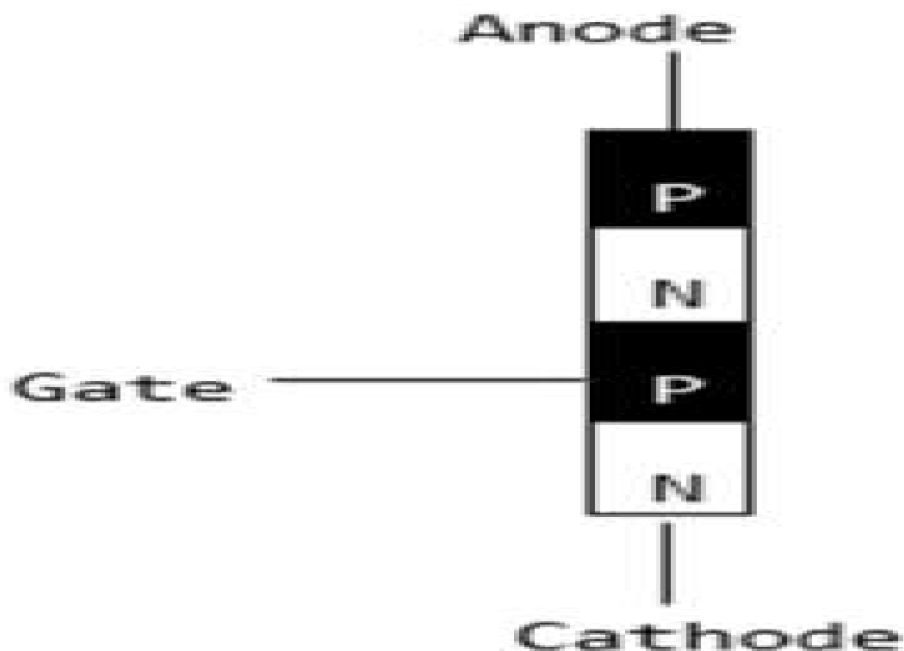
A silicon controlled rectifier or semiconductor-controlled rectifier is a four-layer solidstate currentcontrolling device. The name "silicon controlled rectifier" is General Electric's trade name for a type of thyristor.

SCRs are mainly used in electronic devices that require control of high voltage and power. This makes them applicable in medium and high AC power operations such as motor control function.

An SCR conducts when a gate pulse is applied to it, just like a diode. It has four layers ofsemiconductors that form two structures namely; NPNP or PNPN. In addition, it has three junctions labeled as J1, J2 and J3 and three terminals(anode, cathode and a gate). An SCR is diagrammatically represented as shown below.



The anode connects to the P-type, cathode to the N-type and the gate to the P-type as shown below.



In an SCR, the intrinsic semiconductor is silicon to which the required dopants are infused. However, doping a PNPN junction is dependent on the SCR application .

Modes of Operation in SCR

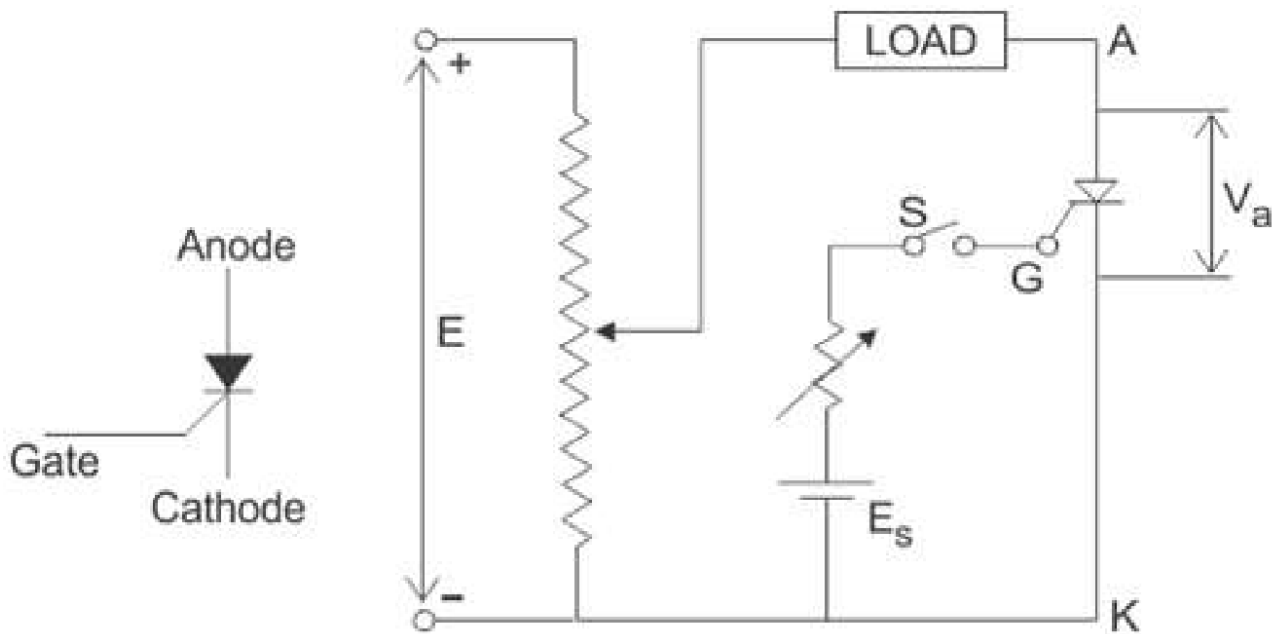
- OFF state (forward blocking mode) – Here the anode is assigned a positive voltage, the gate is assigned a zero voltage (disconnected) and the cathode is assigned a negative voltage. As a result, Junctions J1 and J3 are in forward bias while J2 is in reverse bias. J2 reaches its breakdown avalanche value and starts to conduct. Below this value, the resistance of J1 is significantly high and is thus said to be in the off state.
- ON state (conducting mode) – An SCR is brought to this state either by increasing the potential difference between the anode and cathode above the avalanche voltage or by applying a positive signal at the gate. Immediately the SCR starts to conduct, gate voltage is no longer needed to maintain the ON state and is, therefore, switched off by –
 - Decreasing the current flow through it to the lowest value called holding current
 - Using a transistor placed across the junction.

Reverse blocking – This compensates the drop in forward voltage. This is due to the fact that a low doped region in P1 is needed. It is important to note that the voltage ratings of forward and reverse blocking are equal.

Characteristics of Thyristor

A thyristor is a four layer 3 junction p-n-p-n semiconductor device consisting of at least three p-n junctions, functioning as an electrical switch for high power operations. It has three basic terminals, namely the anode, cathode and the gate mounted on the semiconductor layers of the device. The symbolic diagram and the basic circuit diagram for determining the characteristics of thyristor is shown in the figure below,

V-I Characteristics of a Thyristor

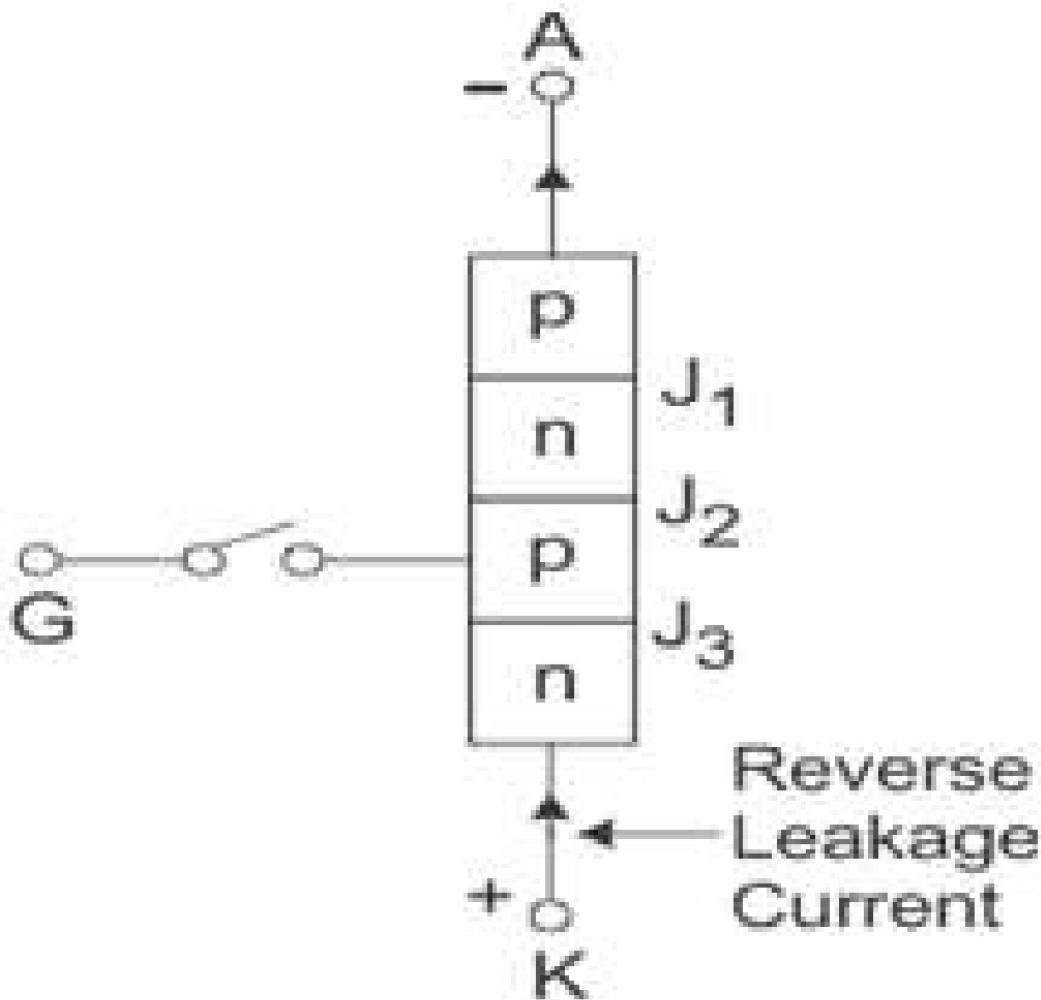


From the circuit diagram above we can see the anode and cathode are connected to the supply voltage through the load. Another secondary supply E_s is applied between the gate and the cathode terminal which supplies for the positive gate current when the switch S is closed. On giving the supply we get the required V-I characteristics of a thyristor show in the figure below for anode to cathode voltage V_a and anode current I_a as we can see from the circuit diagram.

A detailed study of the characteristics reveal that the thyristor has three basic modes of operation, namely the reverse blocking mode, forward blocking(off-state) mode and forward conduction (on-state) mode. Which are discussed in great details below, to understand the overall characteristics of a thyristor.

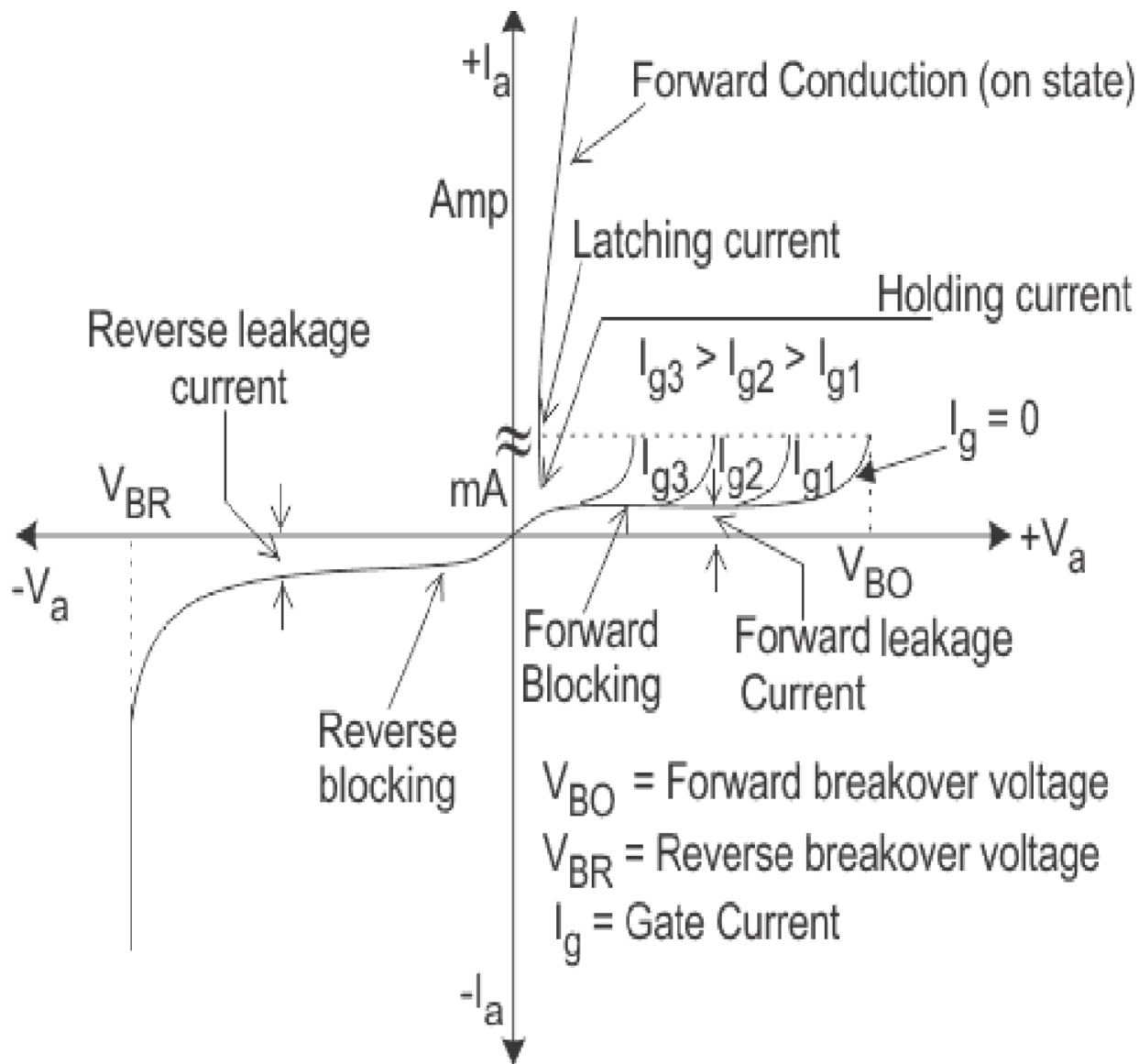
Reverse Blocking Mode of Thyristor

Initially for the reverse blocking mode of the thyristor, the cathode is made positive with respect to anode by supplying voltage E and the gate to cathode supply voltage E_s is detached initially by keeping switch S open. For understanding this mode we should look into the fourth quadrant where the thyristor is reverse biased.



Here Junctions J_1 and J_3 are reverse biased whereas the junction J_2 is forward biased. The behavior of the

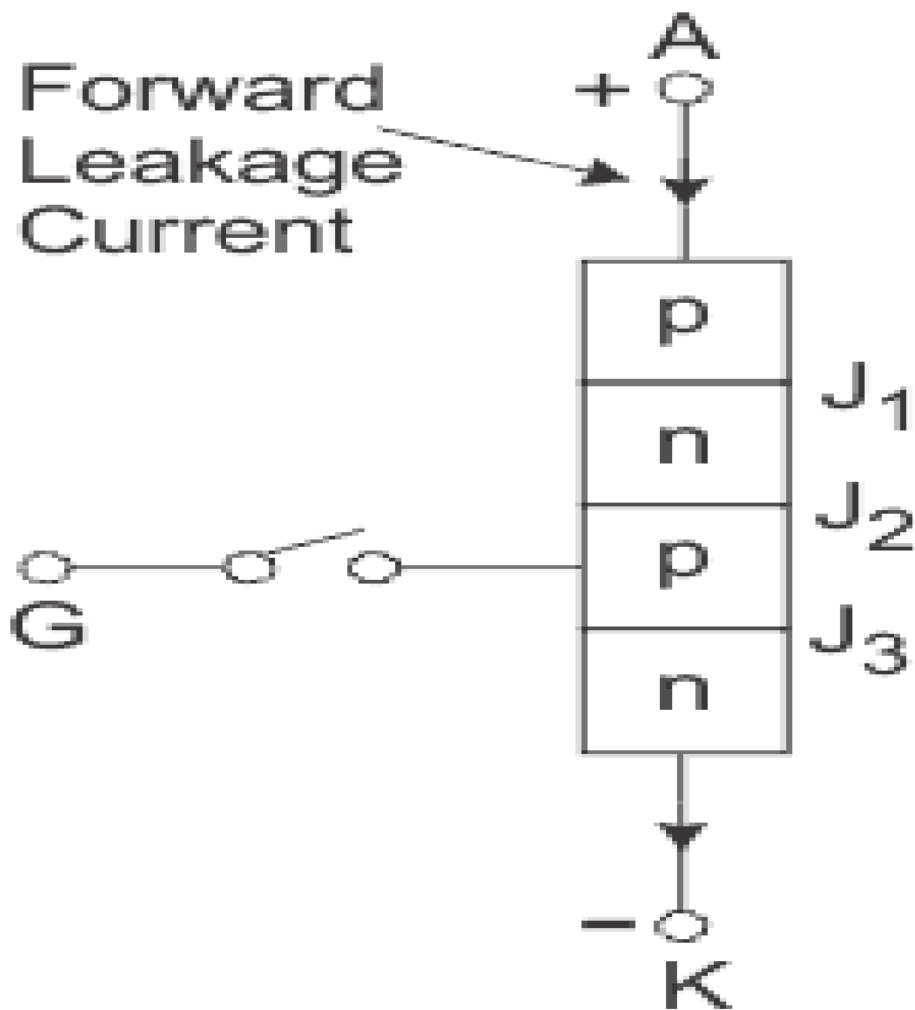
thyristor here is similar to that of two diodes are connected in series with reverse voltage applied across them. As a result only a small leakage current of the order of a few μAmps flows. This is the reverse blocking mode or the off-state, of the thyristor. If the reverse voltage is now increased, then at a particular voltage, known as the critical breakdown voltage V_{BR} , an avalanche occurs at J1 and J3 and the reverse current increases rapidly. A large current associated with V_{BR} gives rise to more losses in the SCR, which results in heating. This may lead to thyristor damage as the junction temperature may exceed its permissible temperature rise. It should, therefore, be ensured that maximum working reverse voltage across a thyristor does not exceed V_{BR} . When reverse voltage applied across a thyristor is less than V_{BR} , the device offers very high impedance .



V- I characteristics of SCR

Forward Blocking Mode

Now considering the anode is positive with respect to the cathode, with gate kept in open condition. The thyristor is now said to be forward biased as shown the figure below.



Forward connection of SCR

As we can see the junctions J₁ and J₃ are now forward biased but junction J₂ goes into reverse biased condition. In this particular mode, a small current, called forward leakage current is allowed to flow initially as shown in the diagram for characteristics of thyristor. Now, if we keep on increasing the forward biased anode to cathode voltage.

In this particular mode, the thyristor conducts currents from anode to cathode with a very small voltage drop across it. A thyristor is brought from forward blocking mode to forward conduction mode by turning it on by exceeding the forward break over voltage or by applying a gate pulse between gate and cathode.

In this mode, thyristor is in on-state and behaves like a closed switch. Voltage drop across thyristor in the on state is of the order of 1 to 2 V depending beyond a certain point, then the reverse biased junction J2 will have an avalanche breakdown at a voltage called forward break over voltage V_{BO} of the thyristor. But, if we keep the forward voltage less than V_{BO} , we can see from the characteristics of thyristor, that the device offers high impedance. Thus even here the thyristor operates as an open switch during the forward blocking mode.

Forward Conduction Mode

When the anode to cathode forward voltage is increased, with gate circuit open, the reverse junction J2 will have an avalanche breakdown at forward break over voltage V_{BO} leading to thyristor turn on.

Once the thyristor is turned on we can see from the diagram for characteristics of thyristor, that the point M at once shifts toward N and then anywhere between N and K. Here NK represents the forward conduction

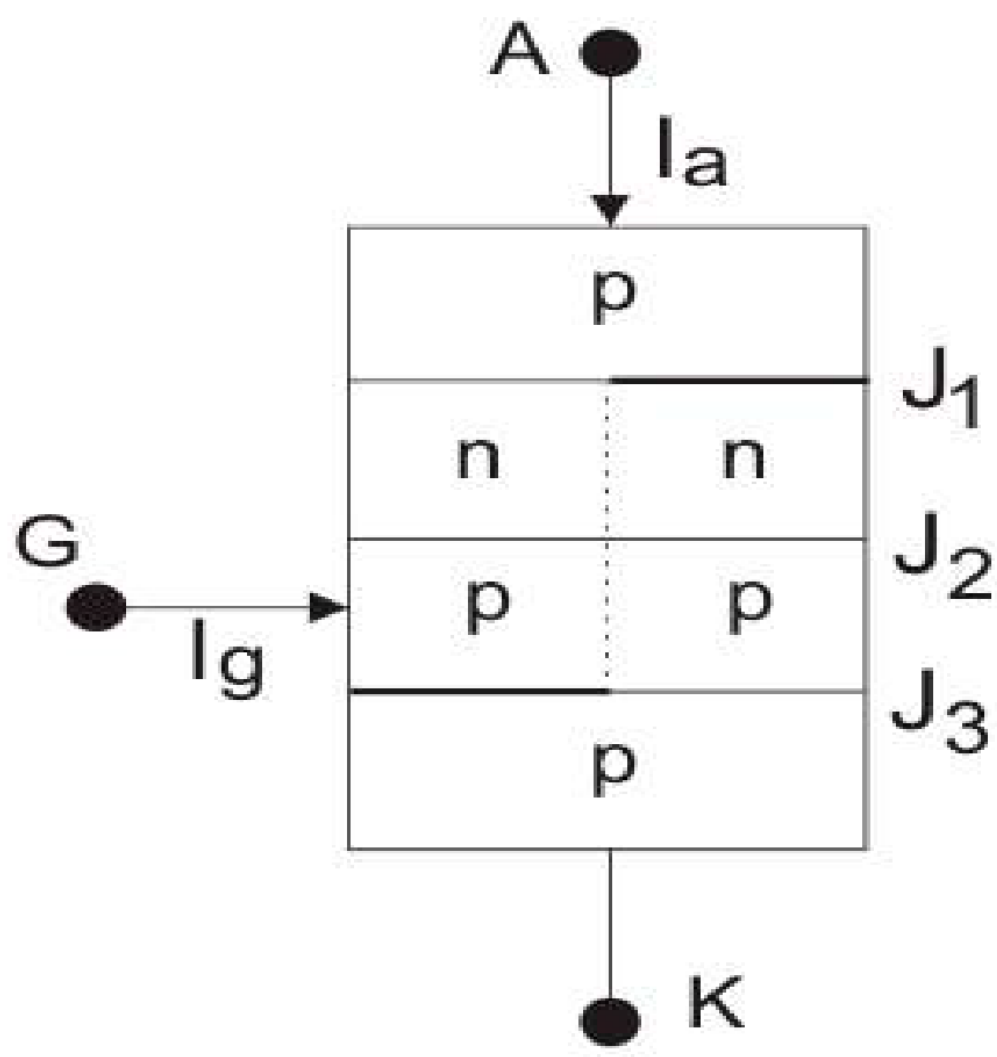
mode of the thyristor. In this mode of operation, the thyristor conducts maximum current with minimum voltage drop, this is known as the forward conduction or the turn on mode of the thyristor.

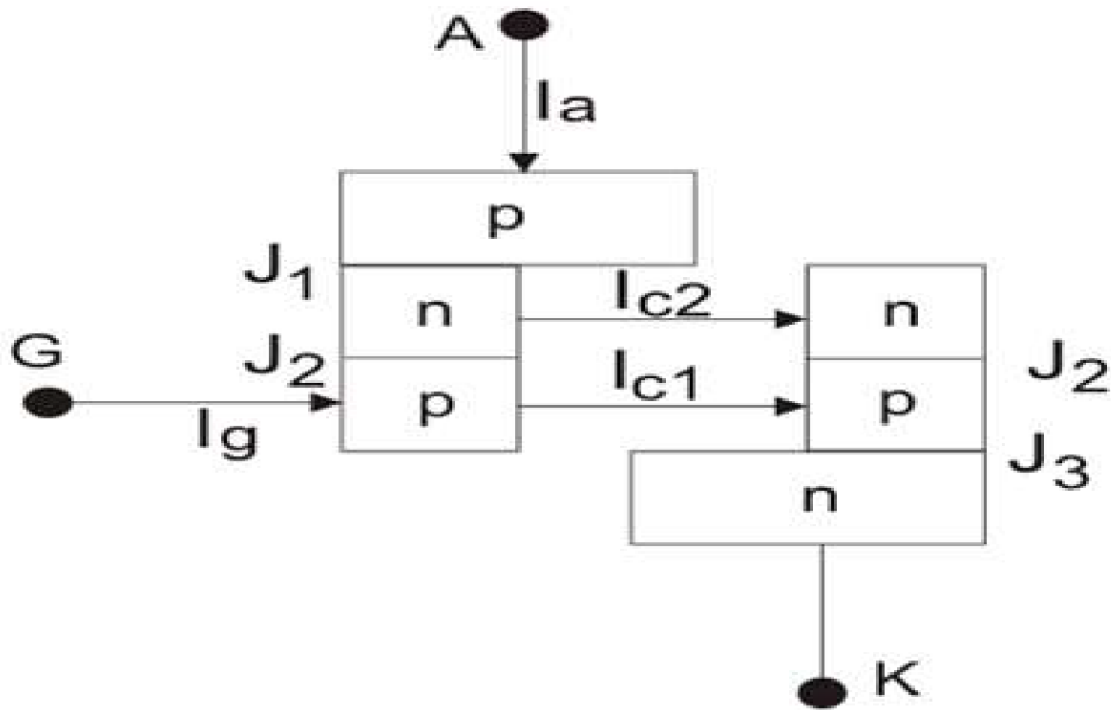
Two transistor analogy of SCR

Basic operating principle of SCR, can be easily understood by the **two transistor model of SCR** or analogy of silicon controlled rectifier, as it is also a combination of P and N layers, shown in figure below

Two transistor structure of SCR

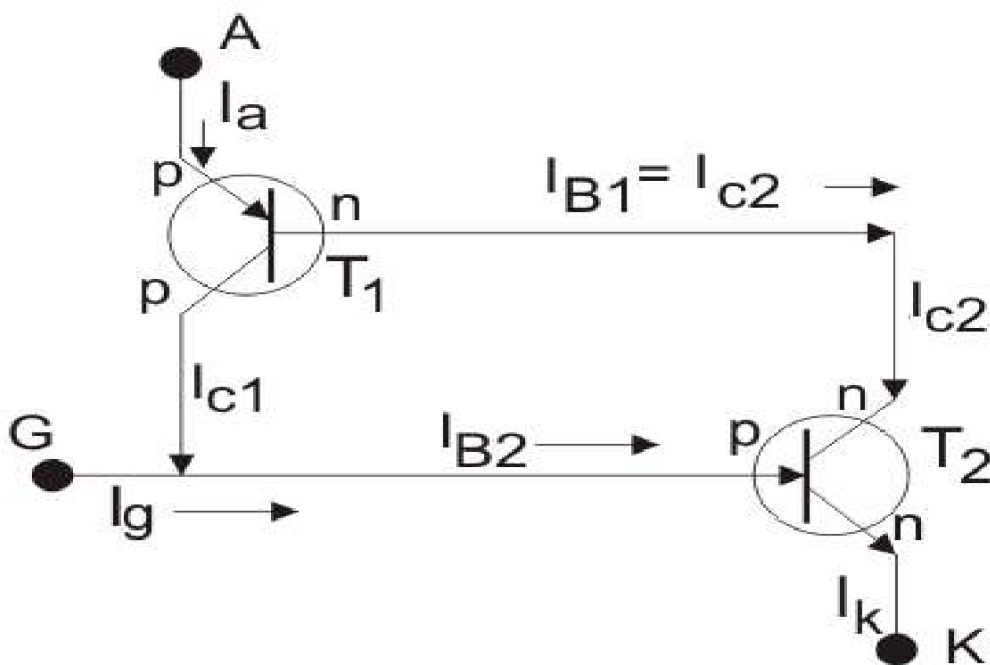
This is a pnpn thyristor. If we bisect it through the dotted line then we will get two transistors i.e. one pnp transistor with J1 and J2 junctions and another is with J2 and J3 junctions as shown in figure below.





Two transistor structure of SCR

When the transistors are in off state, the relation between the collector current and emitter current is shown below .



Here, I_C is collector current, I_E is emitter current, I_{CBO} is forward leakage current, α is common base

forward current gain and relationship between I_C and I_B is $I_C = \beta I_B$ Where, I_B is base current and β is common emitter forward current gain. Let's for transistor T_1 this relation holds

$$I_{C1} = \alpha_1 I_a + I_{CBO1} \dots (i)$$

And that for transistor T_2

$I_{C2} = \alpha_2 I_k + I_{CBO2} \dots (ii)$ again $I_{C2} = \beta_2 I_{B2}$ Now, by the analysis of two transistors model we can get anode current,

$$I_a = I_{C1} + I_{C2} \text{ [applying KCL]}$$

From equation (i) and (ii), we get, $I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \dots (iii)$

From this relation we can assure that with increasing the value of $(\alpha_1 + \alpha_2)$ towards unity, corresponding anode current will increase. Now the question is how $(\alpha_1 + \alpha_2)$ increasing. Here is the explanation using two transistor model of SCR. At the first stage when we apply a gate current I_g , it acts as base current of T_2 transistor i.e. $I_{B2} = I_g$ and emitter current i.e. $I_k = I_g$ of the T_2 transistor. Hence establishment of the emitter current gives rise α_2 as

$$\alpha_2 = \frac{I_{CBO1}}{I_g}$$

Presence of base current will generate collector current as

$$I_{C2} = \beta_2 \times I_{B2} = \beta_2 I_g$$

This I_{C2} is nothing but base current I_{B1} of transistor T_1 , which will cause the flow of collector current,

If applied gate current is I_g then cathode current will be the summation of anode current and gate current

i.e. $I_k = I_a + I_g$

By substituting this value of I_k in (iii) we get,

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$$

$$I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

Turn on methods SCR

The turning on Process of the SCR is known as Triggering. In other words, turning the SCR from Forward-Blocking state to Forward-Conduction state is known as Triggering. The various methods of SCR triggering are discussed here.

The various SCR triggering methods are

- Forward Voltage Triggering
- Thermal or Temperature Triggering
- Radiation or Light triggering
- dv/dt Triggering
- Gate Triggering

(a) Forward Voltage Triggering:-

- In this mode, an additional forward voltage is applied between anode and cathode.
- When the anode terminal is positive with respect to cathode (V_{AK}), Junction J1 and J3 is forward biased and junction J2 is reverse biased.
- No current flow due to depletion region in J2 is reverse biased (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 (even when gate is open).

(a) Thermal (or) Temperature Triggering:-

- The width of depletion layer of SCR decreases with increase in junction temperature.
- Therefore in SCR when V_{AR} is very near its breakdown voltage,

the device is triggered by increasing the junction temperature.

- By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

(b) **Radiation Triggering (or) Light Triggering:-**

- For light triggered SCRs a special terminal niche is made inside the inner P layer instead of gate terminal.
- When light is allowed to strike this terminal, free charge carriers are generated.
- When intensity of light becomes more than a normal value, the thyristor starts conducting.

This type of SCRs are called as LASCR

(c) **dv/dt Triggering:-**

- 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, $i_c = dQ/dt$

$$Q = CV$$

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

$$= CdV/dt + VdC/dt$$

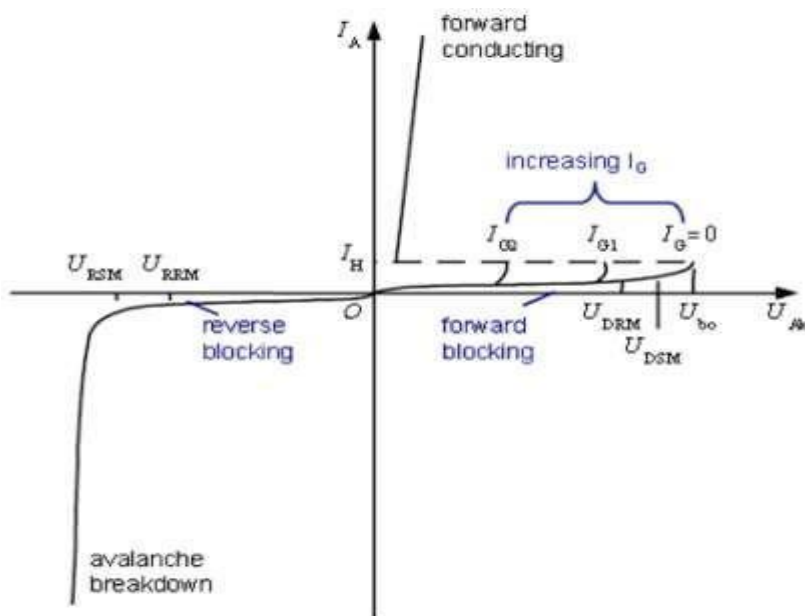
$$\text{as } dC/dt = 0$$

$$i_c = CdV/dt$$

- 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.

(d) Gate Triggering:-

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



Turn off methods of SCR:

SCR can be turned ON by applying appropriate positive gate voltage between the gate and cathode terminals, but it cannot be turned OFF through the gate terminal. The SCR can be brought back to the

forward blocking state from the forward conduction state by reducing the anode or forward current below the holding current level.

The turn OFF process of an SCR is called **commutation**. The term commutation means the transfer of currents from one path to another. So the commutation circuit does this job by reducing the forward current to zero so as to turn OFF the SCR or Thyristor.

To turn OFF the conducting SCR the below conditions must be satisfied.

- The anode or forward current of SCR must be reduced to zero or below the level of holding current and then,

A sufficient reverse voltage must be applied across the SCR to regain its forward blocking state .

When the SCR is turned OFF by reducing forward current to zero there exist excess charge carriers in different layers. To regain the forward blocking state of an SCR, these excess carriers must be recombined. Therefore, this recombination process is accelerated by applying a reverse voltage across the SCR.

SCR Turn OFF Methods

The reverse voltage which causes to commute the SCR is called commutation voltage. Depending on the commutation voltage located, the commutation methods are classified into two major types.

Those are 1) Forced commutation and 2) Natural commutation. Let us discuss in brief about these methods.

Forced Commutation

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

This commutating circuit consists of components like inductors and capacitors called as commutating components. These commutating components cause to apply a reverse voltage across the SCR that immediately bring the current in the SCR to zero.

Based on the manner in which the zero current achieved and arrangement of the commutating components, forced commutation is classified into different types such as class A, B, C, D, and E. This commutation is mainly used in chopper and inverter circuits

Class A Commutation

This is also known as self commutation, or resonant commutation, or load commutation. In this commutation, the source of commutation voltage is in the load. This load must be an under damped R-L-C supplied with a DC supply so that natural zero is obtained.

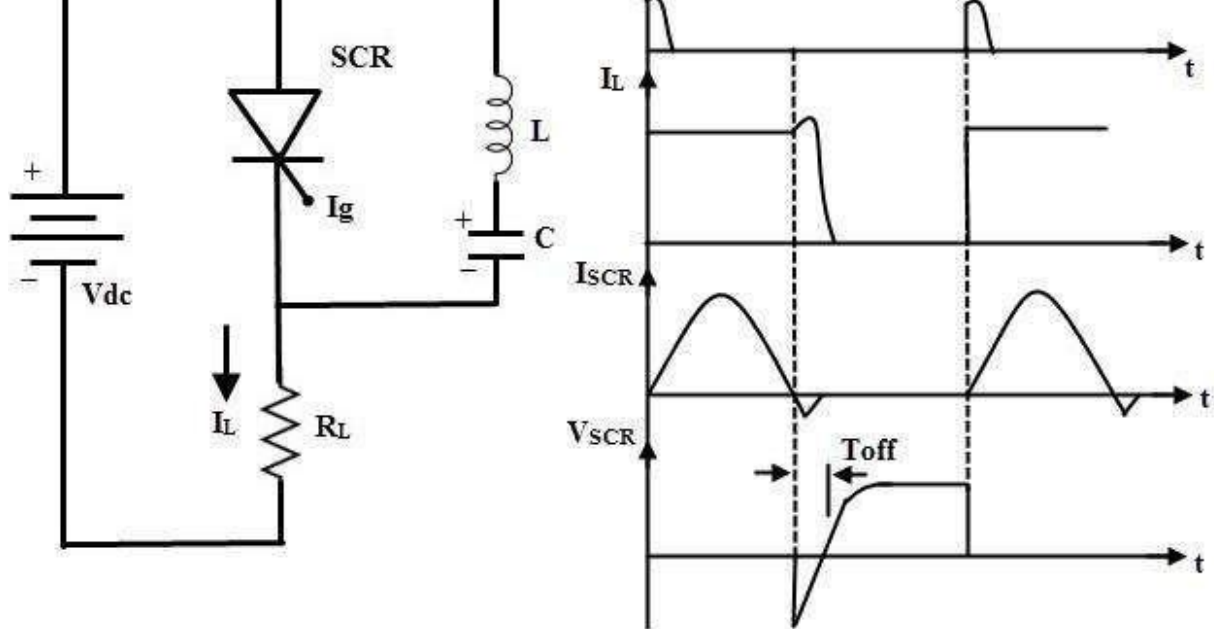
The commutating components L and C are connected either parallel or series with the load resistance R as shown below with waveforms of SCR current, voltage and capacitor voltage.

The value of load resistance and commutating components are so selected that they form a under damped resonant circuit to produce natural zero. When the thyristor or SCR is triggered, the forward current starts flowing through it and during this the capacitor is charged up to the value of E.

Once the capacitor is fully charged (more than the supply source voltage) the SCR becomes reverse biased and hence the commutation of the device. The capacitor discharges through the load resistance to make ready the circuit for the next cycle of operation. The time for switching OFF the SCR depends on the resonant frequency which further depends on the L and C components.

Class B Commutation

This is also a self commutation circuit in which commutation of SCR is achieved automatically by L and C components, once the SCR is turned ON. In this, the LC resonant circuit is connected across the SCR but not in series with load as in case of class A commutation and hence the L and C components do not carry the load current.

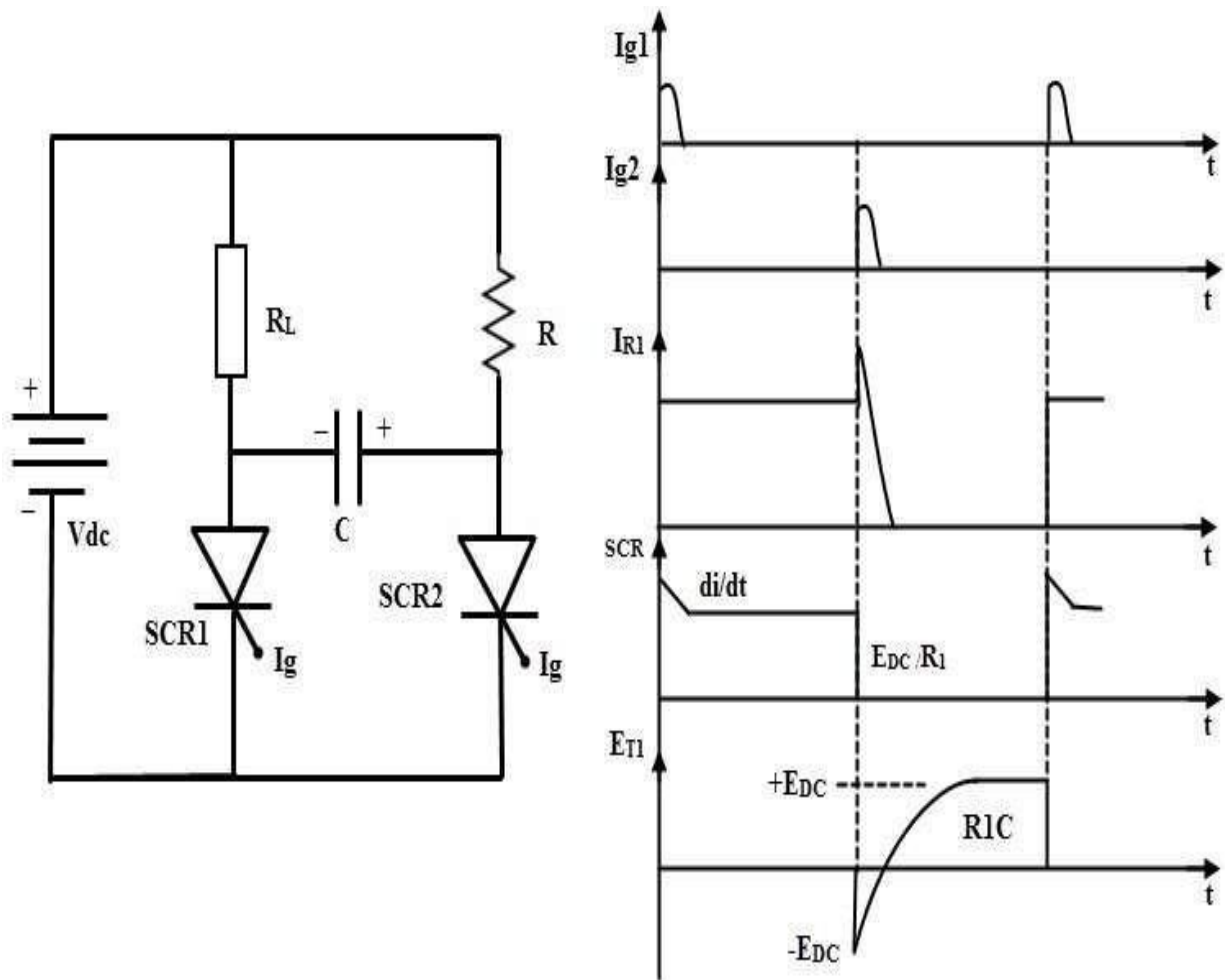


When the DC supply is applied to the circuit, the capacitor charges with an upper plate positive and lower plate negative up to the supply voltage E . When the SCR is triggered, the current flows in two directions, one is through $E+ - SCR - R - E-$ and another one is the commutating current through L and C components.

Once the SCR is turned ON, the capacitor starts discharging through $C+ - L - T - C-$. When the capacitor is fully discharged, it starts charging with a reverse polarity. Hence a reverse voltage applied across the SCR which causes the commutating current I_C to oppose load current I_L .

Class C Commutation In this commutation method, the main SCR is to be commutated is connected in series with the load and an additional or complementary SCR is connected in parallel with main SCR. This method is also called as complementary commutation.

In this, SCR turns OFF with a reverse voltage of a charged capacitor. The figure below shows the complementary commutation with appropriate waveforms.



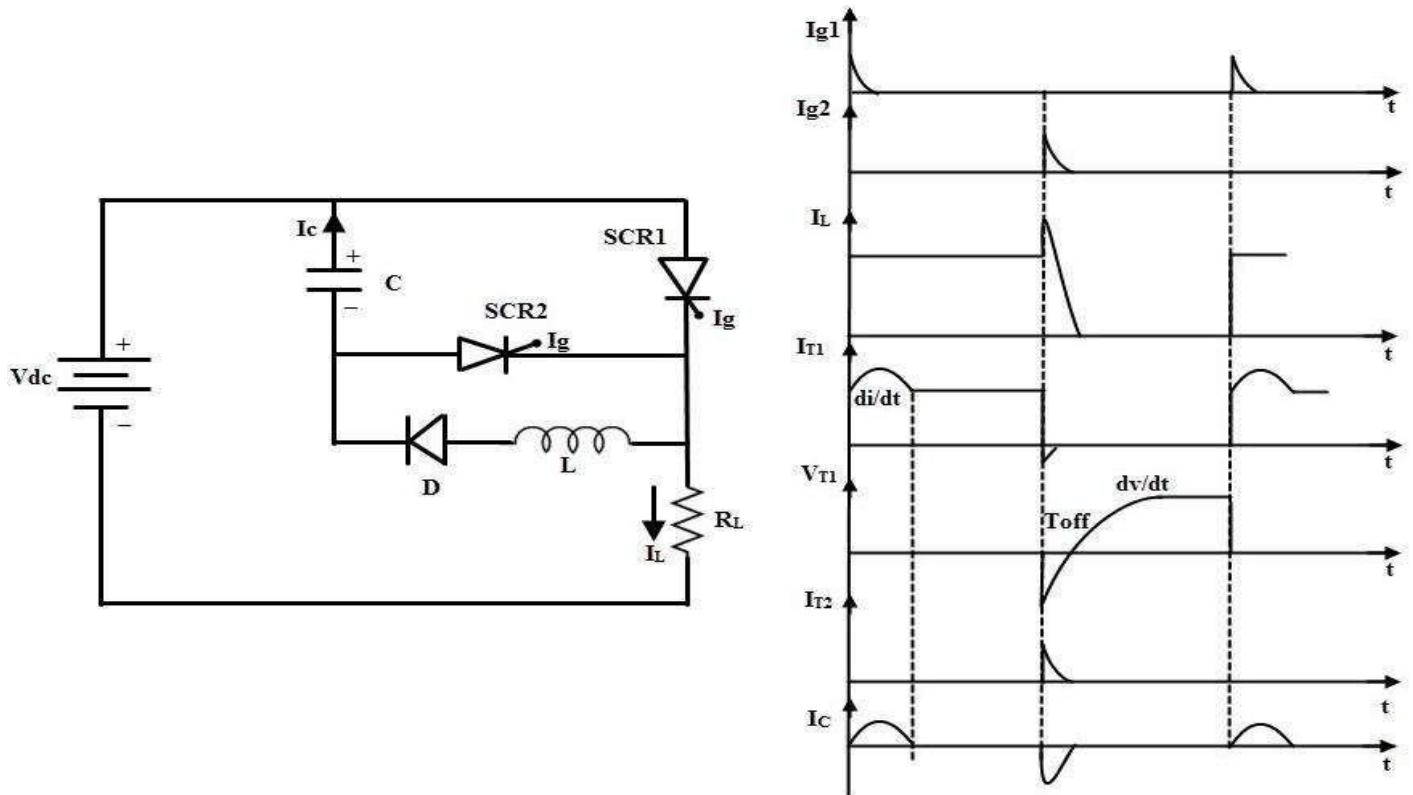
Initially, both SCRs are in OFF state so the capacitor voltage is also zero. When the SCR1 or main SCR is triggered, current starts flowing in two directions, one path is $E^+ - R1 - SCR1 - E^-$ and another path is the charging current $E^+ - R2 - C^+ - C^- - SCR1 - E^-$. Therefore, the capacitor starts charging up to the value E

When the SCR2 is triggered, SCR is turned ON and simultaneously a negative polarity is applied across the SCR1. So this reverse voltage across the SCR1 immediately causes to turn OFF the SCR1. Now the capacitor starts charging with a reverse polarity through the path of $E+ - R1 - C+ - C- - SCR2 - E-$. And again, if the SCR 1 is triggered, discharging current of the capacitor turns OFF the SCR2.

This commutation is mainly used in single phase inverters with a centre tapped transformers. The Mc Murray Bedford inverter is the best example of this commutation circuit. This is a very reliable method of commutation and it is also useful even at frequencies below 1000Hz.

Class D Commutation

This is also called as auxiliary commutation because it uses an auxiliary SCR to switch the charged capacitor. In this, the main SCR is commutated by the auxiliary SCR. The main SCR with load resistance forms the power circuit while the diode D, inductor L and SCR form the ckt .



When the supply voltage E is applied, both SCRs are in OFF state and hence the capacitor voltage is zero. In order to charge the capacitor, SCR2 must be triggered first. So the capacitor charges through the path $E+ - C+ - C- - SCR2 - R - E-$.

When the capacitor is fully charged the SCR2 becomes turned OFF because no current flow through the SCR2 when capacitor is charged fully. If the SCR1 is triggered, the current flows in two directions; one is the load current path $E^+ - SCR1 - R - E^-$ and another one is commutation current path $C^+ - SCR1 - L - D - C$.

When the capacitor is fully charged the SCR2 becomes turned OFF because no current flow through the SCR2 when capacitor is charged fully. If the SCR1 is triggered, the current flows in two directions; one is the load current path $E^+ - SCR1 - R - E^-$ and another one is commutation current path $C^+ - SCR1 - L - D - C$.

As soon as the capacitor completely discharges, its polarities will be reversed but due to the presence of diode the reverse discharge is not possible. When the SCR2 is triggered capacitor starts discharging through $C^+ - SCR2 - SCR1 - C^-$. When this discharging current is more than the load current the SCR1 becomes turned OFF.

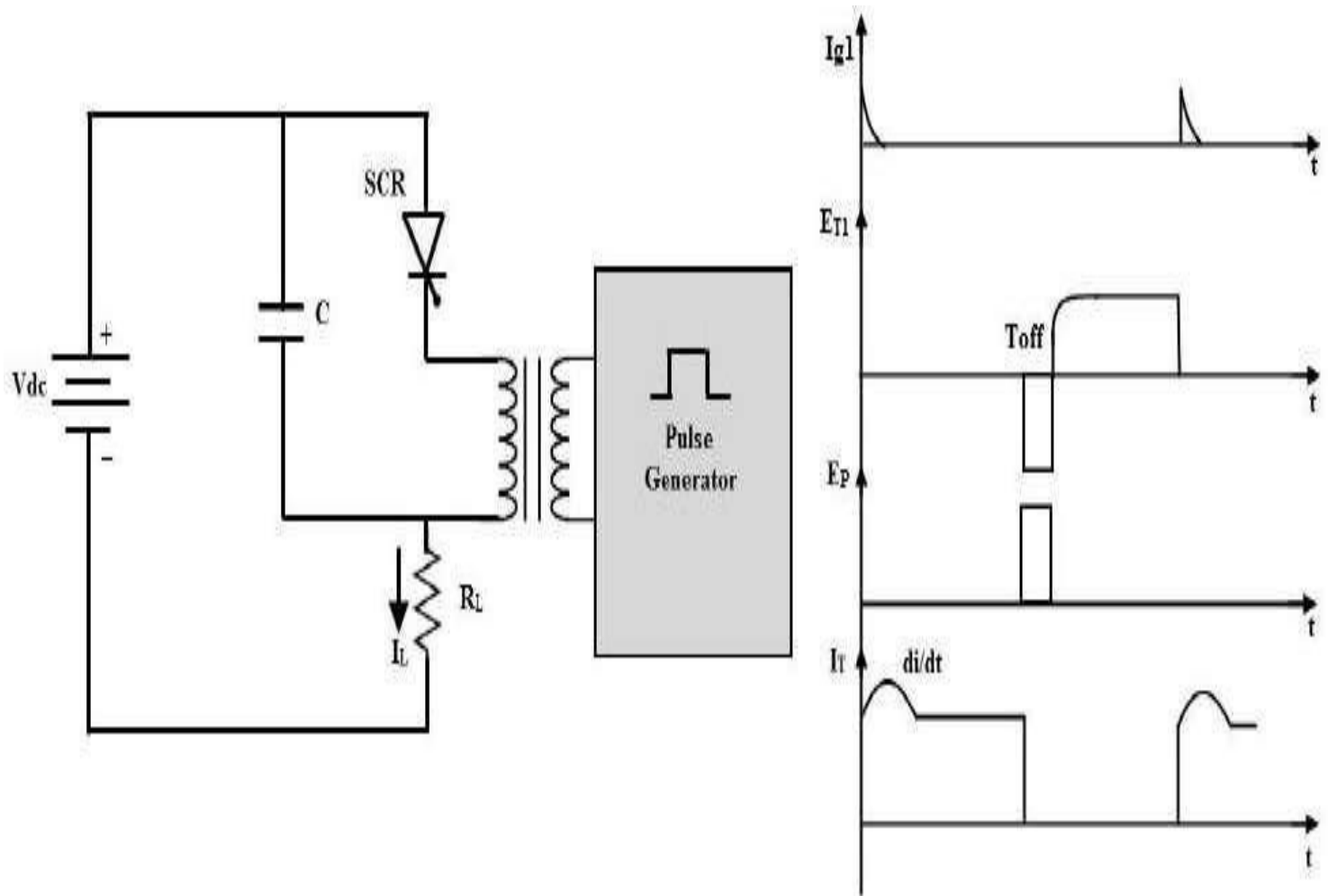
Again, the capacitor starts charging through the SCR2 to a supply voltage E and then the SCR2 is turned OFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated. This commutation method is mainly used in inverters and also used in the Jones chopper circuit.

Class E Commutation

This is also known as external pulse commutation. In this, an external pulse source is used to produce the reverse voltage across the SCR. The circuit below shows the class E commutation circuit which uses a pulse transformer to produce the commutating pulse and is designed with tight coupling between the primary and secondary with a small air gap.

If the SCR need to be commutated, pulse duration equal to the turn OFF time of the SCR is applied. When the SCR is triggered, load current flows through the pulse transformer. If the pulse is applied to the primary of the pulse transformer, an emf or voltage is induced in the secondary of the pulse transformer.

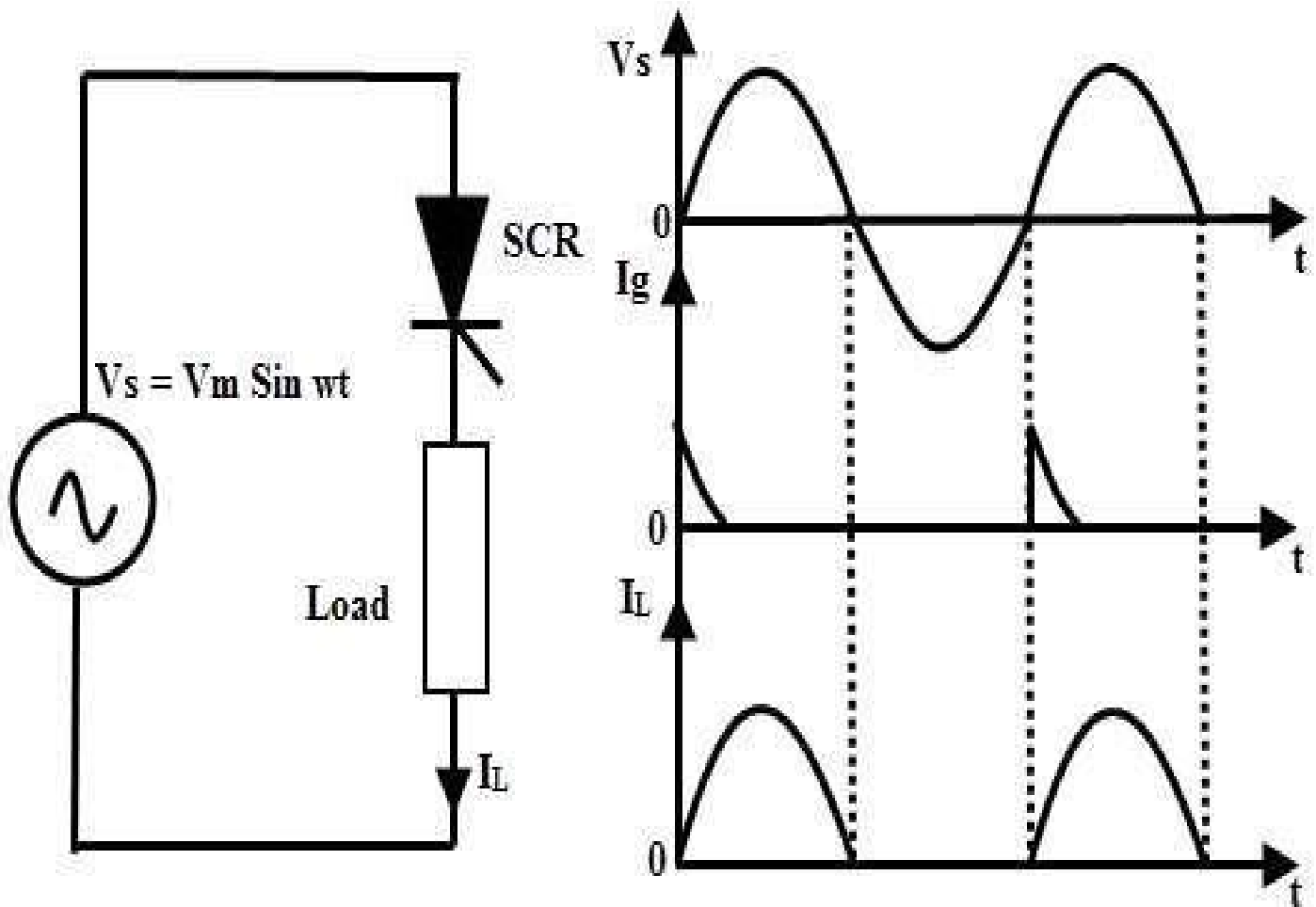
This induced voltage is applied across the SCR as a reverse polarity and hence the SCR is turned OFF. The capacitor offers a very low or zero impedance to the high frequency pulse.



Natural Commutation

In natural commutation, the source of commutation voltage is the supply source itself. If the SCR 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 SCR. These are the conditions to turn OFF the SCR.

This method of commutation is also called as source commutation, or line commutation, or class F commutation. This commutation is possible with line commutated inverters, controlled rectifiers, cyclo converters and AC voltage regulators because the supply is the AC source in all these converters



Dynamic Turn OFF Switching Characteristics

The transition of an SCR from forward conduction state to forward blocking state is called as turn OFF or commutation of SCR. As we know that once the SCR starts conducting, the gate has no control over it to bring back to forward blocking or OFF state.

To turn OFF the SCR, the current must be reduced to a level below the holding current of SCR. We have discussed various methods above to turn OFF the SCR in which SCR turn OFF is achieved by reducing

the forward current to zero. But if we apply the forward voltage immediately after the current zero of SCR, it starts conducting again even without gate triggering.

This is due to the presence of charge carriers in the four layers. Therefore, it is necessary to apply the reverse voltage, over a finite time across the SCR to remove the charge carriers.

Hence the turn OFF time is defined as the time between the instant the anode current becomes zero and the instant at which the SCR retains the forward blocking capability. The excess charge carriers from the four layers must be removed to bring back the SCR to forward conduction mode.

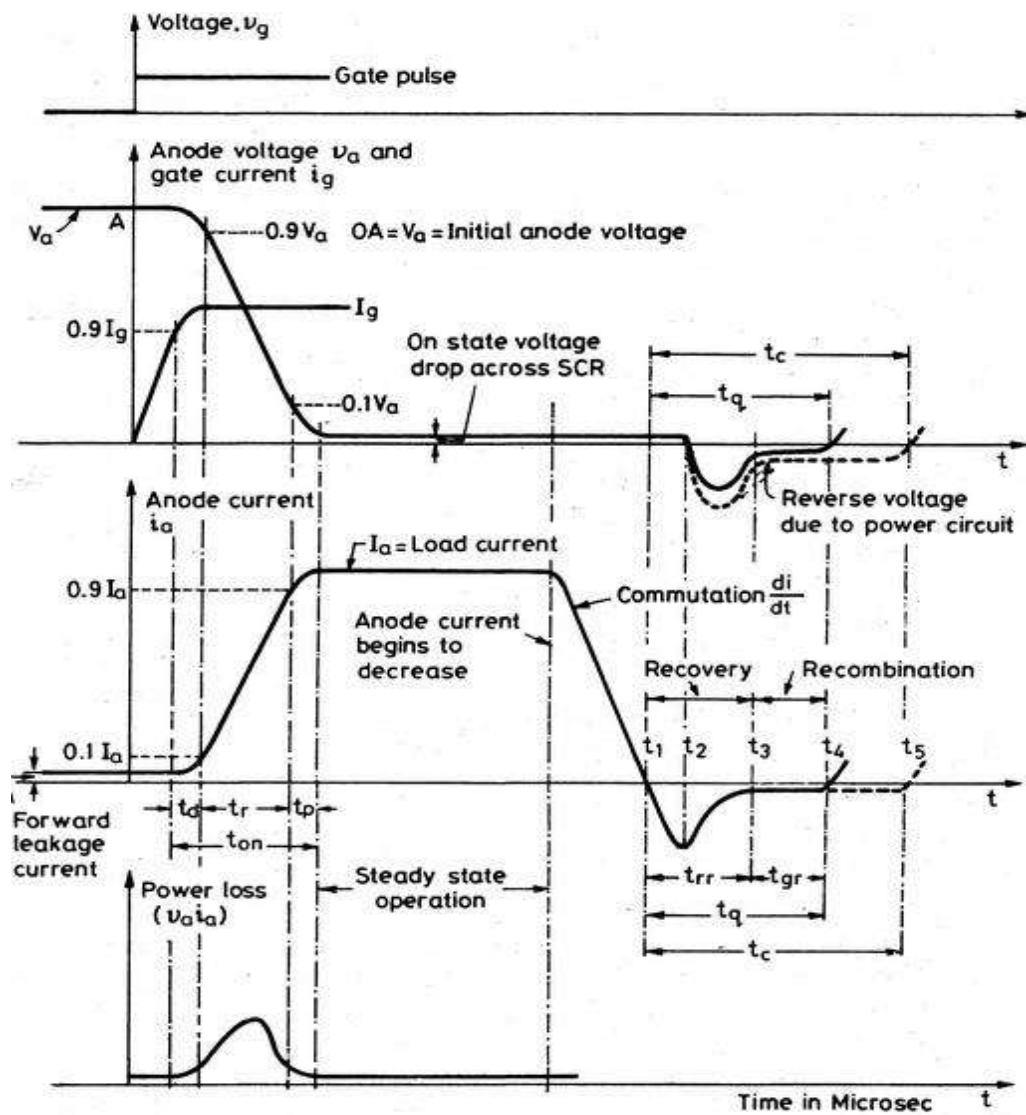
This process takes place in two stages. In a first stage excess carriers from outer layers are removed and in second stage excess carriers in the inner two layers are to be recombined. Hence, the total turn OFF time t_q is divided into two intervals; reverse recovery time t_{rr} and gate recovery time t_{gr} .

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

The figure below shows the switching characteristics of SCR during turn ON and OFF. The time t_1 to t_3 is called as reverse recovery time; at the instant t_1 the anode current is zero and builds up in the reverse direction which is called as reverse recovery current. This current removes the excess charge carriers from outer layers during the time t_1 to t_3 .

The figure below shows the switching characteristics of SCR during turn ON and OFF. The time t_1 to t_3 is called as reverse recovery time; at the instant t_1 the anode current is zero and builds up in the reverse direction which is called as reverse recovery current. This current removes the excess charge carriers from outer layers during the time t_1 to t_3 .

At instant t_3 , junctions J_1 and J_3 are able to block the reverse voltage but, the SCR is not yet able to block the forward voltage due to the presence of excess charge carriers in junction J_2 . These carriers can be disappeared only by the way of recombination and this could be achieved by maintaining a reverse voltage across the SCR



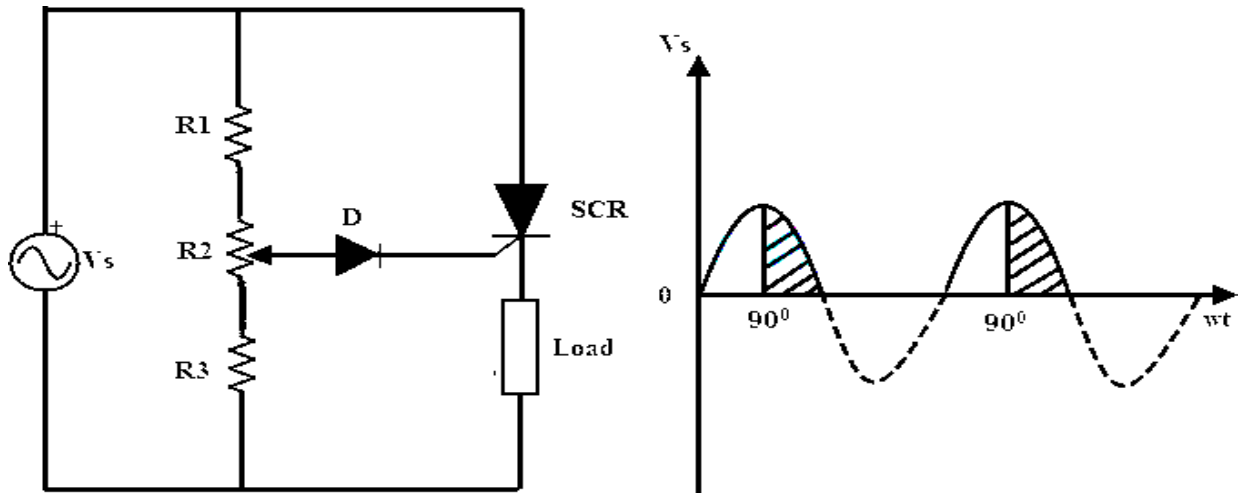
Hence, during the time t_3 to t_4 , the recombination of charges takes place and at the instant t_4 , junction J_2 completely recovers. This time is called gate recovery time t_{gr} .

- From the figure the turn OFF time is the time interval between the t_4 and t_1 . Generally, this time varies from 10 to 100 microseconds. This turn OFF time t_q is applicable to the individual SCR.
- The time required by the commutation circuit to apply the reverse voltage to commutate the SCR is called the circuit turn OFF time (t_c). For a safety margin or reliable commutation, this t_c must be greater than the t_q otherwise commutation failure occurs.
- The SCRs which have slow turn OFF time as in between 50 to 100 microseconds are called as converter grade SCRs. These are used in phase controlled rectifiers, cyclo converters, AC voltage regulators, etc.
- The SCRs which have fast turn OFF time as in between 3 to 50 microseconds are inverter grade SCRs. These are costlier compared to converter grade and are used in choppers, force commutated converters and inverters.

Resistance Firing Circuit

- The circuit below shows the resistance triggering of SCR where it is employed to drive the load from the input AC supply. Resistance and diode combination circuit acts as a gate control circuitry to switch the SCR in the desired condition.
- As the positive voltage applied, the SCR is forward biased and doesn't conduct until its gate current is more than minimum gate current of the SCR.
- When the gate current is applied by varying the resistance R_2 such that the gate current should be more than the minimum value of gate current, the SCR is turned ON. And hence the load current starts flowing through the SCR.
- The SCR remains ON until the anode current is equal to the holding current of the SCR. And it will switch OFF when the voltage applied is zero. So the load current is zero as the SCR acts as open switch.

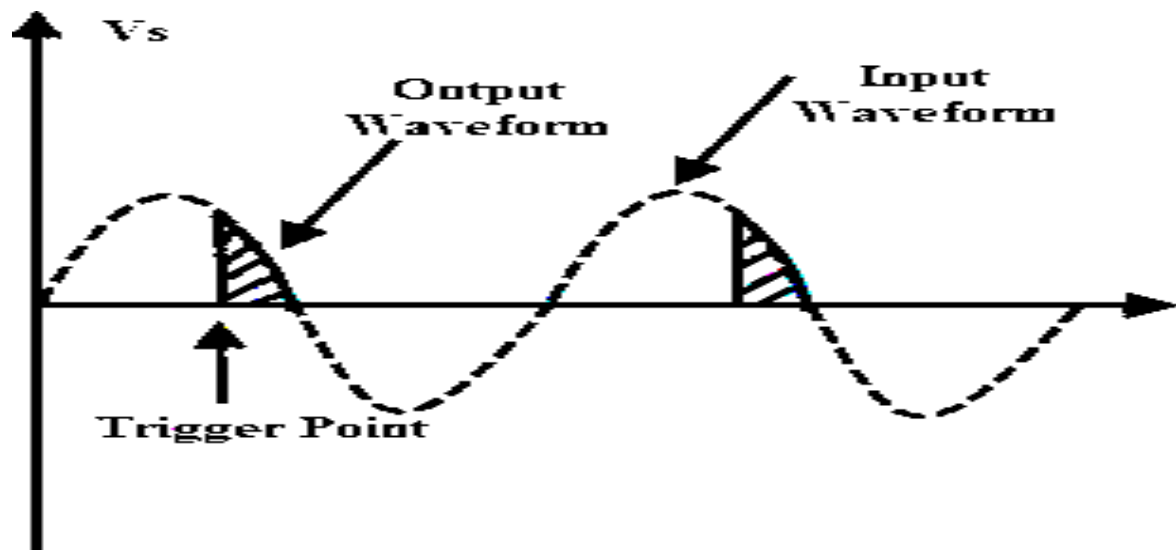
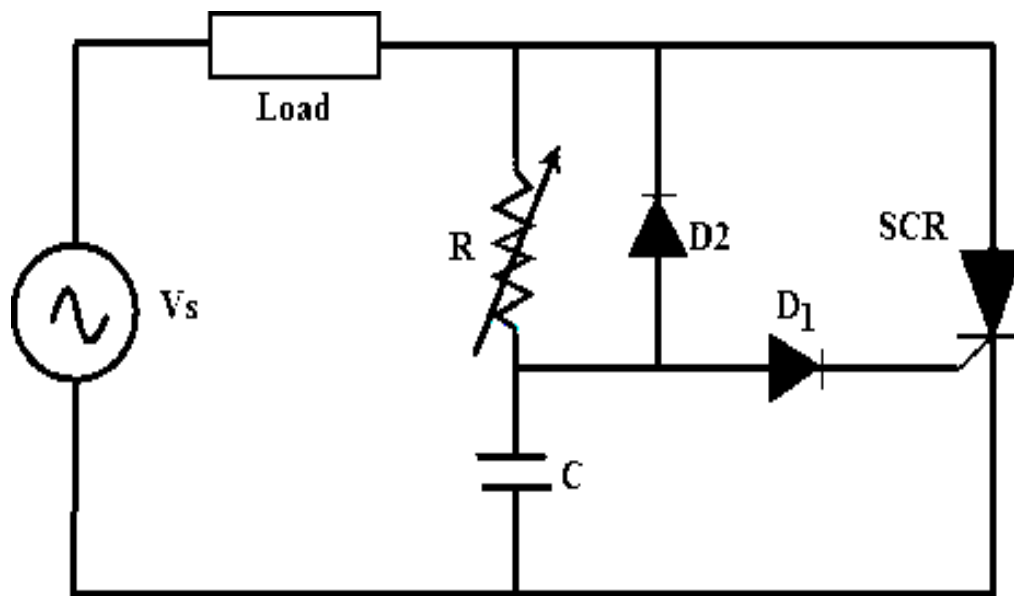
- The diode protects the gate drive circuit from reverse gate voltage during the negative half cycle of the input. And Resistance R1 limits the current flowing through the gate terminal and its value is such that the gate current should not exceed the maximum gate current.
- It is the simplest and economical type of triggering but limited for few applications due to its disadvantages.
- In this, the triggering angle is limited to 90 degrees only. Because the applied voltage is maximum at 90 degrees so the gate current has to reach minimum gate current value somewhere between zero to 90 degrees.



Resistance – Capacitance (RC) Firing Circuit

- The limitation of resistance firing circuit can be overcome by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude of the gate current, a large variation of firing angle is obtained using this circuit.
- Below figure shows the RC triggering circuit consisting of two diodes with an RC network connected to turn the SCR.
- By varying the variable resistance, triggering or firing angle is controlled in a full positive half cycle of the input signal.
- During the negative half cycle of the input signal, capacitor charges with lower plate positive through diode D2 up to the maximum supply voltage V_{max} . This voltage remains at $-V_{max}$ across the capacitor till supply voltage attains zero crossing.
- During the positive half cycle of the input, the SCR becomes forward biased and the capacitor starts charging through variable resistance to the triggering voltage value of the SCR.
- When the capacitor charging voltage is equal to the gate trigger voltage, SCR is turned ON and the capacitor holds a small voltage. Therefore the capacitor voltage is helpful for triggering the SCR even after 90 degrees of the input waveform.

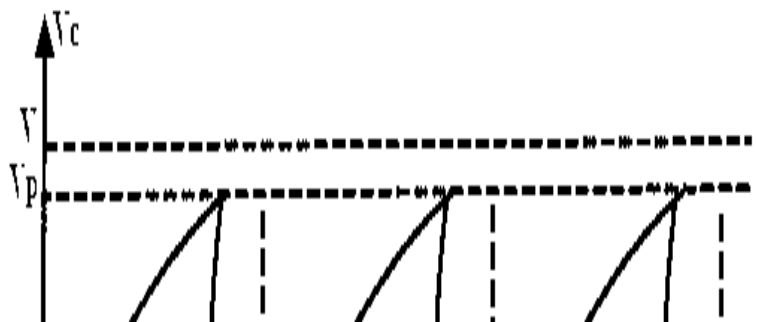
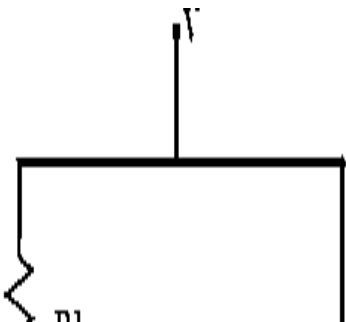
In this, diode D1 prevents the negative voltage between the gate and cathode during the negative half cycle of the input through diode D2



UJT Firing Circuit

- It is the most common method of triggering the SCR because the prolonged pulses at the gate using R and RC triggering methods cause more power dissipation at the gate so by using UJT (Uni Junction Transistor) as triggering device the power loss is limited as it produce a train of pulses.
- The RC network is connected to the emitter terminal of the UJT which forms the timing circuit. The capacitor is fixed while the resistance is variable and hence the charging rate of the capacitor depends on the variable resistance means that the controlling of the RC time constant.
- When the voltage is applied, the capacitor starts charging through the variable resistance. By varying the resistance value voltage across the capacitor get varied. Once the capacitor voltage is equal to the peak value of the UJT, it starts conducting and hence produce a pulse output till the voltage across the capacitor equal to the valley voltage V_v of the UJT. This process repeats and produces a train of pulses at base terminal 1.

The pulse output at the base terminal 1 is used to turn ON the SCR at predetermined time intervals



. UJT Firing circuit for SCR and corresponding waveforms

Snubber circuit

Due to overheating, over voltage, over current or excessive change in voltage or current switching devices and circuit components may fail. From over current they can be protected by placing fuses at suitable locations. Heat sinks and fans can be used to take the excess heat away from switching devices and other components. Snubber circuits are needed to limit the rate of change in voltage or current (di/dt or dv/dt) and over voltage during turn-on and turn-off. These are placed across the semiconductor devices for protection as well as to improve the performance. Static dv/dt is a measure of the ability of a thyristor to retain a blocking state under the influence of a voltage transient. These are also used across the relays and switches to prevent arcing.

Necessity of Using the Snubber Circuit

These are placed across the various switching devices like transistors, thyristors, etc. Switching from ON to OFF state results the impedance of the device suddenly changes to the high value. But this allows a small current to flow through the switch. This induces a large voltage across the device. If this current reduced at faster rate more is the induced voltage across the device and also if the switch is not capable of withstanding this voltage the switch becomes burn out. So auxiliary path is needed to prevent this high induced voltage

Similarly when the transition is from OFF to ON state, due to uneven distribution of the current through the area of the switch overheating will takes place and eventually it will be burned. Here also snubber is necessary to reduce the current at starting by making an alternate path.

Snubbers in switching mode provides one or more of the following functions

Shape the load line of a bipolar switching transistor to keep it in its safe operating area.

Reducing the voltages and currents during turn-ON and turn-OFF transient conditions.

Removes energy from a switching transistor and dissipate the energy in a resistor to reduce junction temperature.

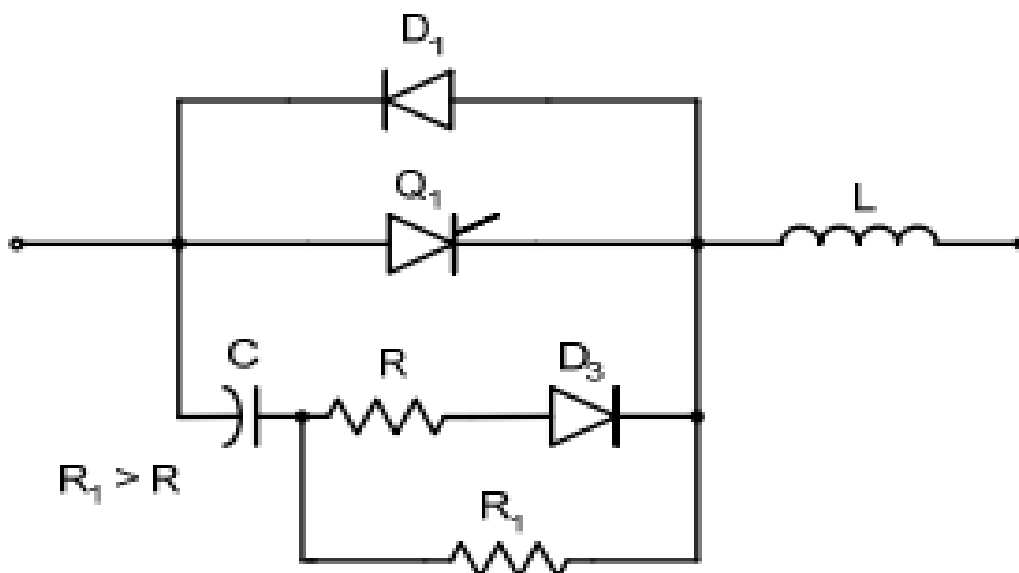
Limiting the rate of change of voltage and currents during the transients.

Reduce ringing to limit the peak voltage on a switching transistor and lowering their frequency.

Design of RC Snubber Circuits: There are many kinds of snubbers like RC, diode and solid state snubbers but the most commonly used one is RC snubber circuit. This is applicable for both the rate of rise control and damping.

This circuit is a capacitor and series resistor connected across a switch. For designing the Snubber circuits. The amount of energy is to dissipate in the snubber resistance is equal to the amount of energy is stored in the capacitors. An RC Snubber placed across the switch can be used to reduce the peak voltage at turn-off and to damp the ring. An RC snubber circuit can be polarized or non-polarized. If you assume the source has negligible impedance, the worst case peak current in the snubber circuit is

$$I = V_o/R_s \text{ and } I = C \cdot dv/dt$$

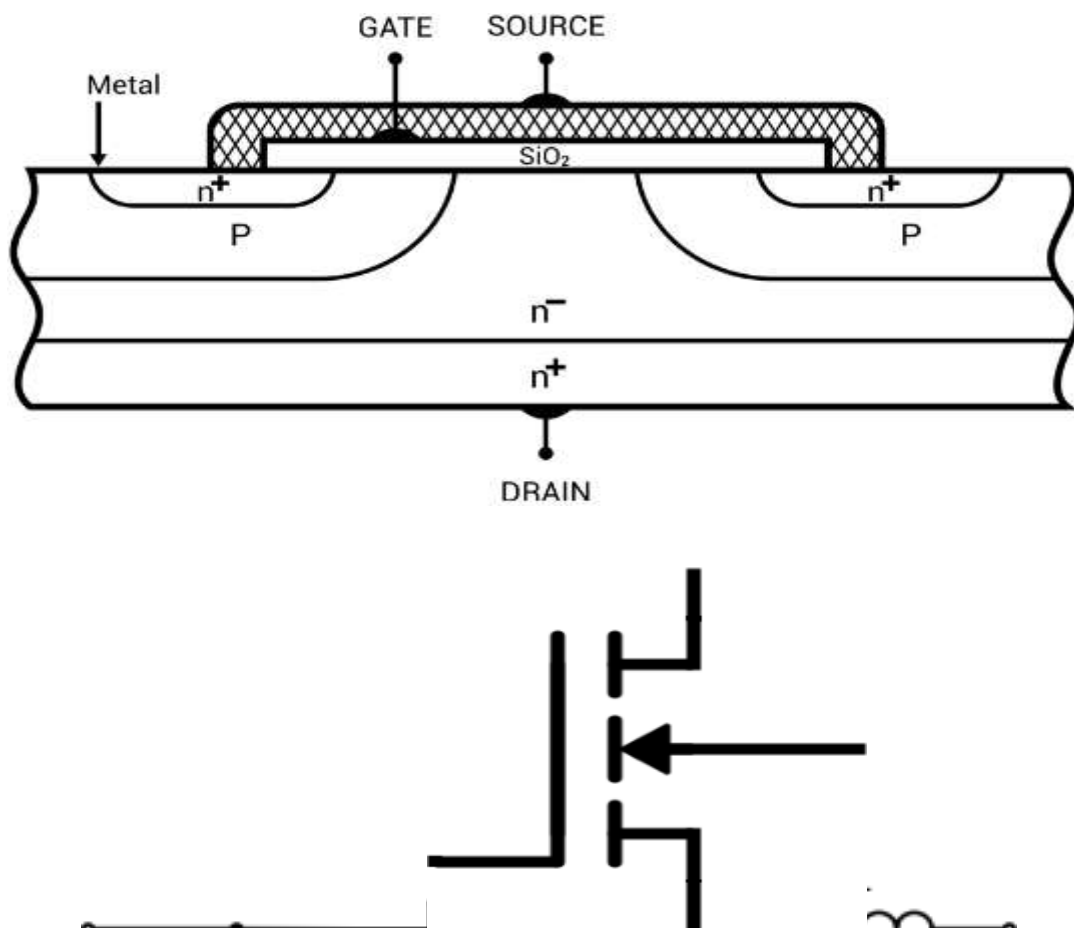


For an appropriate forward-polarized RC snubber circuit a thyristor or a transistor is connected with an anti-parallel diode. R will limit the forward dv/dt and R1 limits the discharge current of the capacitor when transistor Q1 is turned on. These are used as overvoltage snubbers to clamp the voltage.

Metal-Oxide Semiconductor Field-Effect Transistor (Power)

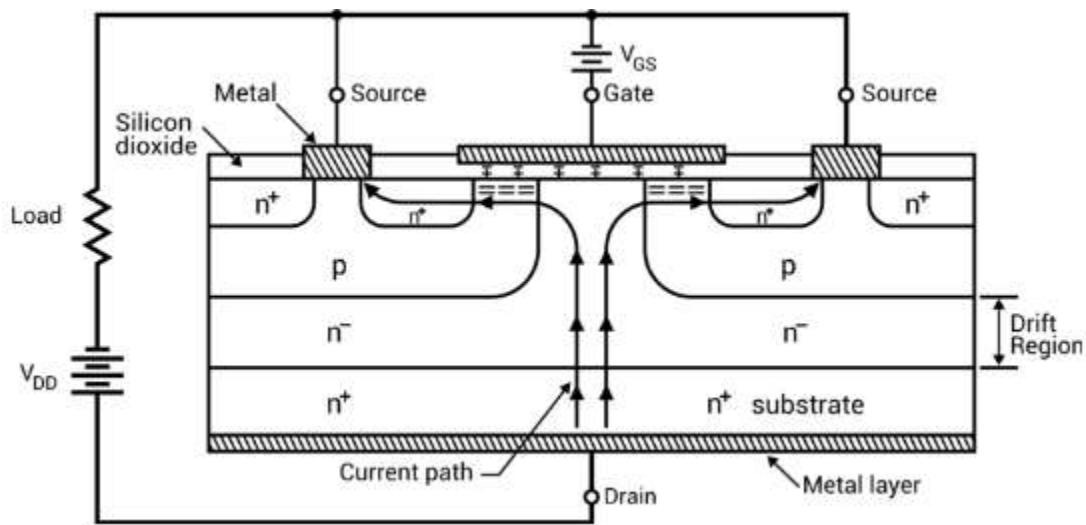
MOSFET is a voltage-controlled majority carrier (or unipolar) three-terminal device. As compared to the simple lateral channel MOSFET for low-power signals, power MOSFET has different structure. It has a vertical channel structure where the source and the drain are on the opposite side of the silicon wafer as shown in Figure. This opposite placement of the source and the drain increases the capability of the power MOSFET to handle larger power.

N-channel enhancement type MOSFET is more common due to high mobility of electrons.



Basic circuit diagram and output characteristics of an n-channel enhancement power MOSFET with load connected are in Fig. 01 and Fig. 02 respectively.

Basic circuit diagram of n-channel enhancement power MOSFET



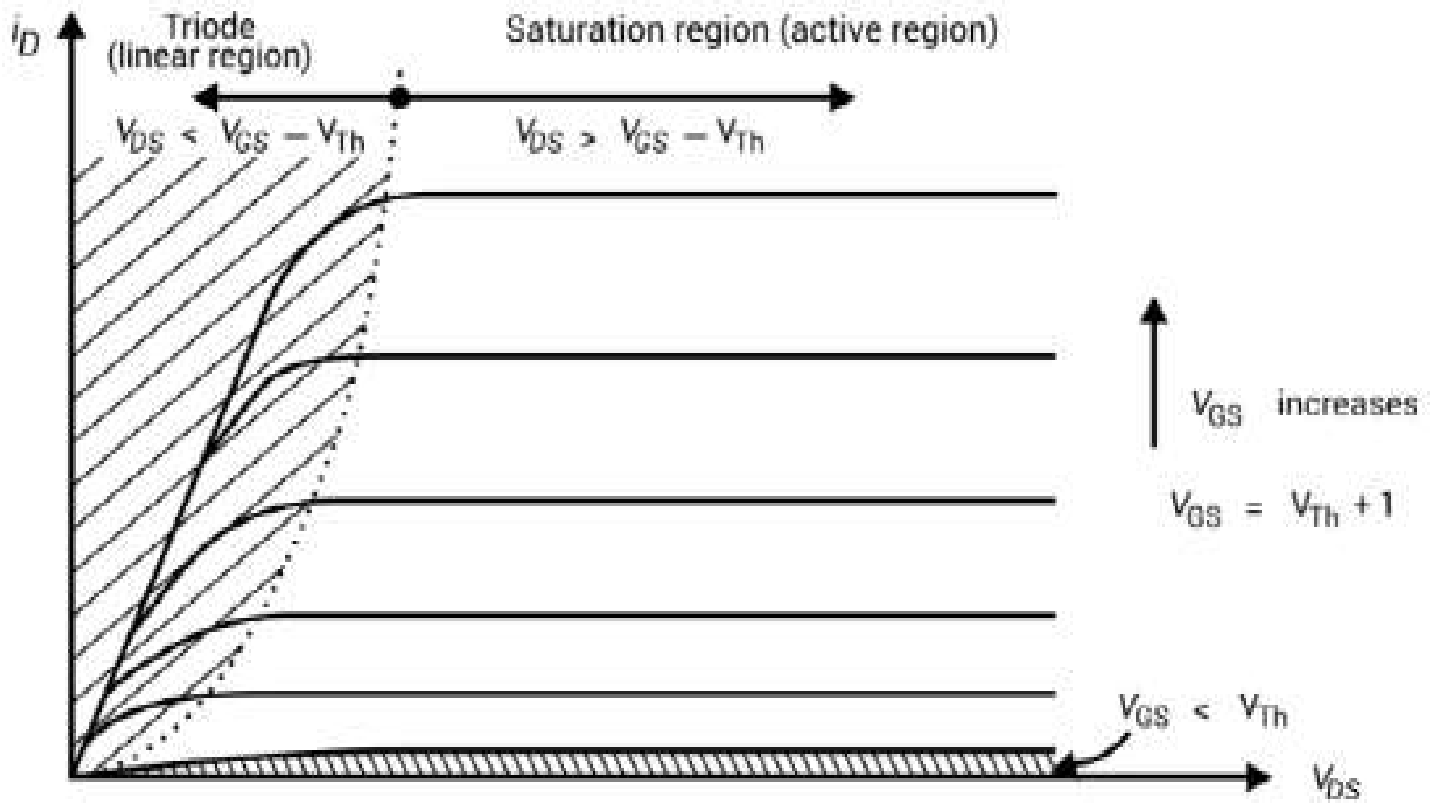
Drift region shown in Fig. 37 determines the voltage-blocking capability of the

MOSFET. When $V_{GS} = 0$,

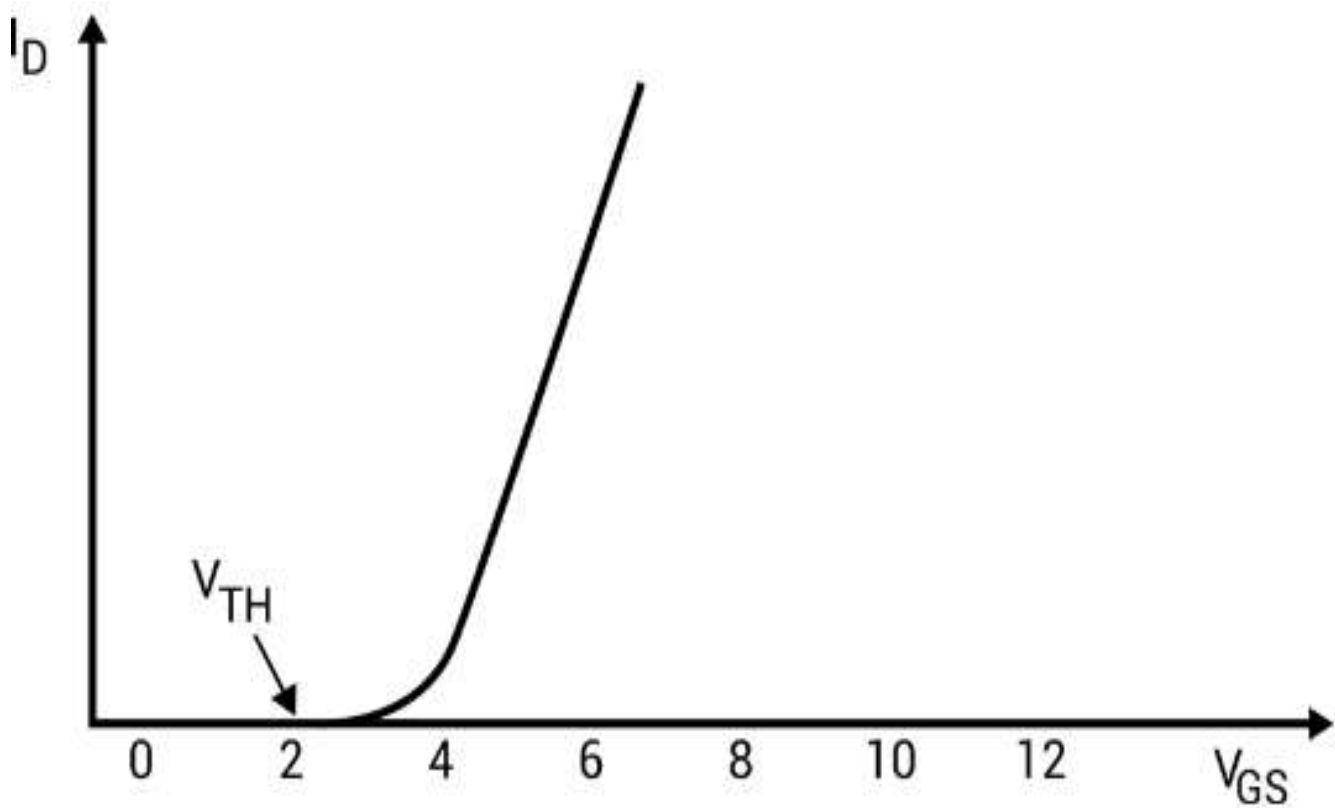
⇒ V_{DD} makes it reverse biased and no current flows from

drain to source. When $V_{GS} > 0$,

⇒ Electrons form the current path as shown in Fig. 37. Thus, current from the drain to the source flows. Now, if we will increase the gate-to-source voltage, drain current will also increase



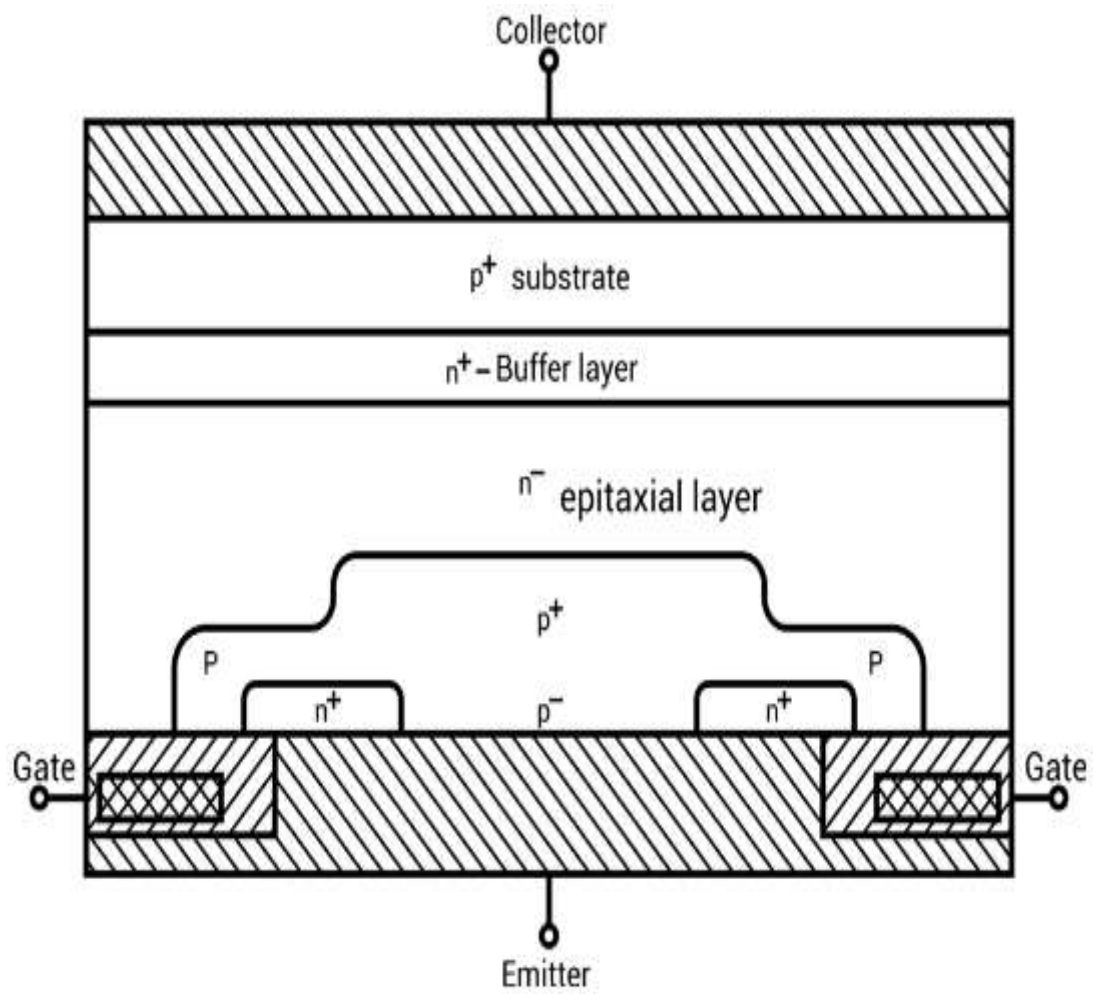
For lower value of V_{DS} , MOSFET works in a linear region where it has a constant resistance equal to V_{DS} / I_D . For a fixed value of V_{GS} and greater than threshold voltage V_{Th} , MOSFET enters a saturation region where the value of the drain current has a fixed value.



. Transfer characteristics of an n-channel enhancement power MOSFET

Insulated-Gate Bipolar Transistor (IGBT)

IGBT combines the physics of both BJT and power MOSFET to gain the advantages of both worlds. It is controlled by the gate voltage. It has the high input impedance like a power MOSFET and has low on-state power loss as in case of BJT. There is no even secondary breakdown and not have long switching time as in case of BJT. It has better conduction characteristics as compared to MOSFET due to bipolar nature. It has no body diode as in case of MOSFET but this can be seen as an advantage to use external fast recovery diode for specific applications. They are replacing the MOSFET for most of the high voltage applications with less conduction losses. Its physical cross-sectional structural diagram and equivalent circuit diagram is presented in Fig. 40 to Fig. 41. It has three terminals called collector, emitter and gate.

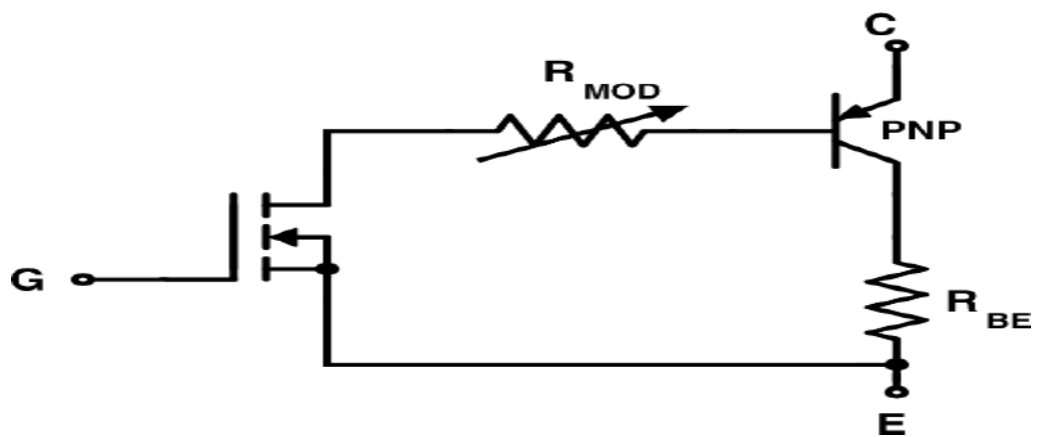
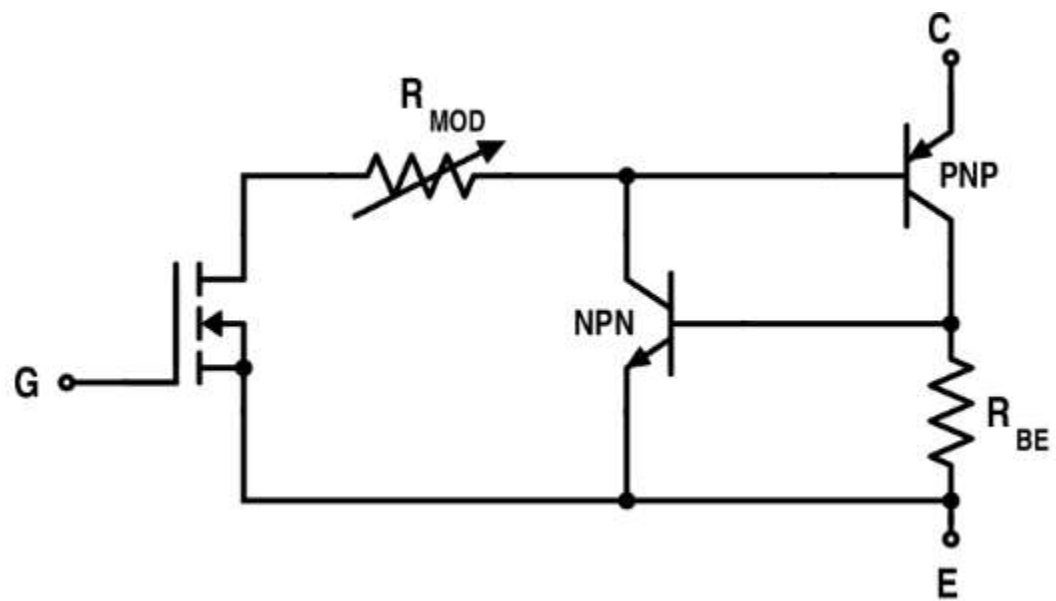


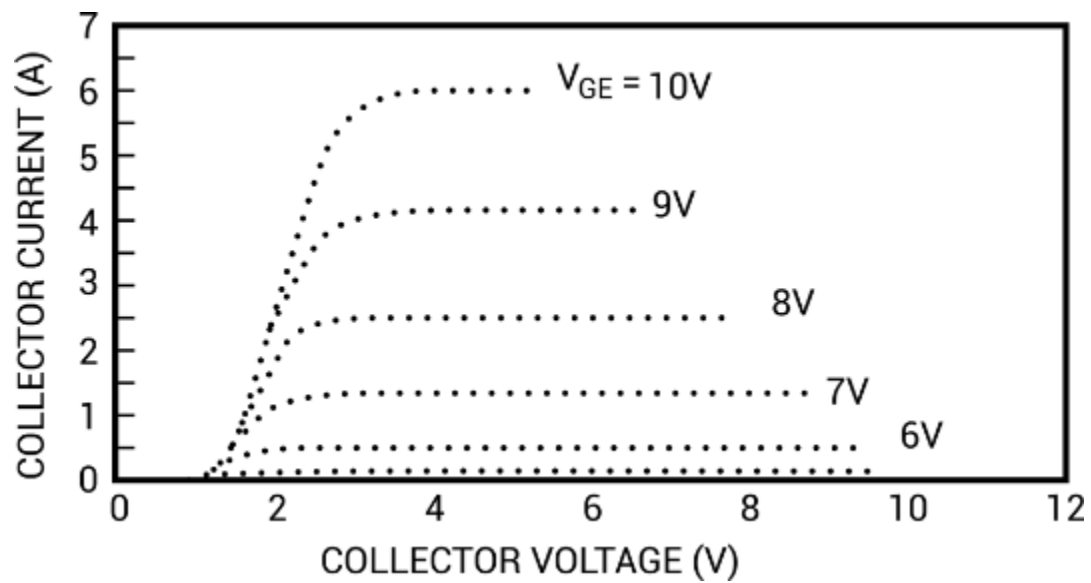
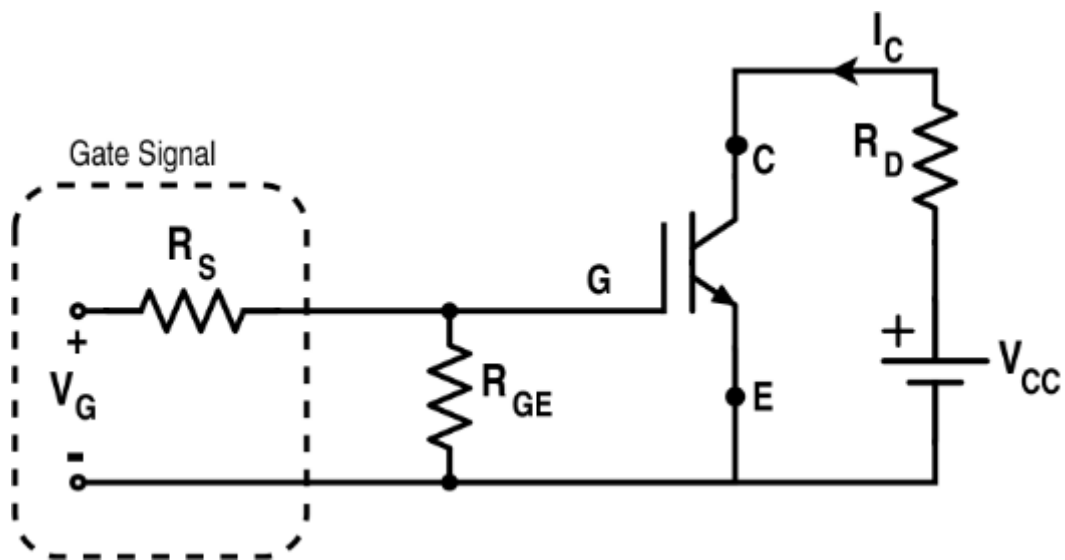
There is a p^+ substrate which is not present in the MOSFET and responsible for the minority carrier injection into the n-region. Gain of NPN terminal is reduced due to wide epitaxial base and n^+ buffer layer.

There are two structures of IGBTs based on doping of buffer layer:

- a) Punch-through IGBT: Heavily doped n buffer layer $\rightarrow$ less switching time
- b) Non-Punch-through IGBT: Lightly doped n buffer layer $\rightarrow$ greater carrier lifetime $\rightarrow$ increased conductivity of drift region $\rightarrow$ reduced on-state voltage drop

(Note: $\rightarrow$ means implies)



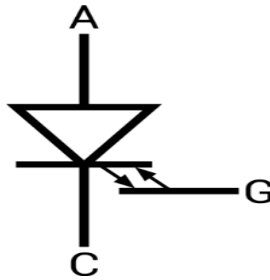


GTO (Gate Turn-off Thyristor)

GTO can be turned on with the positive gate current pulse and turned off with the negative gate current pulse. Its capability to turn off is due to the diversion of PNP collector current by the gate and thus breaking the regenerative feedback effect.

Actually the design of GTO is made in such a way that the pnp current gain of GTO is reduced. A highly doped n spot in the anode p layer form a shorted emitter effect and ultimately decreases the current gain of GTO for lower current regeneration and also the reverse voltage blocking capability. This reduction in reverse blocking capability can be improved by diffusing gold but this reduces the carrier lifetime. Moreover, it requires a special protection.

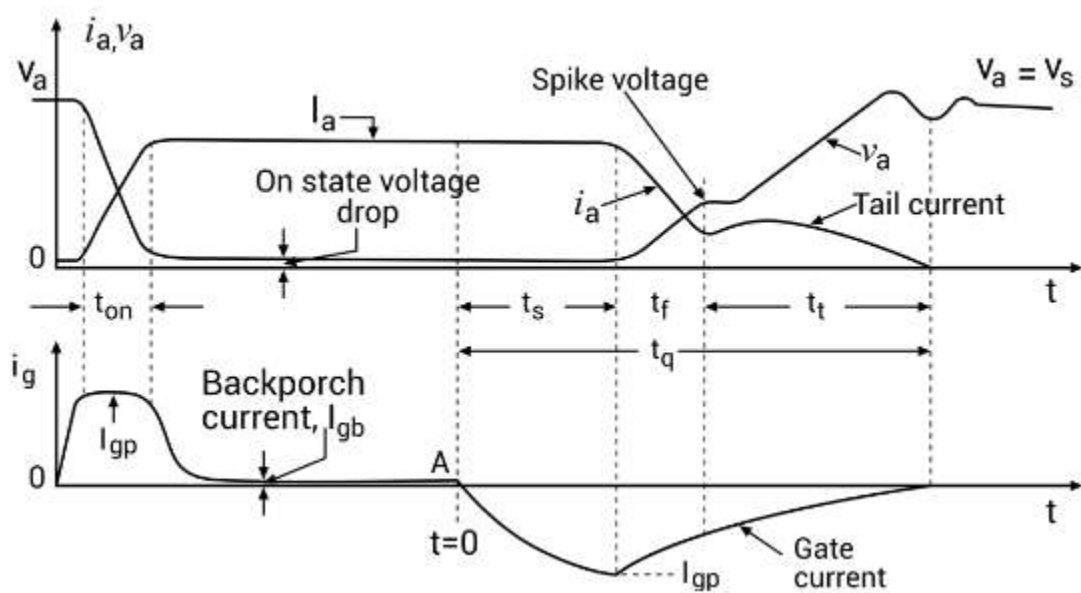
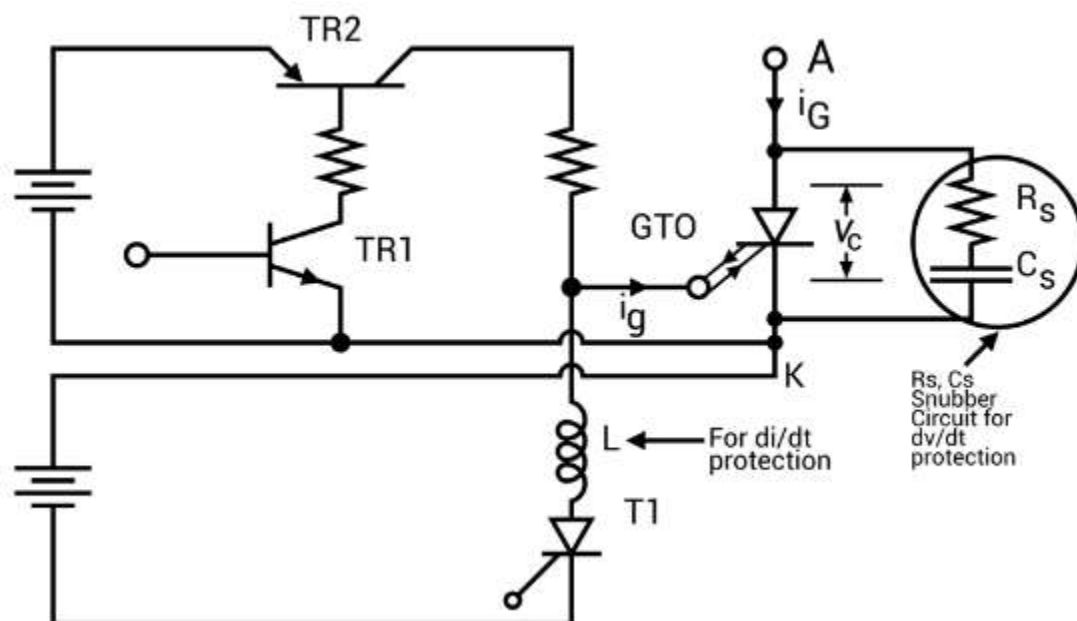
The symbol for GTO is shown in Fig



Overall switching speed of GTO is faster than thyristor (SCR) but voltage drop of GTO is larger. The power range of GTO is better than BJT, IGBT or SCR.

The static voltage current characteristics of GTO are similar to SCR except that the latching current of GTO is larger (about 2 A) as compared to SCR (around 100-500 mA).

The gate drive circuitry with switching characteristics is given in Fig. 01 and Fig. 02



SCR Specifications and Ratings:

The main specifications of the SCR are its voltage rating and current rating. In this post, let us see various ratings of thyristor.

Voltage Ratings

Peak Inverse Voltage (V_{PIV})

The peak inverse voltage is defined as the maximum voltage which SCR can safely withstand in its OFF state. The applied voltage should never be exceeded under any circumstances.

On State Voltage:

The voltage which appears across the SCR during its ON state is known as its ON state Voltage. The maximum value of voltage which can appear across the SCR during its conducting state is called its maximum on state voltage. Usually it will be 1V to 4V.

Finger Voltage:

The minimum voltage, which is required between the anode and cathode of an SCR to trigger it to conduction mode, is called its finger voltage.

Rate of Rise of Voltage (dV/dt)

The rate at which the voltage across the device rises (for forward condition) without triggering the device, is known as its rate of rise of voltage.

Voltage Safety Factor:

The normal operating voltage of the SCR is kept well below its peak inverse voltage(V_{PIV}) to avoid puncture of SCR due to uncertain conditions. The operating voltage and peak inverse voltage are related by voltage safety factor V_f

$V_f = \text{Peak inverse voltage} / (2 \times \text{RMS value of input voltage})$ Normally V_f value lies between 2 and 2.5

Current Ratings:

The current carrying capacity of the device is known as its current rating. It can be of two types.

1. Continuous
2. Intermittent

Maximum average ON state current (I_{mac}):

This is the average value of maximum continuous sinusoidal ON state current with conduction angle 180deg, at frequency 40 to 60Hz, which should not be exceeded even with intensive cooling.

Maximum rms ON-state current: (I_{mrc})

It is the rms value of the maximum continuous sinusoidal ON state current at the frequency 40 to 60 Hz and conduction angle 180deg, which should not be exceeded even with intensive cooling.

Maximum surge - ON state Current (I_{msc})

It is the maximum admissible peak value of a sinusoidal half cycle of ten milliseconds duration at a frequency of 50Hz.

Latching Current (I_l)

It is the minimum current, which is required to latch the device from its OFF state to its ON state. In other words, it is the minimum current required to trigger the device.

Holding Current (I_H)

It is the minimum current required to hold the SCR conducting. In other words, It is the minimum current, below which the device stops conducting and returns to its OFF state.

Gate Current:

The current which is applied to the gate of the device for control purposes is known as gate current.

Minimum Gate Current:

The minimum current required at the gate for triggering the device.

Maximum Gate Current:

The maximum current which can be applied to device safely. Current higher than this will damage the gate terminal.

Gate Power Loss:

The mean power loss, which occurs due to flow of gate current between the gate and the main terminals.

Turn ON time:

The time taken by the device before getting latched from its OFF state to ON state. In other words, it is the time for which the device waits before achieving its full conduction. Usually it will be 150 to 200μsec. **Turn OFF time:**

After applying reverse voltage, the device takes a finite time to get switched OFF. This time is called as turn-OFF time of the device. Usually it will be 200μsec.

Rate of rise of current (dI/dt)

The rate at which the current flowing in the device rises is known as its rate of rise (dI/dt) of current.

Sl No	BJT	MOSFET
1	It is a Bipolar Device	It is majority carrier Device
2	Current control Device	Voltage control Device.
3	Output is controlled by controlling base current	Output is controlled by controlling gate voltage
4	Negative temperature coefficient	Positive temperature coefficient
5	So paralleling of BJT is difficult.	So paralleling of this device is easy.
6	Dive circuit is complex. It should provide constant current(Base current)	Dive circuit is simple. It should provide constant voltage(gate voltage)
7	Losses are low.	Losses are higher than BJTs.
8	So used in high power applications.	Used in low power applications.
9	BJTs have high voltage and current ratings.	They have less voltage and current ratings.
10	Switching frequency is lower than MOSFET.	Switching frequency is high.

