SOLUTION OF POWER ELECTRONICS (REE-601)

SECTION A

1a) Type of power converters are: Inverter, chopper, phase controlled rectifier, cycloconverter

1b) The **latching current** is the smallest amount of anode **current** is required for preserving the thyristor in the ON condition instantly once a thyristor is turned ON then the gate signal has been detached.This **current** is connected with the process of turning ON.

1c) **Secondary breakdown** is a failure mode in bipolar power transistors. In a power transistor with a large junction area, under certain conditions of current and voltage, the current concentrates in a small spot of the base-emitter junction. This causes local heating, progressing into a short between collector and emitter.

1d) Advantage of power converters:

- Large **efficiency** due to low loss in power semiconductor devices.
- High reliability of power electronic converter systems.
- Long life and low maintenance due to the absence of any moving parts.
- Small size and less weight result in less space, therefore, lower installation **costs**.

1e) As mobility of electron is greater then hole due to which the n – type semiconductor is prefer over p- type semiconductor

SECTION B

2a) Explain the reverse recovery characteristics of power diode ; also derive the expression for it .

Ans 2a)

- Unlike in majority-carrier devices like Schottky diodes, forward current in power diodes, is due to the flow of electrons as well as holes.
- This current results in an accumulation of electrons in the p-region and of holes in the n-region.
- The charges (called "stored charge") which had been carrying forward current must be "swept out" from the junction region before the reverse non-conducting state can be established.
- When forward voltage is applied to a power diode, a short turn-on time elapses before the charges (electrons & holes) at the PN junction reach equilibrium to carry full forward current.
- This time is in terms of nanoseconds.
- Similarly when reverse voltage is applied to turn off the power diode, a short time elapses before reaching full blocking mode.
- This time is in terms of microseconds.
- When the diode is conducting (in forward conduction mode), to turn it off, reverse voltage is applied.
- As shown in the above figure, the diode current momentarily becomes negative before becoming zero .

  Ie, when the reverse voltage is applied, the forward diode current (I_F) decreases linearly(due to leakage inductance) to zero, the diode continues to conduct in the reverse direction because of the presence of stored charges in the two layers.
- The reverse current flows for a time called reverse recovery time t_{rr}.
- The t_{rr} is defined as the time between the instant forward diode current(I_F) becomes zero and the instant reverse recovery current(I_{RRM}) decays to 25% of its peak reverse value I_{RRM}.

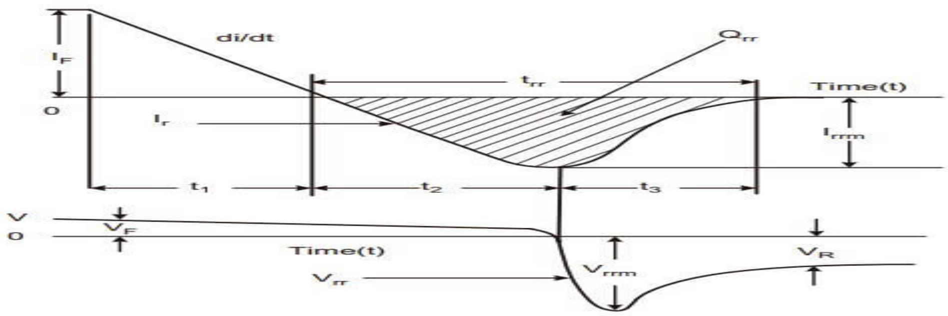
T_{rr} consists of two segments t_2 & t_3 $t_{rr} = t_2+t_3$

t_2 = time between zero crossing of forward current and peak reverse current I_{RRM}.

During this time charged stored in the depletion layer is removed.

t_3 = time between the instant I_{RRM} to the instant where 0.25 I_{RRM} is reached.
During this time, charge from the two semiconductor layers is removed.
The reverse recovery charge Q_{RR} must be removed during t_{RR}.
As a thumb rule, the lower t_{RR} the faster the diode can be switched.
The ratio of t_2/t_3 is called as softness factor.
When
The Reverse Recovery Time (t_{RR}) and Peak Inverse Current (I_{RRM}) depends on forward current(I_F).

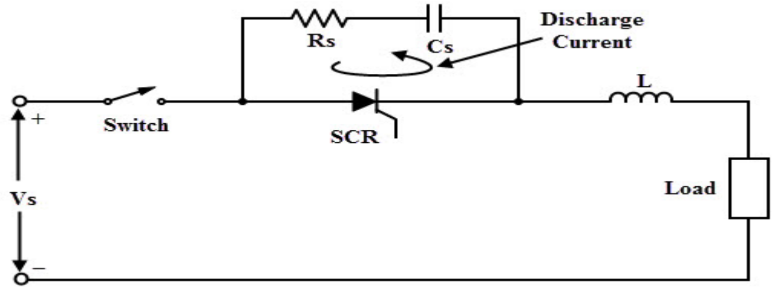
- High di/dt at turn-off causes a reverse voltage (V_{rrm}) that is higher than the applied voltage (V_R).
- Peak reverse current (I_{RM}), Stored charge (Q_{RR}), S-factor, PIV (usually mentioned in datasheets) important diode parameters to select the power diode for the particular application.



2b) Explain di/dt and dv/dt method for protection.
Ans 2b) di/dt :When a thyristor or SCR is forward biased and is turned on by gate pulse, the conduction of anode current begins in the immediate neighborhood of the gate cathode junction. Thereafter, the anode current spread over the entire gate cathode junction area. The theyristor or SCR is designed in such a way to permit the speared of current in the entire junction are as soon as possible. But in case, the rate of rise of anode current di/dt is more than the spread velocity of the current in the junction area, then there will a chance for the formation of local hot spot. Since the current rises in the vicinity of the gate to cathode junction, hot spot may be formed in that region. This hot spot formation is harmful for the SCR and may damage it.This necessitates for a method of protection of SCR from high di/dt during turn on.
dv/dt : When the SCR is forward biased, junctions J1 and J3 forward biased and junction J2 is reverse biased. This reverse biased junction J2 exhibits the characteristics of a capacitor. Therefore, if the rate of forward voltage applied is very high across the SCR, charging current flows through the junction J2 is high enough to turn ON the SCR even without any gate signal.
This is called as dv/dt triggering of the SCR which is generally not employed as it is false triggering process. Hence, the rate of rise of anode to cathode voltage, dv/dt must be in specified limit to protect the SCR against false triggering. This can be achieved by using RC snubber network across the SCR.

Working of Snubber Circuit

As we discussed above, the protection against high voltage reverse recovery transients and dv/dt is achieved by using an RC snubber circuit. This snubber circuit consists of a series combination of capacitor and resistor which is connected across the SCR. This also consist an inductance in series with the SCR to prevent the high di/dt. The resistance value is of few hundred ohms. The snubber network used for the protection of SCR is shown below.



When the switch closed, a sudden voltage appears across the SCR which is bypassed to the RC network. This is because the capacitor acts as a short circuit which reduces the voltage across the SCR to zero. As the time increases, voltage across the capacitor builds up at slow rate such that dv/dt across the capacitor is too small to turn ON the SCR. Therefore, the dv/dt across the SCR and the capacitor is less than the maximum dv/dt rating of the SCR.
Normally, the capacitor is charged to a voltage equal the maximum supply voltage which is the forward blocking voltage of the SCR. If the SCR is turned ON, the capacitor starts discharging which causes a high current to flow through the SCR.

This produces a high di/dt that leads to damage the SCR. And hence, to limit the high di/dt and peak discharge current, a small resistance is placed in series with the capacitor as shown in above. These snubber circuits can also be connected to any switching circuit to limit the high surge or transient voltages.

2c) Explain the significance of latching and holding currents.
Ans 2c) HOLDING CURRENT: The holding current for different devices like electronic, electrical, and electromagnetic is the smallest amount current which should flow throughout a circuit to maintain the 'ON' state. This can be useful for a single switch otherwise to a complete device. The best example of holding current is within a spark gap.
Generally in basic circuits, whenever the flow of current drops under the holding current, then the circuit will be turned 'OFF'. But, complex devices and circuits may contain dissimilar delays fixed among the time when the flowing current drops below this level & the time when the device is switched OFF.
A design issue in a circuit is when the flow of current is restored in case a device is switched ON. The threshold current can be defined as the required current to reinstate the circuit to the 'ON' state, possibly much better than the holding current.
But, wherever the device is considered to switch 'ON' for current restoration & wherever the circuit is working at small differences in the current, then it can reason for flicker when the device cycles ON & OFF.
LATCHING CURRENT: The latching current is the smallest amount of anode current is required for preserving the thyristor in the ON condition instantly once a thyristor is turned ON then the gate signal has been detached.
This current is connected with the process of turning ON. The worth of this current is around two to three times to that of holding current. The worth of holding current as well as latching current is stable. So it does not be dependent on the magnitude of gate current.
Holding Current in SCR

Holding current in thyristor or SCR can be defined as, the smallest amount of current under which anode current has to drop to enter OFF status. This means, if the holding current value is 5 mA, subsequently thyristor's anodes current have to turn into less than 5 mA to discontinue performing.

Latching Current in SCR

The minimum current is the Latching current of SCR in forwarding bias which anode current has to achieve to maintain to stay in the mode of forwarding conduction even as gate current is detached. If the anode current value is under this value, then the SCR will not maintain to perform in the direction of forward if the gate current is detached. However when anode current turns into greater than latching current, then the gate terminal loses its power & it may be detached. Finally, the SCR will go on to conduct.

2d) Basic structure and working of IGBT.

Ans 2d) **IGBT** is a relatively new device in power electronics and before the advent of IGBT, Power MOSFETs and Power BJT were common in use in power electronic applications. Both of these devices possessed some advantages and simultaneously some disadvantages. On one hand, we had bad switching performance, low input impedance, secondary breakdown and current controlled Power BJT and on the other we had excellent conduction characteristics of it. Similarly, we had excellent switching characteristics, high input impedance, voltage controlled PMOSFETs, which also had bad conduction characteristics and problematic parasitic diode at higher ratings. Though the unipolar nature of PMOSFETs leads to low switching times, it also leads to high ON-state resistance as the voltage rating increases.

The **structure of IGBT** is very much similar to that of PMOSFET, except one layer known as injection layer which is p^+ unlike n^+ substrate in PMOSFET. This injection layer is the key to the superior characteristics of IGBT. Other layers are called the drift and the body region. The two junctions are labeled J_1 and J_2. Figure below show the structure of n-channel 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 ($>V_{GET}$) with respect to emitted. 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.

The collector current I_c in IGBT constitutes of two components- I_e and I_h. I_e is the current due to injected electrons flowing from collector to emitter through injection layer, drift layer and finally the channel formed. I_h is the hole current flowing from collector to emitter through Q_1 and body resistance R_b. Although I_h is almost negligible and hence $I_c \approx I_e$.

A peculiar phenomenon is observed in IGBT known as Latching up of IGBT. This occurs when collector current exceeds a certain threshold value (I_{CE}). In this the parasitic thyristor gets latched up and the gate terminal loses control over collector current and IGBT fails to turn off even when gate potential is reduced below V_{GET}. For turning OFF of IGBT now, we need typical commutation circuitry as in the case of forced commutation of thyristors. If the device is not turned off as soon as possible, it may get damaged.

3a) Draw the I-V characteristics of SCR

Ans 3a) <u>Forward Blocking Mode [V_{AK} = +ve & V_G = 0]</u>

- When a positive voltage is applied to anode with respect to cathode, the junctions J1 and J3 are forward biased, junction J2 is reverse biased.
- The SCR is in Forward Blocking state. At this time the Gate signal is not applied.
- A depletion layer is formed in junction J2 and no current flows from anode to cathode.

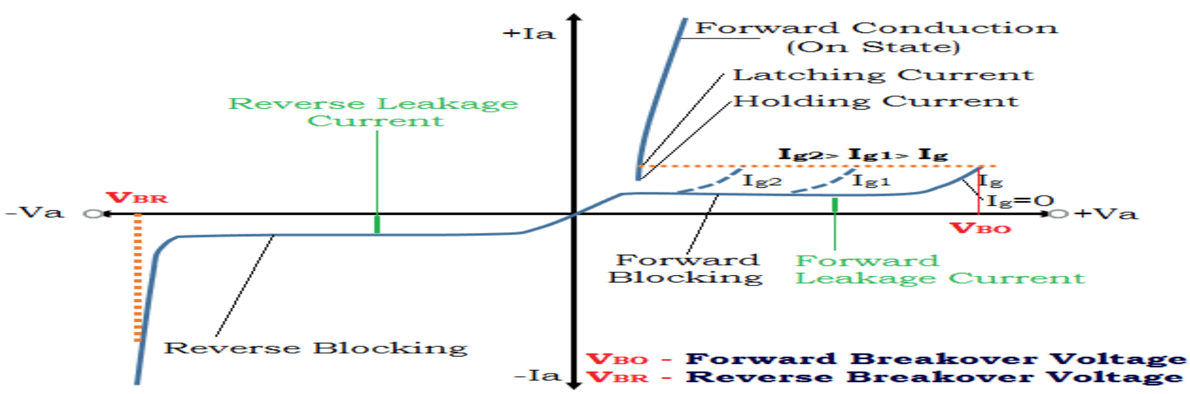
- As shown in VI Characteristic, a small amount of current called *forward leakage current* flows through the device.

<u>Forward Conducting Mode [V_{AK} = +ve & V_G = +ve]</u>

- When the small amount of positive voltage is applied to gate terminal, while positive voltage is applied to anode with respect to cathode, the junction J3 becomes forward biased.
- So the SCR acts as a closed switch and conducts a large value of forward current with small voltage drop.
- With the application of gate signal the SCR changed from forward blocking state to forward conducting state. It is called as *latching*.
- Without gate signal SCR changed from forward blocking state to forward conducting state at *forward breakdown voltage (V_{fbd})*.
- When the gate signal value is increased, the latching happens for low V_{ak} voltages as mentioned in the figure.
- In the presence of forward current (i.e. after the thyristor is turned on by a suitable gate voltage) it will not turn off even after the gate voltage has been removed. The thyristor will only turn off when the forward current drops below holding current.
- The *holding current* is defined as the minimum current required to hold the SCR in the forward conduction

<u>Reverse Blocking Mode [V_{AK} = -ve]</u>

- When a negative voltage is applied to anode with respect to cathode, the junctions J1 and J3 are reverse biased, but the junction J2 is forward biased.
- The SCR is in its reverse blocking state. ie, it acts as an open switch.
- As shown in figure a small amount of reverse leakage current flows through the device.



3b) Explain the different method use for turn-on of SCR

Ans 3 b) The various SCR triggering methods are

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

<u>(a) Forward Voltage Triggering:-</u>

- 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 flows due to depletion region in J2 are 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)

<u>(b) Thermal (or) Temperature Triggering:-</u>

- 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.

<u>(c) Radiation Triggering (or) Light Triggering:-</u>

- 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

<u>(d) dv/dt Triggering:-</u>

- 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,

$$I=C$$

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.

<u>(e) Gate Triggering:-</u>

- 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.

4a) Compare power MOSFET and Power BJT.

Ans 4a)

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

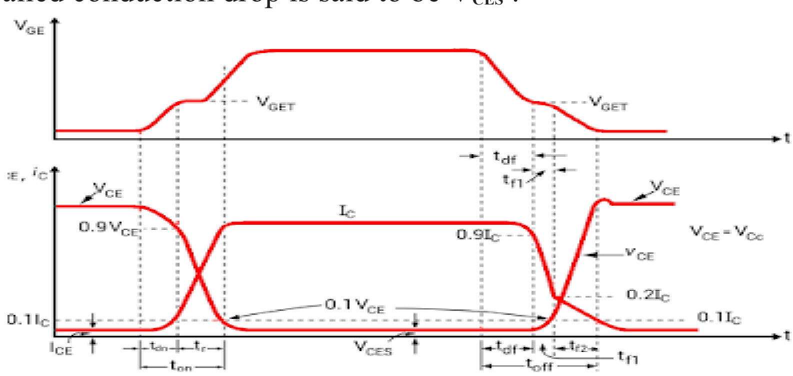
5	So paralleling of BJT is difficult.	So paralleling of this device is easy.
6	Dive circuit is complex. It should provide constant current(Base current)	Dive circuit is simple. It should provide constant voltage(gate voltage)
7	Conduction Losses are low.	Losses are higher than BJTs.
8	So used in high 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 and switching loss is low

4b) Draw and explain switching characteristics IGBT

Ans 4b) IGBT switching characteristics

Switching characteristics of an IGBT during turn-on and turn-off are sketched in fig. Turn on time is defined as the time between the instant of forward blocking to forward on state. Turn on time is composed of delay time t_{dn} and rise time ton = t_{dn} +t_r.

- The delay time is defined as the time for the collector emitter voltage to fall from V_{CE} to 0.9 V_{CE}. Here V_{CE} is the initial collector emitter voltage.
- Time t_{dn} may also be defined as the time for the collector current to rise from its initial leakage current I_{CE} to 0.1 I_c. Here I_c is the final value of collector. The rise time t_r is the time during which collector-emitter voltage fall from V_{CE}.
- It is also defined as the time for the collector current to rise from 0.1 I_C to its final value I_C. After time t_{on}, the collector current I_C is and the collector-emitter voltage fall to small value called conduction drop is said to be V_{CES} .

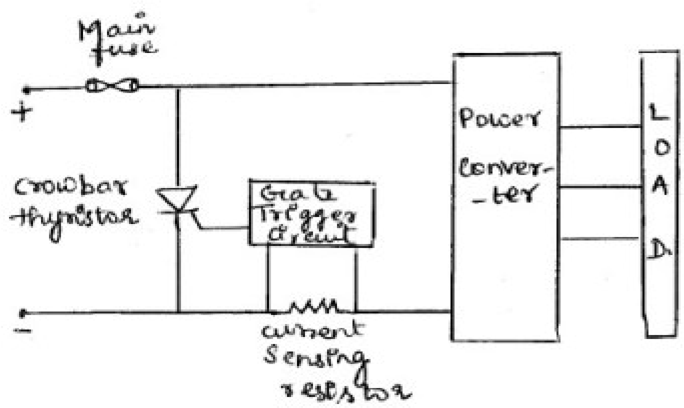


- The turn-off time is somewhat complex.
- It consists of three intervals : (i) delay time , (ii) initial fall time and (iii) final fall time.
- $t_{off} = t_{df} + t_{f1} + t_{f2.}$
- The delay time is the time during which gate voltage fall forms V_{GE} to threshold V_{GET}.
- As V_{GE} falls to V_{GET} during t_{df}, the collector current falls from I_c to 0.9 I_c . At the end of t_{df}, collector emitter voltage begins to rise.
- The first fall time t_{f1} is defined as the time during which collector current fall from 90 to 20 % of its initial value of current I_C, or the time during which collector emitter voltage rise from V_{CES} to 0.1 V_{CE}.
- The final fall time t_{f2} is the time during which collector current fall from 20 to 10% of

I_c or the time during which collector emitter voltage rise from 0.1 V_{CE} to final value V_{CE} .

5a) Explain crowbar protection of thyristor .

Ans5a)



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

5b) Draw and Explain the Switching characteristics of SCR.

Ans 5 b) Turn ON Time of SCR

A forward biased thyristor can be turned on by applying a positive voltage between gate and cathode terminal. But it takes some transition time to go from forward blocking mode to forward conduction mode. This transition time is called **turn on time of SCR** and it can be subdivided into three small intervals as delay time (t_d) rise time(t_r), spread time(t_s).

Delay Time of SCR

After application of gate current, the thyristor will start conducting over a very tiny region. **Delay time of SCR** can be defined as the time taken by the gate current to increase from 90% to 100% of its final value I_g. From another point of view, **delay time** is the interval in which anode current rises from forward leakage current to 10% of its final value and at the same time anode voltage will fall from 100% to 90% of its initial value V_a.

Rise time of SCR : In the time taken by the anode current to rise from 10% to 90% of its final value. At the same time anode voltage will fall from 90% to 10% of its initial value V_a. The phenomenon of decreasing anode voltage and increasing anode current is entirely dependent upon the type of the load. For example if we connect a inductive load, voltage will fall in a faster rate than the current increasing.

This is happened because induction does not allow initially high voltage change through it. On the other hand if we connect a capacitive load it does not allow initial high voltage change through it, hence current increasing rate will be faster than the voltage falling rate.

High increasing rate of di_a/dt can create local hot spot in the device which is not suitable for proper operation. So, it is advisable to use a inductor in series with the device to tackle high di_a/dt. Usually, the value of the maximum allowable di/dt is in the range of 20 to 200 A per microsecond

Spread Time of SCR: It is the time taken by the anode current to rise from 90% to 100% of its final value. At the same time the anode voltage decreases from 10% of its initial value to smallest possible value. In this interval of time conduction spreads all over the area of cathode and the SCR will go to fully ON State**. Spread time of SCR** depends upon the cross-sectional area of cathode.