CHAPTER - 3

SWITCHING CHARACTERISTICS OF POWER SEMI CONDUCTOR DEVICES

3.1. Introduction:

Power transistors have controlled turn-on and turn-off characteristics. The transistors which are used as switching elements, are operated in the saturation region, resulting in a low on-state voltage drop. The switching speed of modern transistors is much higher than that of thyristors and they are extensively employed in dc-dc and dc-ac converters, with inverse parallel connected diodes to provide bidirectional current flow.

The power transistors can be classified as follows :

1. Bipolar Junction Transistor (BJTs)
2. Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs)
3. Insulated Gate Biplar Transistors (IGBTs)

When power transistor conduct an appreciate current, the forward voltage drop is in the order of 0.3 to 0.8V as compared to 1.2 to 2V for thyristors. Therefore the power loss in a power transistor is lower than that in a thyristor of similar power rating.

3.2. Bipolar Junction Transistors :

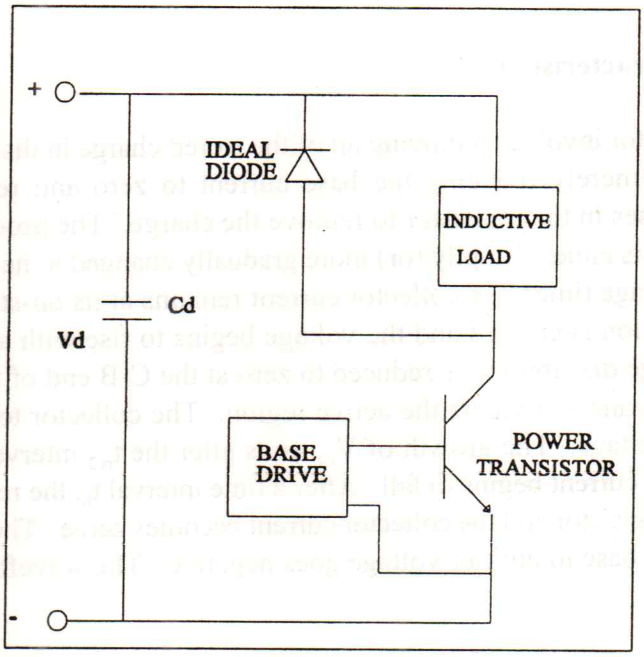
Theory:

As is well known, the bipolar junction transistor is a three layer device with emitter(E), base(B) and collector (C) regions. The term bipolar indicates that current flow consists of a movement of both positive and negative charges, that is holes and electrons. The outer elements may be of N-type material, separated by a P-type base region. This is the N-P-N transistor which has the circuit symbol shown. Alternatively an N-type base region separates P-type elements, giving PNP transistor.

For a normal transistor operation, the base-emitter junction is forward biased and the emitter acts as a source of mobile carriers which enter the base region, these injected carriers are electroncs in the NPN transistor. In general, the emitter region is made of heavily doped material to increase the number of injected carriers, which become minority carriers when they enter the base. Most of these minority carriers diffuse through the base region, which is vary narrow, and arrive at the collector base junction. This junction is reversed by an external voltage and hence the minority base carriers injected by the emitter are swept into the collector region by the electric field at the collector base junction. Some electron recombine in the base region and do not reach the collector. Hence, collector current I_c is slightly less than emitter current I_E.

There are three operating regions of a transistor: cut-off, active and saturation. In the cut-off region, the transistor is off (or) thebase current is not enough to turn it on and both junctions are reversed biased. In the active regions, the transistor acts as an amplifier, where the collector current is amplified by a gain and the collector-emitter voltage decreases with the base current. The collector-base junction is reverse biased and base emitter junction is forward biased. In the saturation region, the base current is sufficiently high so that the collector-emitter voltage is low, and the transistor acts as a switch. Both junctions are forward biased.

3.2.1. Turn-On Characteristics of BJT:



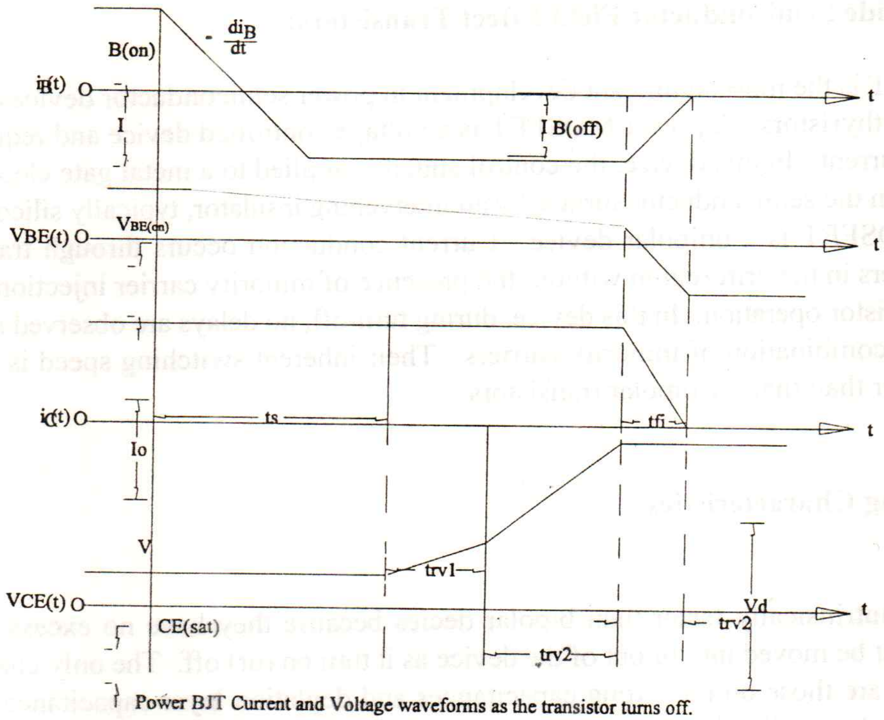
•Fig:3.1. Switching Circuit of BJT

BJT switching circuit with a free wheeling diode clamp is shown in the figure(3.1). To switch the transistor from the off-state to the on-state, charge must be supplied to the transistor so that stored charge distributions are established and maintained in the transistor. The characteristics of the transistor and of the external circuit in which the device is embedded interact to determine just how fast the device can turn-on. The external circuit determines the collector current that can flow in the on-state. The stored charge distribution grows during turn-on for a forward-bias base current applied at t=0. For an initial time period called the turn-on delay time t_d(on), there is no build-up of stored charge because the negative charge on the base-emitter space charge capacitance must be discharged and the junction forward biased so that carrier injection can commence. During this interval only base current flows and only the base-emitter voltage changes.

After the t_d (on) interval, the base-emitter junction is forward biased and the growth of the stored charge proceeds and the collector current rises quickly, reaching its on-state value in a timer t_{ri}, and current rise time. The voltage V_{CE} is unchanged during this interval because of the diode clamp so that the transistor is still in the active region. After the t_{ri} interval, the collector-emitter voltage falls quickly since the diode no longer can act as a clamp. After a short interval t_{fv1}, quasi-saturation is entered as carrier injection into the drift region begins from the C-B junction. During quasi-saturation, the rate of the collector voltage falls slow because of the reduction in beta that accompanies transistor operation in quasi saturation. Hard saturation commences when the excess carriers have completely swept across the drift region, which occurs after the timer interval t_{vf2} indicated on the switching waveforms. The waveforms are shown in the figure (3.3).

3.2.2 Turn-Off Characteristics

Turn-off of the transistor involves removing all of the stored charge in the transistor. This could be accomplished by merely reducing the base current to zero and relying on the internal recombination processes in the transistor to remove the charge. The process is initiated at t=0, when the base current is either abruptly (or) more gradually changed to negative-bias value. For a time interval t_s (storage time), the collector current remains at its on-state value. After the t_s interval, quasi-saturation is entered and the voltage begins to rise with a rather shallow slope. When the stored charge distribution is reduced to zero at the C-B end of the drift region after a time interval t_{rv1}, the transistor enters the active region. The collector to emitter voltage (V_{ce}) increases to supply voltage. The growth of V_{CE} ends after the t_{rv2} interval shown in the figure (3.2), and the collector current begins to fall. After a time interval t_{fi}, the rest of the stored charge is removed from the transistor and the collector current becomes zeroe. The transistor now enters into cut-off region and base to emitter voltage goes negative. The waveforms are shown in the figure (3.2).



Power BJT Current and Voltage waveforms as the transistor turns off.

Fig - 3.2 Power BJT Current and Voltage waveforms as the transistor turns off

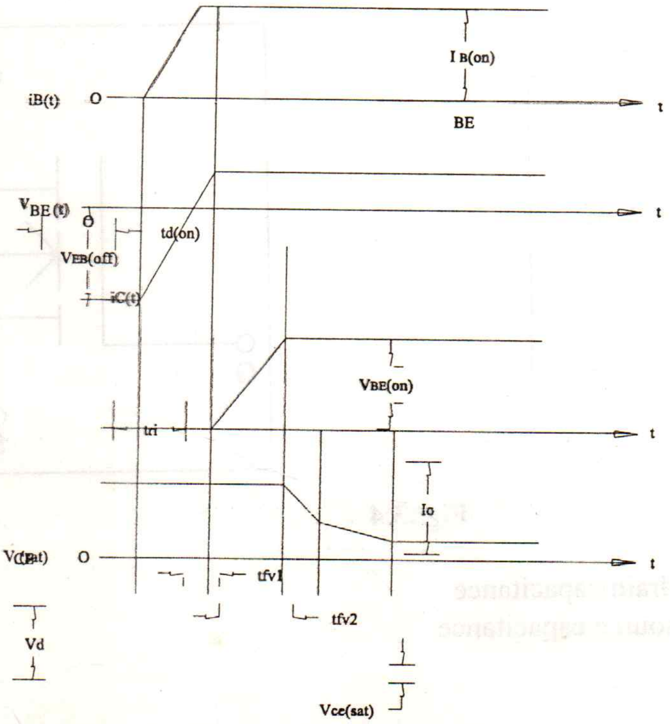


Fig - 3.3 Power BJT Currnet and Voltage waveforms as the transistor turns on

3.3. Metal-Oxide Semiconductor Field Effect Transistors:

Power MOSFET is the most significant development in power semiconductor devices since the introduction of thyristors. A power MOSFET is a voltage controlled device and requires only a small input current. In this device, the control signal is applied to a metal gate electrode that is separated from the semiconductor surface by an intervening insulator, typically silicon dioxde. The power MOSFET is a unipolar device. Current conduction occurs through transport of majorities carriers in the drift region without the presence of minority carrier injection required for bipolar transistor operation. In this device, during turn-off, no delays are observed as a result of storage or recombination of minority carriers. Their inherent switching speed is orders of magnitude faster than that for bipolar transistors.

3.3.1. Switching Characteristics

MOSFETs are intrinsically faster than bipolar decies because they have no excess minority carriers that must be moved into or out of the device as it turn on (or) off. The only charges that must be moved are those on the strong capacitances and depletion layer capacitances. These capaticances can be modled by the equivalent circuit shown in the figure (3.4), which is valid when the MOSFET is in cutoff (or) in the active region. Circuit models such as this are needed for turn-on and turn-off characteristics of MOSFET.

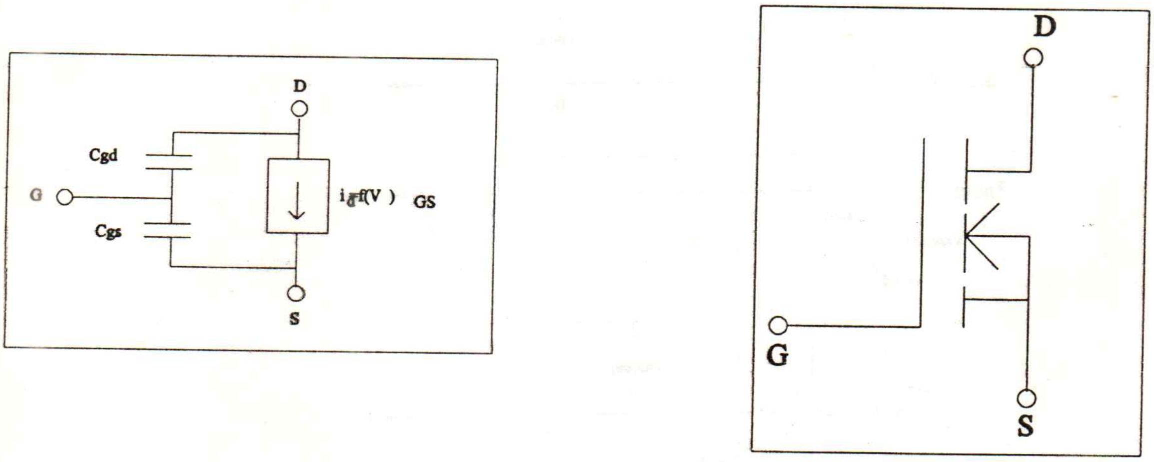


Fig .3.4

where c_{gd} = gate-drain capacitance
c_{gs} = gate-source capacitance

3.3.2. Turn-On Characteristics:

The turn-on waveforms are shown in the figure (3.6), where the gate drive voltage changes in a step function manner at t=0 from zero to V_{GG}, which is well above V_{GS} (threshold). V_{GG} is an ideal voltage source which drives the gate of the MOSFET. During the turn-on delay time t_d(on) the gate-source voltage V_{GS} rises from zero to V_{GS} (th) because of the currents flowing through C_{GS} and C_{GD}. The rate of rise of V_{GS} in this region is almost linear, although it is a part of an exponential curve, which has a time constant $T_1 = R_G (C_{GS} + C_{GD1})$, where R_G is the gate resistance. Beyond V_{GS}(th), V_{GS} continues to rise as before, and the drain current begins to increase. In switching circuit, the inductive load is connected in parallel with the free wheeling diode D1. The current flow through the inductive load is I_O.

The circuit shown in the figure (3.5).

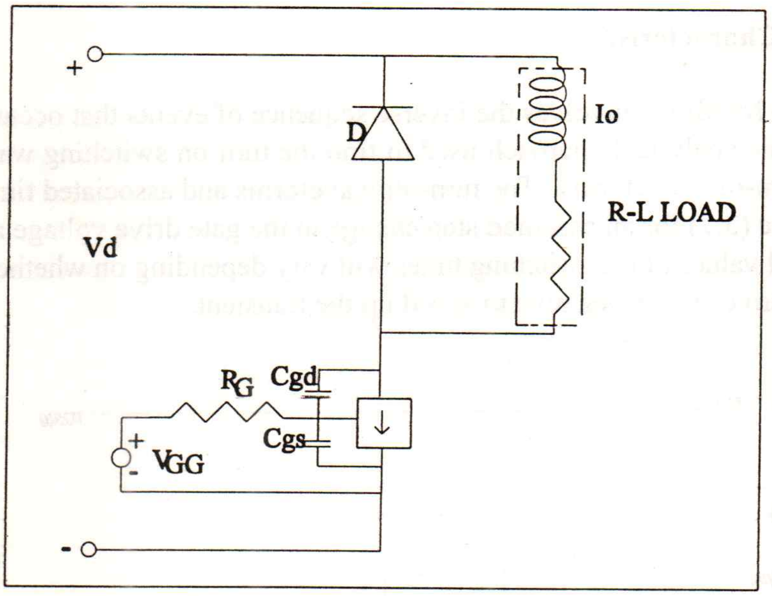


Fig 3.5. Switching circuit of MOSFET.

The drain-source voltage remains at Vd as long as $i_D < I_O$ and the free wheeling diode D is conducting. The time required for i_D to build up from zero to I_O is the current rise time t_{ri}.

Once the MOSFET is carrying the full load current I_O but is still in the active region, the gate-source voltage becomes temporarily clamped at V_{GS}, I_O, which is the gate-source voltage needed to maintain $i_D = I_O$.

The gate current i_G, which is given by

$$i_G = \frac{V_{GG} - V_{GS,\ I_O}}{R_G}$$

flows through C_{GD}.

The decrease in V_{DS} occurs in two different time intervals t_{fv1} and t_{fv2}. The first time interval corresponds to the traverse through the active region where $c_{gd} = c_{gd1}$. The second time interval corresponds to the completion of the transient in the ohmic region and $c_{gd} = c_{gd2}$.

Once the drain-source voltage has completed its drop to the on-state value of IorDS (on), the gate-source voltage becomes unclamped and continues its exponential growth to $V_{GG.}$ This part of the growth occurs with a time constant $T_2 = R_G\ (c_{gs}\ + c_{gd2})$, and simultaneously the gate current decays toward zero with the same time constant as is shown in the waveforms.

3.3.3. Turn-Off Characteristics:

The turn-off of the MOSFET involves the inverse sequence of events that occured during turn-on. The same basic analytical approach used to find the turn-on switching waveforms can be used to find the turn-off waveforms. The turn-off waveforms and associated timer intervals are shown in the figure (3.7) for an assumed step change in the gate drive voltage at t=0 from V_{GG} to zero. The actual values of the switching times will vary depending on whether the gate drive voltage is set to zero or made negative to speed up the transient.

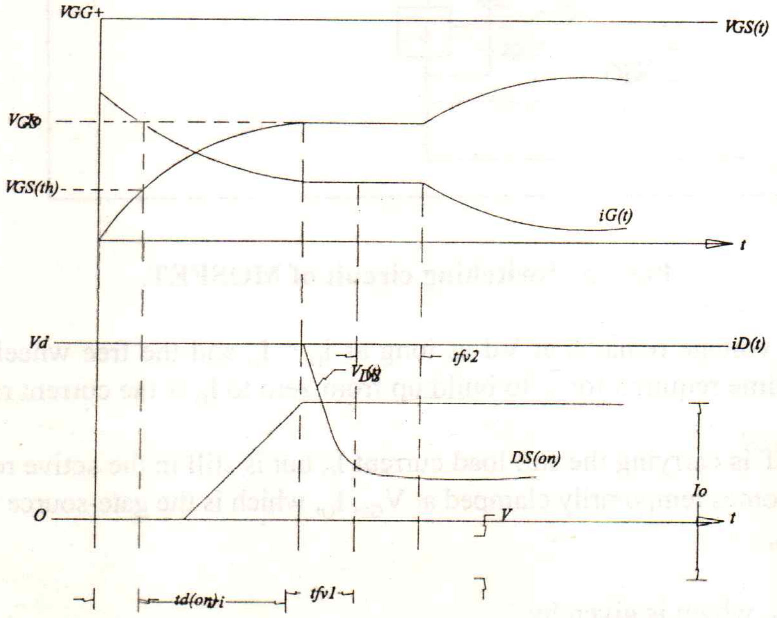


Fig 3.6. The MOSFET Voltage and Current waveforms at turn-on

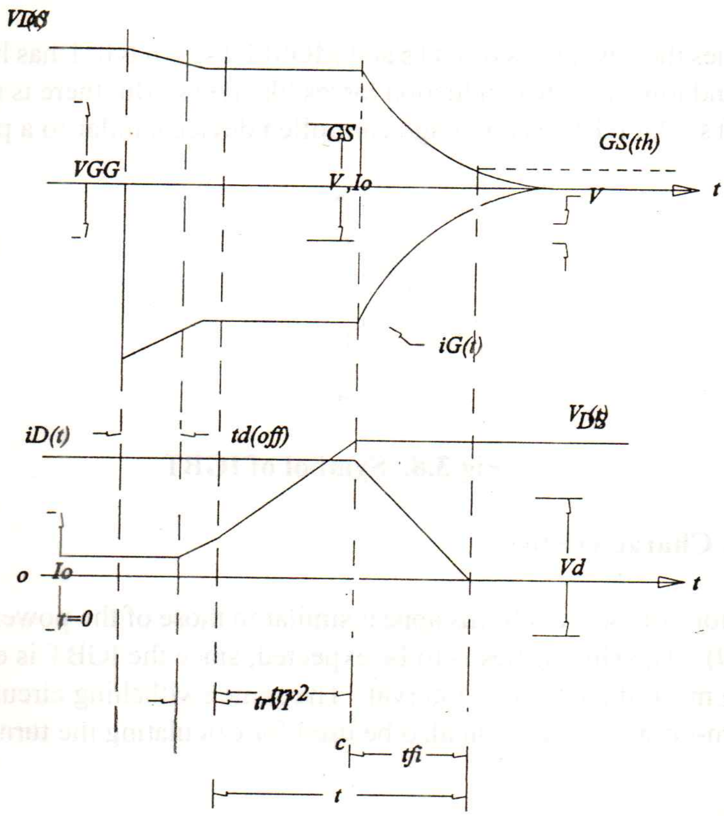


Fig 3.7 The MOSFET Current and Voltage waveforms at turn-off

3.4. Insulated Gate Bipolar Transistors:

An IGBT combines the advantates of BJTs and MOSFETs. An IGBT has high input impedance, like MOSFETs and low on-state conduction losses like BJTs. But there is no second breakdown problem like BJTs. An IGBT is a voltage controlled device similar to a power MOSFETs.

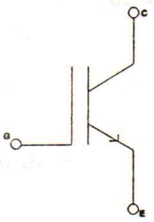


Fig 3.8. Symbol of IGBT

3.4.1. Turn-On Characteristics

The turn-on portions of the waveforms appear similar to those of the power MOSFET as shown in the figure (3.9). The similarities is to be expected, since the IGBT is essentially acting as a MOSFET during most of the turn-on interval. The same swithching circuit used for discussing the MOSFET turn-on waveforms can also be used for calculating the turn-on characteristics of IGBT.

The t_{fv2} interval observed in the MOSFET drain-source voltage waveform in figure (3.9) is isually observed in the IGBT drain-source voltage waveform. Two factors will contributed to the t_{fv2} interval in the IGBT waveform. First the gate-drain capacitance C_{gd} will increase in the MOSFET portion of the IGBT at low drain-source voltages in a manner similar to that observed with power MOSFET. Second the PNP transistor portion of the IGBT traverses the active region to its on state more slowly than the MOSFET portion of the IGBT.

3.4.2. Turn-Off Characteristics

The turn-off voltage and current waveforms for the IGBT are shown in the figure (3.10). The intial time intervals, the turn-off delay time td (off), and the voltage rise time t_{rv} are governed by the MOSFET portion of the IGBT. In the drain current waveform, there are two different time intervals. The rapid drop that occurs during the t_{fi1} interval corresponds to the turn-off of the MOSFET section of the IGBT. The tailing of the drain current during the second interval t_{fi2} is due to the stored charge. Since the MOSFET section is off and there is no reverse voltage applied to the IGBT terminals that could generate a negative drain current, there is no possibility for removing the stored charge by carrier sweep out. These excess carriers can be removed by recombination process. Since it is desirable that the excess carrier life time in this region be large so that the on-state voltage drop i slow, then the duration of the t_{fi2} interval at turn-off till be correspondingly long. The power dissipation in this interval is very large. So the long interval is undesirable.

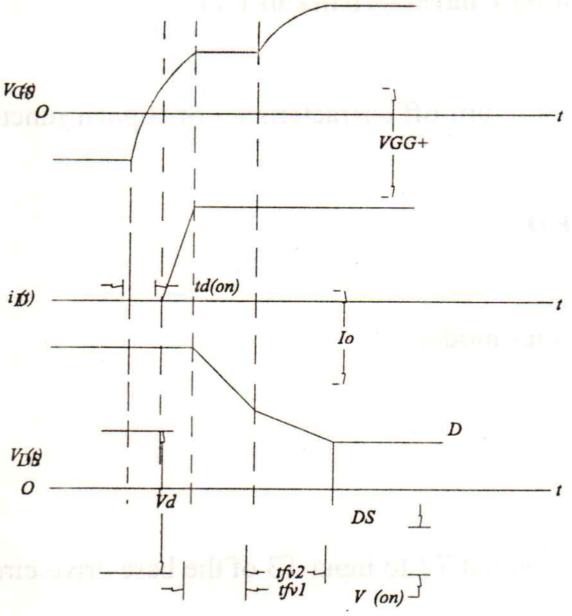


Fig 3.9 Turn-on voltage and current waveforms of an IGBT

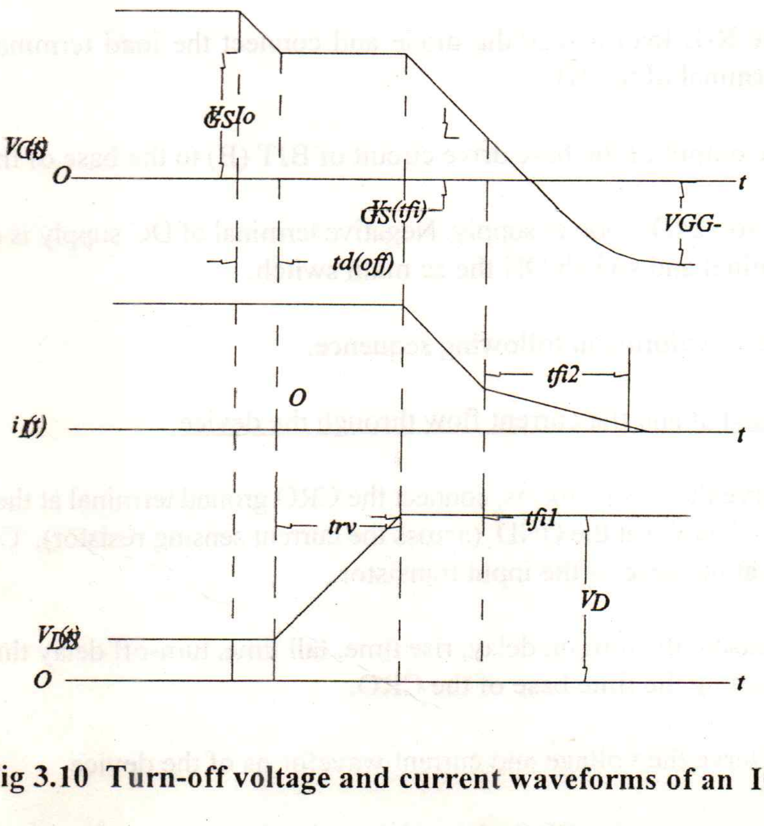


Fig 3.10 Turn-off voltage and current waveforms of an IGBT

EXPERIMENT 1: Switching Characteristics of BJT

AIM : To study the turn-on and turn-off characteristics of Bipolar junction transistors.

EQUIPMENTS REQUIRED :

1. Step down transformer.
2. Switching characteristics module.
3. CRO.
4. Patch chords.

PROCEDURE :

1. Connect the oscillator output T1 to input T3 of the base drive circuit of BJT.

2. Set the output frequency of the oscillator (switching frequency) either at 2KHz (or) 4 Khz by using the switch SW1.

3. Connect the R-L load across the diode and connect the load terminal L2 to anyone collector terminal of the BJT.

4. Connect the output of the base drive circuit of BJT (B) to the base of the BJT (B1).

5. Connect L1 to +24DC power supply. Negative terminal of DC supply is connected to the ground terminal and switch ON the ac main switch.

6. Observe the waveforms in following sequence.

   i) Gating signal and the current flow through the device.

   To observe these waveforms, connect the CRO ground terminal at the emitter and the channel - 2 probe at the GND. (across the current sensing resistor). Connect channel-1 probe at the base of the input transistor..

   Now measure the turn-on delay, rise time, fall time, turn-off delay time, storage time by expanding the time base of the CRO.

   ii) Now observe the voltage and current waveforms of the device.

   For this, remove the CRO channel-1 probe from the base and connect it to the collector terminal of the transistor.

7. Plot these waveforms on a graph sheet, mark turn-on, turn-off time on this graph sheet.
8. Tabulate the measured values of turn-on and turn-off timings in Table-1.

TABLE-1

Sl.No.	Frequency Position.	Turn-on time	Turn-off time

EXPERIMENT-2: Switching Characteristics of MOSFET

AIM : To study the turn-on and turn-off characteristics of MOSFET.

EQUIPMENTS REQUIRED :

1. Step down transformer
2. Switching characteristis Module .
3. CRO.
4. Patch chords.

PROCEDURE :

1. Connect the oscillator output T1 to input T2 of base drive circuit of MOSFET.
2. Set the output frequency of the oscillator (Switching frequency) either at 2KHz (or) 4 Khz by using the switch SW1. Observe the output waveforms of oscillator on a CRO at T1.
3. Connect the RL load across the diode and connect the load terminal L2 to drain terminal (D) of the MOSFET.
4. Connect the output of the base drive circuit of MOSFET to the gate terminal (F2) of the MOSFET.
5. Connect 4 to +24 V DC power supply. Negative terminal of DC supply is connected to the ground terminal.
6. Switch ON the main supply.
7. Observe the waveforms in following sequence.

   i) Gating signal and the current flow through the device.

   To observe these waveforms, connect the CRO ground terminal at the drain and the channel - 2 probe at the GND. (across the current sensing resistor). Connect channel-1 probe at the gate of the input transistor..

   Now measure the turn-on delay, rise time, fall time, turn-off delay time, storage time by expanding the time base of the CRO.

ii) Now observe the voltage and current waveforms of the device.

For this, remove the CRO channel-1 probe from the base and connect it to the source terminal of the transistor.

8. Plot these waveforms on a graph sheet, mark turn-on, turn-off time on this graph sheet.
9. Tabulate the measured values of turn-on and turn-off timings in Table-2.

TABLE - 2

Sl.No.	Frequency Position.	Turn-on time	Turn-off time

EXPERIMENT 3: Switching Characteristics of IGBT

AIM : To study the turn-on and turn-off characteristics of IGBT.

EQUIPMENTS REQUIRED :

1. Step down transformer
2. Switching characteristicsModule.
3. CRO.
4. Patch chords.

PROCEDURE :

1. Connect the oscillator output T1 to input T2 of base drive circuit of IGBT.

2. Set the output frequency of the oscillator (switching frequency) either at 2KHz (or) at 4 Khz by using the switch SW1. Observe the output waveforms of oscillator on a CRO at T1.

3. Connect the RL Load across the diode and connect the load terminal L2 to connector terminal of the IGBT.

4. Connect the output of the base drive circuit of IGBT to the gate terminal (G1) of the IGBT.

5. Connect L1 to +24V DC power supply. Negative terminal of DC power supply is connected to the ground terminal.

6. Switch ON the main supply.

7. Observe the waveforms in following sequence.

   i) Gating signal and the current flow through the device.

   To observe these waveforms, connect the CRO ground terminal at the drain and the channel - 2 probe at the GND. (across the current sensing resistor). Connect channel-1 probe at the gate of the input transistor..

Now measure the turn-on delay, rise time, fall time, turn-off delay time, storage time by expanding the time base of the CRO.

ii) Now observe the voltage and current waveforms of the device.

For this, remove the CRO channel-1 probe from the base and connect it to the source terminal of the transistor.

8. Plot these waveforms on a graph sheet, mark turn-on, turn-off time on this graph sheet.
9. Tabulate the measured values of turn-on and turn-off timings in Table-3.

TABLE - 3

Sl. No	Frequency Position	Turn-on time	Turn-off time