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POWER ELECTRONICS

Dr. Mahmoud Shaker Al-Shemmary
Associate Prof.

Power electronics is the technology to convert and control electric power from one form to another using electronic power Devices.

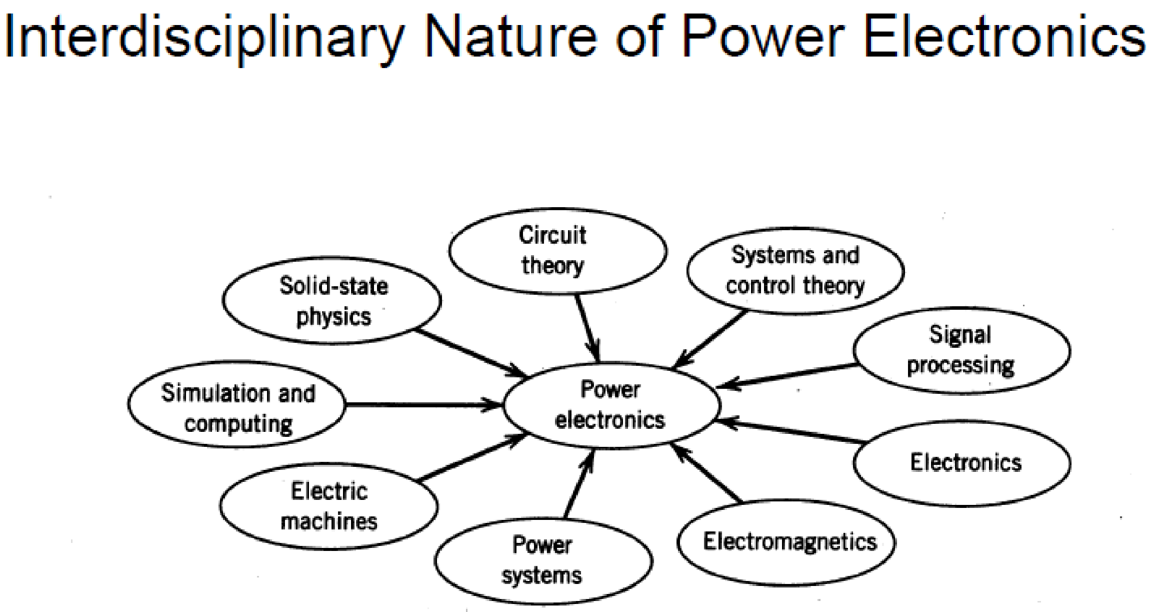
CHAPTER ONE : INTRODUCTION

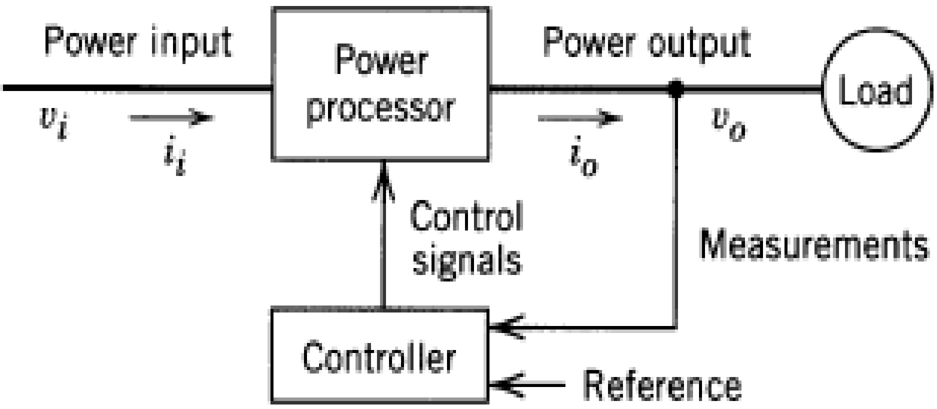
1. What is the power electronics.

Applications of solid-state electronics in the electrical power field are steadily increasing; the term power electronics has been used since 1960s, after the introduction of the silicon controlled rectifier (SCR) by general electric. Power electronics has shows rapid growth in recent years with the development of power semiconductor devices that can switch large current efficiently at high voltages. Since these devices offer high reliability and small size. The scope of applications of power electronic systems as regulating power supply, variable speed of AC and DC machines, high voltage DC transmission lines, frequency changer and load matching in solar system.

The broad field of electrical engineering can be divided into three major areas, namely, electric power, electronic, and control. Power electronics deal the application of power semiconductor devices, such as thyristors and transistors, for the conversion and control of electrical energy at high power levels. This conversion is usually from AC to DC or vice versa, while the parameters controlled are voltage, current, or frequency. For example, a DC/DC converter has constant input and performs an output of variable voltage and current.

The process of power conversion or control is realized by controlling the adequate operation of power switches devices. The control signals necessary are generated by electronic or digital means, so the power flow is controlled by electronic means. That is why the power electronics terms is used for these system. Figures (1) and (2) below demonstrate the combination between power, electronic, control, and various branches.





Figures (1) and (2)Relation between power, electronics, and control (power electronics)

2. Why the power electronics.

Transfer of electric power from a source to a load can be controlled by varying the supply voltage (by using a variable transformer) or by inserting a regulator (such as a rheostat, variable reactor or switch). Semiconductor devices used as switches have the advantage of being relatively small, inexpensive, and efficient, and they can be used to control power automatically. An addition advantage of using a switch as a control element (compared to using adjustable resistance provided by rheostat or potentiometer) can be presented as follows:

a) A Rheostat as a control device.

Figure (3) shows a rheostat controlling a load. When R1 is set to zero resistance, full power is delivered to the load. When R1 is set for maximum resistance, the power

delivered is close to zero. When R1 equal to R_L , 50% of the power is consumed in the load and 50% in R1, so the efficiency is 50%. Moreover, the rheostat must be physically larger than the load to dissipate additional power.
In industrial applications where the power to be controlled is large, the efficiency of conversion is important. Poor efficiency means large losses, an economical consideration, and it also generates heat that must be removed from the system to prevent overheating.

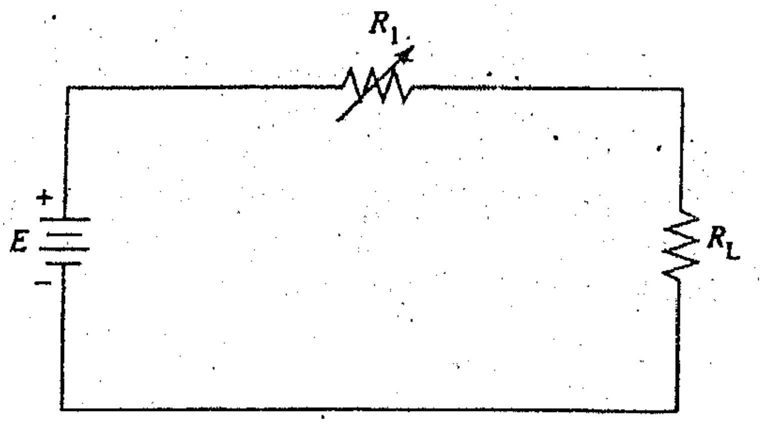


Figure (3) A rheostat controlling a load.

EX.1 A DC source of 100 V is supplying 10 ohms resistive load. Find the power delivered to the load (P_L), the power loss in the rheostat (P_R), the total power supplied by the source (P_T), and the efficiency (η) if the rheostat is set at : a)0 ohms, b)10 Ohms c)100 Ohms.

Sol.

a) Voltage across the load (V_L) = 100 V
Power supplied to the load (P_L) = $100^2/10$ = 1 KW
Power dissipated in the rheostat (P_R) = 0 W
Power supplied by the source (P_T) = $P_L + P_R$ = 1 KW
Efficiency (η) = P_L/P_T * 100 = 100 %

b) Voltage across the load (V_L) = 10 * 100 / 20 = 50 V
Power supplied to the load (P_L) = $50^2/10$ = 250 W
Power dissipated in the rheostat (P_R) = $50^2/10$ = 250W
Power supplied by the source (P_T) = $P_L + P_R$ = 500 W
Efficiency (η) = P_L/P_T * 100 = 50 %

c) Voltage across the load (V_L) = 10 * 100 / 110 = 9.09 V
Power supplied to the load (P_L) = $9.09^2/10$ = 8.26 W
Power dissipated in the rheostat (P_R) = $90.91^2/100$ = 82.64 W
Power supplied by the source (P_T) = $P_L + P_R$ = 90.9 W
Efficiency (η) = P_L/P_T * 100 = 9.08 %

It is clear from this example that the efficiency of power transfer from the source to the load is decrease as the rheostat resistance increase.

b) A switch as a control device.

In Figure (4), a switch is used to control the load. When the load is ON, maximum power is delivered to the load. The power loss in the switch is zero since it has no voltage across it. When the switch is OFF, 0 power is delivered to the load, again, the switch has no power loss since there is no current through it. The efficiency is 100 % because the switch does not waste power in either of its two positions.

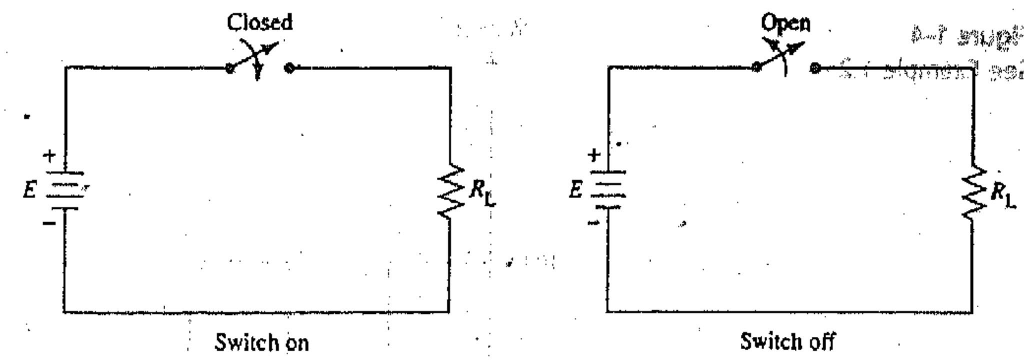


Figure (4) A switch controlling the load.

The problem of this method is that unlike a rheostat, a switch cannot be set at intermediate positions to vary the power. However, we can create the same effect by periodically turning the switch ON and OFF. If we need more power, the switch is set ON for longer periods and OFF for shorter periods. When less power is needed, it is set OFF longer.

EX.2 A DC source of 100 V is supplying 10 ohms resistive load through a switch. Find the power delivered to the load (P_L), the power loss in the switch (P_S), the total power supplied by the source (P_T), if the switch is : a) Closed, b) Open, C) Closed 50% of the time, & d) Closed 20% of the time.

Sol.

a) Voltage across the load (V_L) = 100 V
Power supplied to the load (P_L) = $100^2/10$ = 1 KW
Power loss in the switch (P_S) = 0 W
Power supplied by the source (P_T) = $P_L + P_S$ = 1 KW

b) Voltage across the load (V_L) = 0 V
Power supplied to the load (P_L) = 0 W
Power loss in the switch (P_S) = 0 W
Power supplied by the source (P_T) = $P_L + P_S$ = 0 W

c) With the switch closed 50% of the time (see figure 5)
Average Voltage across the load $(V_L) = 50$ V
Power supplied to the load $(P_L) = 50^2/10 = 250$ W
Power loss in the switch $(P_S) = 0$ W
Power supplied by the source $(P_T) = P_L + P_S = 250$ W

d) With the switch closed 20% of the time
Average Voltage across the load $(V_L) = 20$ V
Power supplied to the load $(P_L) = 20^2/10 = 40$ W
Power loss in the switch $(P_S) = 0$ W
Power supplied by the source $(P_T) = P_L + P_S = 40$ W

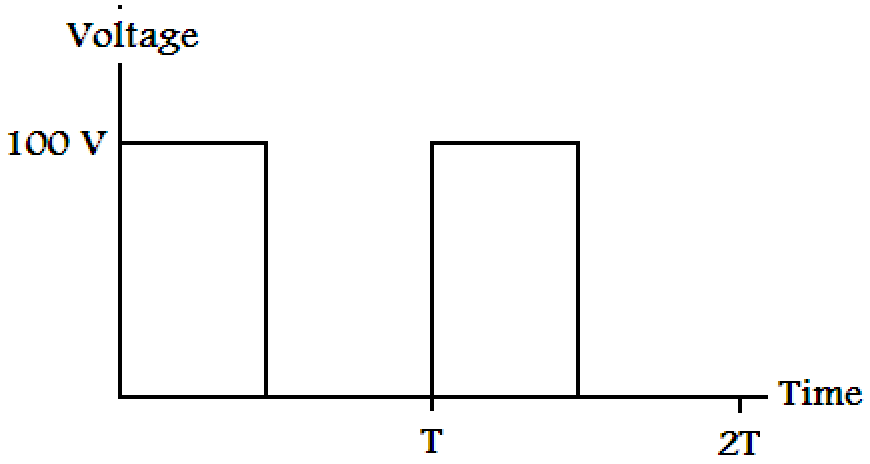


Figure (5) Load voltage using ON & OFF periods.

As this example shows, all the power supplied by the source is delivered to the load. The efficiency of power transfer is 100%. Don't forget that the switch is assumed to be ideal, but in practice the power loss in the electronic switches such as any type transistors or thyristors are very low.

3.General Switching Characteristics

3.1 The Ideal Switch

It is always desired to have the power switches perform as close as possible to the ideal case. Device characteristically speaking, for a semiconductor device to operate as an ideal switch, it must possess the following features:

1. No limit on the amount of current (known as forward or reverse current) the device can carry when in the conduction state (*on*-state).
2. No limit on the amount of the device-voltage ((known as forward or reverse blocking voltage) when the device is in the non-conduction state (*off*-state).
3. Zero *on*-state voltage drop when in the conduction state.

4. Infinite *off*-state resistance, i.e. zero leakage current when in the non-conduction state.
5. No limit on the operating speed of the device when changes states, i.e. zero rise and fall times.
6. It dissipates zero power.
7. It uses little power to control its operation.
8. It is highly reliable.
9. It is small in size and weight.
10. It is low in cost and needs no maintenance.

Both during the switching and conduction periods, the power loss is zero, resulting in a 100% efficiency, and with no switching delays, an infinite operating frequency can be achieved. In short, an ideal switch has infinite speed, unlimited power handling capabilities, and 100% efficiency. It must be noted that it is not surprising to find semiconductor-switching devices that can almost, for all practical purposes, perform as ideal switches for number of applications.

3.2. The Practical Switch

The practical switch has the following switching and conduction characteristics:

1. Limited power handling capabilities, i.e. limited conduction current when the switch is in the *on*-state, and limited blocking voltage when the switch is in the *off*-state.
2. Limited switching speed that is caused by the finite turn-*on* and turn-*off* times. This limits the maximum operating frequency of the device.
3. Finite *on*-state and *off*-state resistance's i.e. there exists forward voltage drop when in the *on*-state, and reverse current flow (leakage) when in the off-state.
4. Because of characteristics 2 and 3 above, the practical switch experiences power losses in the on and the off states (known as conduction loss), and during switching transitions (known as switching loss).

4. Losses in real power switch

Unlike an ideal switch, an actual switch, such as a bipolar junction transistor, has two major sources of power loss : conduction loss and switching loss.

4.1. Conduction loss

When the transistor in figure (6-a) is off, it carries a leakage (I_{LEAK}). The power loss associated with leakage current is $P_{OFF} = Vs*I_{LEAK}$. Since the leakage current is quite small and does not significantly with voltage , it is usually neglected and thus the transistor power loss is essentially zero.

When the transistor is ON, figure (6-b), it has a small voltage drop across it. This voltage is called saturation voltage ($V_{CE(SAT)}$). The transistor's power dissipation or conduction loss due to the saturation voltage is

$$PON = V_{CE(SAT)} * Ic \qquad \ldots\ldots\ (1)$$

Where

$$Ic = (Vs - V_{CE(SAT)})/ R_L \approx Vs / R_L \qquad \ldots\ldots\ldots\ (2)$$

Equation (1) gives the power loss due to the conduction if the switch remains ON indefinitely. However, to control the power for a given application, the switch is turned ON and OFF in a periodic manner. Therefore, to find the average power loss we must consider the duty cycle (d) :

$$P_{ON}(avg) = V_{CE(SAT)} * Ic * T_{ON}/ T = V_{CE(SAT)} * Ic * d$$

Similarly,

$$P_{OFF}(avg) = V_S * I_{LEAK} * T_{OFF}/ T$$

Where : d is the duty cycle = T_{ON}/T

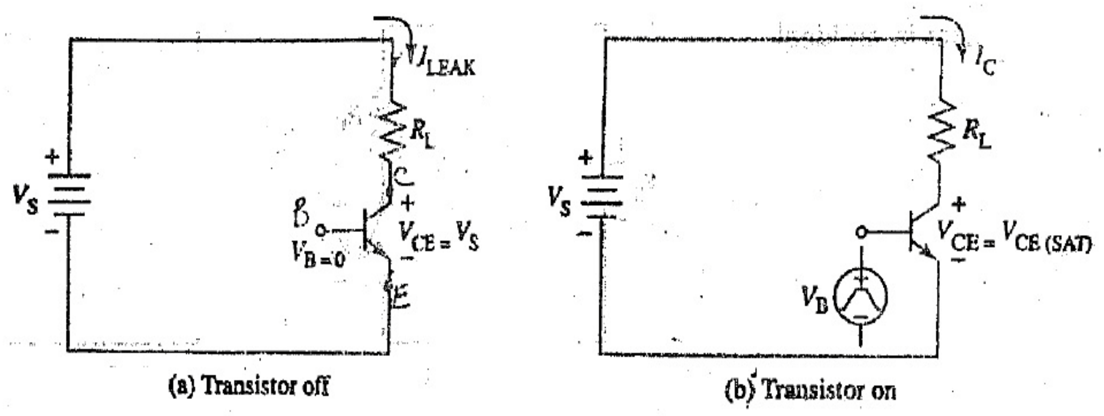


Figure (6) Power losses in a transistor.

4.2. Switching loss

In addition to the conduction loss, a real switch has switching losses because it cannot change from the ON state to OFF state (or vice versa) instantaneously. A real switch takes a finite time $t_{sw(ON)}$ to turn ON and a finite time $t_{sw(OFF)}$ to turn OFF. These times not only introduce power dissipation but also limit the highest frequency possible. $t_{sw(ON)}$ and $t_{sw(OFF)}$ are not equal with $t_{sw(ON)}$ generally being larger.
In our discussion we will assume that $t_{sw(ON)}$ is equal to $t_{sw(OFF)}$. Figure (7) shows switching waveforms for (a) the voltage across the switch and (b) the current through it. When the switch is OFF, the voltage across it is equal to source voltage. During

turn-ON, which takes a finite time, the voltage across the switch decreases to zero. During the same time, the current through the switch increases from zero to Ic. The transistor has a current through it and a voltage across it during the switching time; therefore it has a power loss.

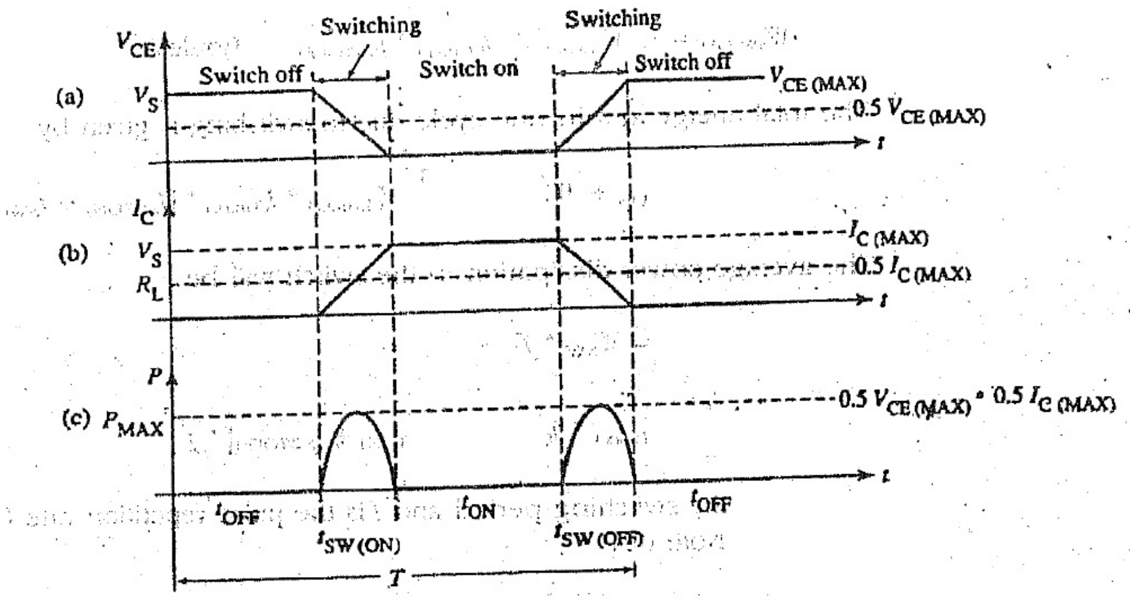


Figure (7) Waveform during switching operation: (a) voltage across the switch (b) current through the switch (c) power dissipated in the switch.

To find the power dissipated in a transistor during the switching interval, we multiply the instantaneous value of Ic and the corresponding value of V_{CE}. This power is illustrated in figure (7-c). The energy dissipated in the switch is equal to the area under the power waveform. Note that the maximum power is dissipated when both the current and voltage are passing their midpoint values. Therefore, the maximum power loss when switching from the OFF state to the ON state is :

$$P_{SW\ ON(max)} = 0.5\ V_{CE(max)} * 0.5\ I_{C(max)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

It is interesting to note that the power curve looks like essentially like a rectified sine wave. The average value of this waveform is

$$P_{SW\ ON(avg)} = 0.636 * P_{SW\ ON(max)} = 0.636 * 0.5\ V_{CE(max)} * 0.5\ I_{C(max)}$$
$$= (1/6) * V_{CE(max)} * I_{C(max)}$$

The energy loss (power * time) during turn-ON will be $P_{SW\ ON(avg)} * t_{SW\ ON}$

$$W_{SW\ ON} = (1/6)\ V_{CE(max)} * I_{C(max)} * t_{SW\ ON} \qquad \text{(Joules)}$$

A similar analysis gives the energy loss during turn-OFF ;

$$W_{SW\,OFF} = (1/6)\ V_{CE(max)} * I_{C(max)} * t_{SW\,OFF} \qquad \text{(Joules)}$$

The total energy loss in one cycle due to switching is given by

$$W_{SW} = W_{SW\,ON} + W_{SW\,OFF} = (1/6)\ V_{CE(max)} * I_{C(max)} * (t_{SW\,OFF} + t_{SW\,ON})$$

The average power dissipation in the switch will be

$$P_{SW} = W_{SW} / T = W_{SW} * f \qquad ; \ f = 1/T$$

$$P_{SW} = (1/6)\ V_{CE(max)} * I_{C(max)} * (t_{SW\,OFF} + t_{SW\,ON}) * f$$

Where T is the switching period and f is the pulse repetition rate (frequency of switching). Note that

$$T = t_{ON} + t_{SW(ON)} + t_{OFF} + t_{SW(OFF)}$$

If we let

$$t_{SW(ON)} = t_{SW(OFF)} = t_{SW}$$

Then

$$P_{SW} = (1/6)\ V_{CE(max)} * I_{C(max)} * (2\ t_{SW}) * f$$

The total power loss in the switch is

$$P_T = P_{ON(avg)} + P_{OFF(avg)} + P_{SW} \approx P_{ON(avg)} + P_{SW}$$

$$= V_{CE(SAT)} * I_{C(max)} * d + V_{CE(max)} * I_{Leak} * T_{off}/T + (1/3)\ V_{CE(max)} * I_{C(max)} * t_{SW} * f$$

<u>EX.3</u>

Referring to figure (6) if Vs=50 V, R_L=5 ohms, and the switch is ideal with no switching loss. If the on state voltage drop is 1.5 V and the leakage current is 1.5 mA, calculate the power loss in the switch when it is (a) ON (b) OFF,.

<u>SOL.</u>

a) Conduction current = (50-1.5)/5 = 9.7 A
   Power loss during ON state = 1.5 * 9.7 = 14.55 W

b) Power loss during OFF state P_{OFF} = 50 V * 1.5 mA = 75 mW.

For normal load condition the power dissipation during OFF state can be neglected in comparison to the power loss during ON state.

EX.4

Calculate the maximum and average power loss for the switch in previous example if the switching frequency is 500 Hz with duty cycle of 50%.

SOL.

Switching period T = 1/f = 1/500 = 2 ms.

Duty cycle d = 0.50

Then t_{ON}=1 ms and t_{OFF} = 1 ms

Average power loss during ON state = P_{ON} * t_{ON}/T = 14.55*0.5 = 7.27 W

Average power loss during OFF state = P_{OFF} * t_{OFF}/T = 0.075*0.5=0.037 W

Average power loss in one cycle = $P_{ON(avg)}$ + $P_{OFF(avg)}$ = 7.27+0.037=7.3 W

Remember that the maximum power dissipated is 14.55 W.

EX.5

Assume Vs=120 V, RL=6 ohms, and the transistor is ideal for conduction loss. If $t_{SW(ON)}$=$t_{SW(OFF)}$ = 1.5 µs, calculate the average switching power loss at the switching frequency of 1 KHz.

SOL.

$I_{C(max)}$ = 120/6 = 20 A

$P_{SW\ ON(avg)}$ = (1/6) * $V_{CE(max)}$ * $I_{C(max)}$ = 120 * 20 / 6 = 400 W

The energy loss is

$W_{SW\ ON}$ = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * $t_{SW\ ON}$ = 400 * 1.5X10^{-6}=0.6 mJ

$W_{SW\ OFF}$ = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * $t_{SW\ OFF}$ = 400 * 1.5X10^{-6}=0.6 mJ

W_{SW} = $W_{SW\ ON}$ + $W_{SW\ ON}$ = 1.2 mJ

P_{SW} = W_{SW} / T = W_{SW} * f = 1.2 mJ * 1000 = 1.2 W

OR

P_{SW} = (1/6) $V_{CE(max)}$ * $I_{C(max)}$ * (2 t_{SW}) * f = (1/6)*120 * 20 *2*1.5X10^{-6} *1000

= 1.2 W

It is clear from the examples that when we select a power switch, it is necessary to select the adequate frequency of switching in order to minimize the losses in the switch and obtain a good waveform on the load.

5. Classification of power electronics devices

Power electronics devices can be classified by more than one manner :

- **Uncontrolled device**: diode
  Uncontrolled device has only two terminals and can not be controlled by control signal. The on and off states of the device are determined by the power circuit.

- **Half-controlled device:** thyristor
  Half-controllable device is turned-on by a control signal and turned-off by the power circuit

- **Fully-controlled device:** Power MOSFET, IGBT,GTO, IGCT
  In Fully-controllable device the on and off states of the device are controlled by control signals.

Other classifications

power electronic devices
- Current-driven (current-controlled) devices.
- Voltage-driven (voltage-controlled) devices.

power electronic devices
- Pulse-triggered devices
- Level-sensitive (level-triggered) devices

power electronic devices
- Unipolar devices (Unidirectional)
- Bipolar devices (Bidirectional)

6. Power semiconductor switches.

The main types of semiconductor switches in common use are

1. Diodes
2. Power transistors
   a. Bipolar junction transistor (BJT)
   b. Metal oxide semiconductor field effect transistor (MOSFET)
   c. Insulated gate bipolar transistor (IGBT)
   d. Static induction transistor (SIT)

3. Thyristor devices
    a. Silicon controlled rectifier (SCR)
    b. Static induction thyristor (SITH)
    c. Gate turn-off thyristor (GTO)
    d. MOS controlled thyristor (MCT)
    e. Triac

6.1 The power Diode

Power diodes Play an important role in power electronics circuits. They are used mainly in uncontrolled rectifiers to convert AC to fixed DC voltages and as freewheeling diodes to provide a path for the current for the current flow in inductive loads.

The structure of a semiconductor diode and its symbol is shown in figure (8). The diode has two terminals: an anode **A** terminal (P-junction) and a cathode **K** terminal (N-Junction).

When the anode voltage is more positive than the cathode, the diode is said to be **forward-biased** and it conducts current readily with a relatively low voltage drop. When the cathode voltage is more positive the anode, the anode is said to be **reverse-biased** and it blocks the current flow. The arrow on the diode symbol shows the direction of current flow when it conducts.

Figure (8) also shows the V-I characteristics of a diode. When forward biased, the diode begins to conduct current as the voltage across its anode is increased. When the voltage approaches the so called **Knee voltage** (about 0.6, 0.7, .. 1V) for silicon diode and about 0.3 V for germanium diode a slight increase in voltage causes the current to increase rapidly. (This increase in current can e limited only by resistance connected in series with the diode).

When the diode is reversed biased, a small amount of current called the reverse leakage current flows as the voltage from anode to cathode is increased; this simply indicate that a diode has a very high resistance in the reverse direction. This large resistance characteristic is maintained with increasing reverse voltage until the reverse breakdown voltage is reached. At a breakdown, a diode allows a large current and the diode will destroyed.

AC diode parameters. The commonly used parameters are the followings:

• ***Forward recovery time,*** t_{FR} is the time required for the diode voltage to drop to a particular value after the forward current starts to flow.

• ***Reverse recovery time trr*** is the time interval between the application of reverse voltage and the reverse current dropped to a particular value

In Practice, a design engineer frequently needs to calculate the reverse recovery time. This is in order to evaluate the possibility of high frequency switching.

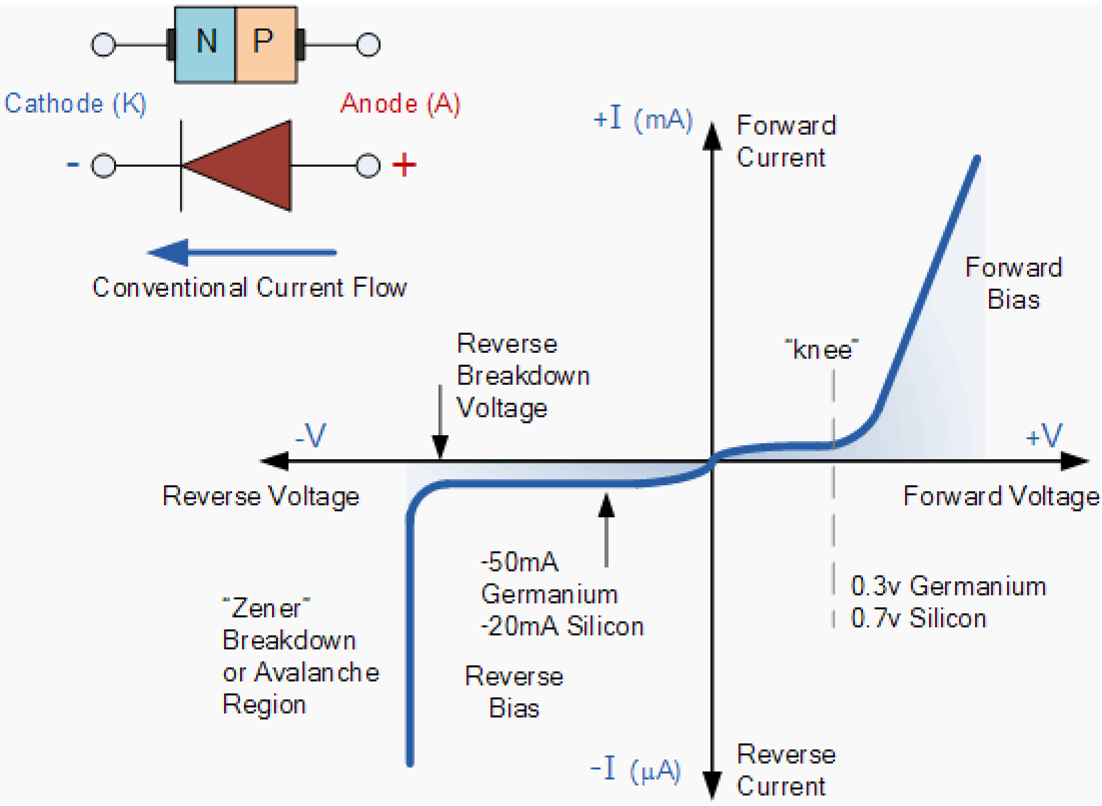


Figure (8) Symbol and characteristics of a diode.

Examples of commercial power diodes

Part No.	**Rated maximum Voltage (V)**	**Rated Avg Current (A)**	**V_F (typical) (V)**	**Trr maximum**
1N3913	**400**	**30**	**1.1**	**400 ns.**
SD453N25S20PC	**2500**	**400**	**2.2**	**2 µs**
1N4007	**400**	**6**	**1**	**500 ns**

6.2. Schottky Diode

The Schottky diode is a low voltage, high speed device that works on a difference principle from that of the P-N junction diode. It is constructed without the usual PN junction. Instead, a thin barrier layer metal (such as platinum or tungsten) is interfaced with the N-type semiconductor. This construction results in a low on-state voltage (about 0.15 to 0.45 V) across the diode when conducts. It can turn off much

faster than a classical diode, so switching frequency can be high. However, the reverse leakage current is much higher, and the breakdown voltage is lower compared with PN diode. Schottly diodes are therefore used as rectifier in low voltage applications where the efficiency of conversion is important. These diode are widely used in switching power supplies that operate at frequencies of 20 KHz or higher.
The symbol of the Schottky diode is shown in figure (9).

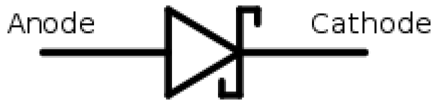


Figure (9) The symbol of a Schottky diode

6.3. Zener Diode

A **Zener diode** is a special kind of diode which allows current to flow in the forward direction same as an ideal diode, but will also permit it to flow in the reverse direction when the voltage is above a certain value known as the breakdown voltage, "Zener knee voltage" or "Zener voltage." See figure (10).
A Zener diode exhibits almost the same properties, except the device is specially designed so as to have a greatly reduced breakdown voltage, the so-called Zener voltage. By contrast with the conventional device, a reverse-biased Zener diode will exhibit a controlled breakdown and allow the current to keep the voltage across the Zener diode close to the Zener breakdown voltage. For example, a diode with a Zener breakdown voltage of 3.2 V will exhibit a voltage drop of very nearly 3.2 V across a wide range of reverse currents. The Zener diode is therefore ideal for applications such as the generation of a reference voltage (e.g. for an amplifier stage), or as a voltage stabilizer for low-current applications.

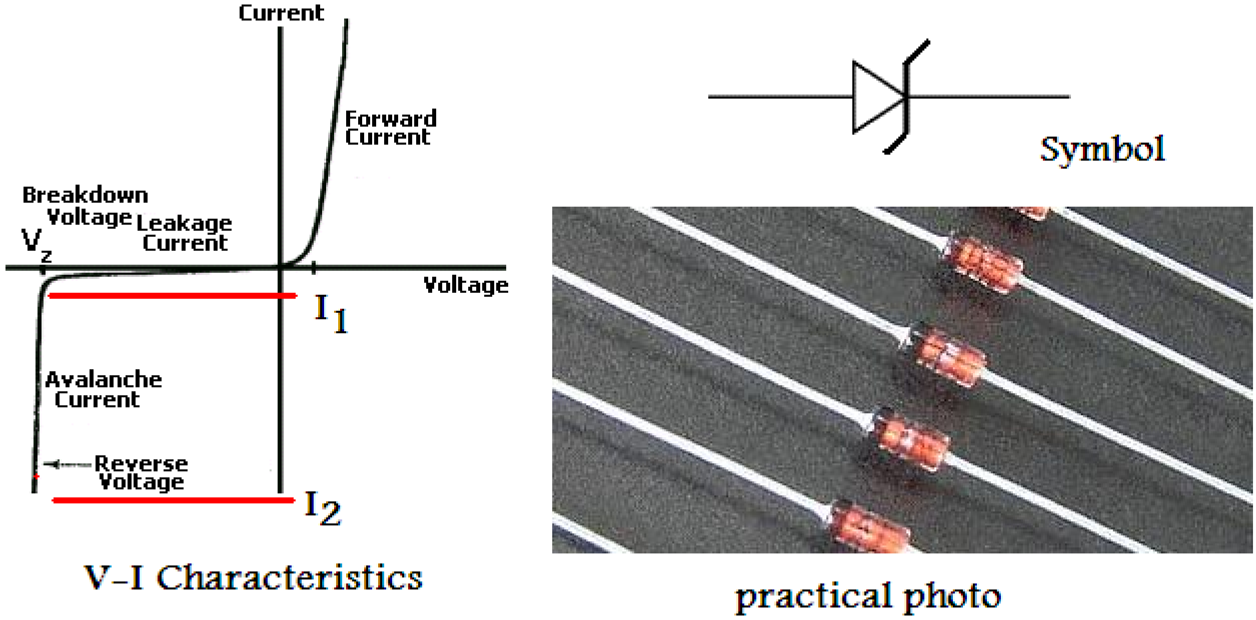


Figure (10) Symbol and Characteristics of zener diode.

Zener Diode Voltage Regulator Circuit

Zener diodes are widely used as voltage references and as shunt regulators to regulate the voltage across small circuits. When connected in parallel with a variable voltage source (see figure 11) so that it is reverse biased, a Zener diode conducts when the voltage reaches the diode's reverse breakdown voltage. From that point on, the relatively low impedance of the diode keeps the voltage across the diode at that value.

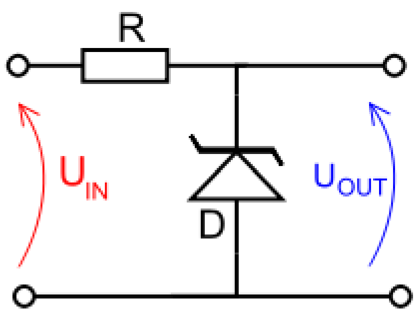


Figure (11) The connection of zener diode as a voltage regulator.

In this circuit, a typical voltage reference or regulator, an input voltage, U_{IN}, is regulated down to a stable output voltage U_{OUT}. The intrinsic voltage drop of diode D is stable over a wide current range and holds U_{OUT} relatively constant even though the input voltage may fluctuate over a fairly wide range. Because of the low impedance of the diode when operated like this, Resistor R is used to limit current through the circuit.

In the case of this simple reference, the current flowing in the diode is determined using Ohms law and the known voltage drop across the resistor R. $I_{Diode} = (U_{IN} - U_{OUT}) / R$.

The value of *R* must satisfy two conditions:

1. *R* must be small enough that the current through D keeps D in reverse breakdown. The value of this current is given in the data sheet for D. For example, the common BZX79C5V6 device, a 5.6 V 0.5 W Zener diode, has a recommended reverse current of 5 mA. If insufficient current exists through D, then U_{OUT} will be unregulated, and less than the nominal breakdown voltage (this differs to voltage regulator tubes where the output voltage will be higher than nominal and could rise as high as U_{IN}). When calculating *R*, allowance must be made for any current through the external load, not shown in this diagram, connected across U_{OUT}.
2. *R* must be large enough that the current through D does not destroy the device. If the current through D is I_D, its breakdown voltage V_B and its maximum power dissipation P_{MAX}, then $I_D V_B < P_{MAX}$.

A load may be placed across the diode in this reference circuit, and as long as the zener stays in reverse breakdown, the diode will provide a stable voltage source to the load.

6.4 The DIAC

A diac is an important member of the thyristor family and is usually employed for triggering triacs. A diac is a two-electrode bidirectional avalanche diode which can be switched from off-state to the on-state for either polarity of the applied voltage. This is just like **a TRIAC** without gate terminal, as shown in figure. Its equivalent circuit is a pair of inverted four layer diodes. Two schematic symbols are shown in figure. Again the terminal designations are arbitrary since the diac, like triac, is also a bilateral device. The switching from off-state to on-state is achieved by simply exceeding the avalanche break down voltage in either direction.

Construction of a Diac.

A diac is a P-N-P-N structured four-layer, two-terminal semiconductor device, as shown in figure (12). MT_2 and MT_X are the two main terminals of the device. There is no control terminal in this device. From the diagram, a diac unlike a diode, resembles a bipolar junction transistor (BJT) but with the following exceptions.

- there is no terminal attached to the middle layer (base),
- the three regions are nearly identical in size,
- the doping level at the two end P-layers is the same so that the device gives symmetrical switching characteristics for either polarity of the applied voltage.

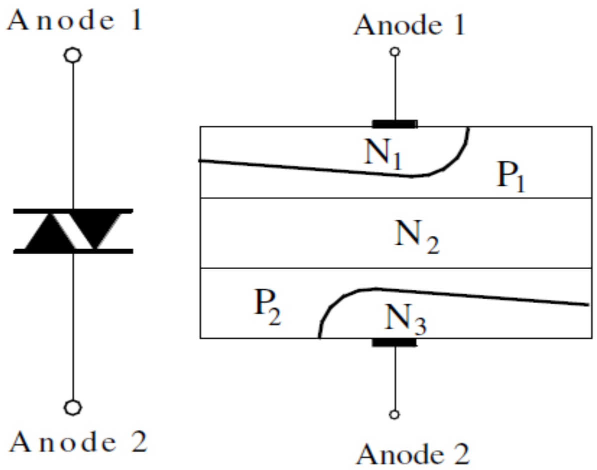
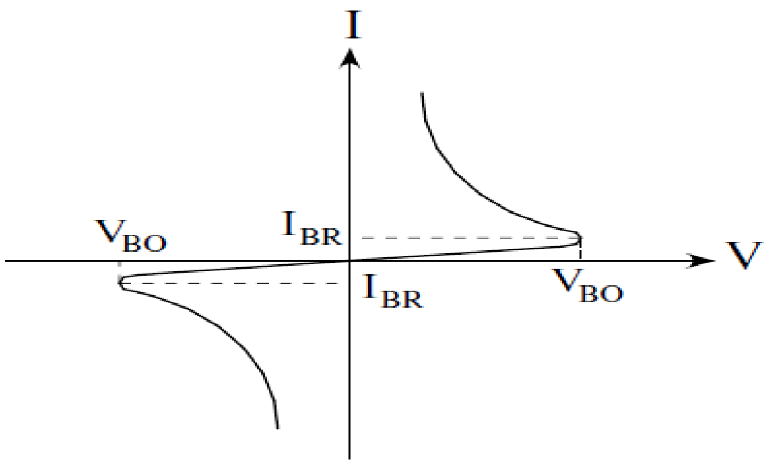


Figure (12) The DIAC symbol and structure.

Operation of a Diac.

When the terminal MT_2 is positive, the current flow path is P_1-N_2-P_2-N_3 while for positive polarity of terminal MT_1 the current flow path is P_2-N_2-P_1-N_1. The operation of the diac can be explained by imagining it as two diodes connected in series. When applied voltage in either polarity is small (less than breakover voltage) a very small amount of current, called the *leakage current,* flows through the device. Leakage current caused due to the drift of electrons and holes in the depletion region, is not sufficient to cause conduction in the device. The device remains in non-conducting mode. However, when the magnitude of the applied voltage exeeds the avalanche breakdown voltage, breakdown takes place and the diac current rises sharply, as shown in the characteristics shown in figure (13).



Characteristics of a Diac

Volt-ampere characteristic of a diac is shown in figure. It resembles the English letter Z because of the symmetrical switching characteristics for either polarity of the applied voltage.

The diac acts like an open-circuit until its switching or breakover voltage is exceeded. At that point the diac conducts until its current reduces toward zero (below the level of the holding current of the device). The diac, because of its peculiar construction, does not switch sharply into a low voltage condition at a low current level like the SCR or triac. Instead, once it goes into conduction, the diac maintains an almost continuous negative resistance characteristic, that is, voltage decreases with the increase in current. This means that, unlike the SCR and the triac, the diac cannot be expected to maintain a low (on) voltage drop until its current falls below a holding current level.

6.5 Thyristors (SCR):

Thyristors, or silicon-controlled rectifiers (SCRs) have been the traditional workhorses for bulk power conversion and control in industry. The modern era of solid-state power electronics started due to the introduction of this device in the late 1950s. Often, it is a family name that includes SCR, triac, GTO,MCT & IGCT. Thyristors can be classified as standard, or slow phase-control-type and fast-switching, voltage-fed inverter-type.

Volt-ampere characteristics:

Figure (14) shows the tyristor symbol and its volt-ampere characteristics. Basically. It is a three-junction P-N-P-N device, where P-N-P & N-P-N component transistors are connected in regenerative feedback mode. The thyristor has three terminals namely, A (anode), K (cathode), and G (gate).

The device blocks voltage in both the forward and reverse directions (symmetric blocking). When the anode is positive, the device can be triggered into conduction by a short positive gate current pulse; but once the device is conducting, the gate loses its control to turn off the device. A thyristor can also turn on by excessive anode voltage. Its rate of rise (dv/dt) , by a rise in junction temperature(Tj), or by light shinning on the junction.

The voltge-ampere characteristics of the device indicate that at gate current I_G=0. If forward voltage is applied on the device, there will be a leakage current due to blocking of the middle junction. If the voltage exceeds a critical limit (breakover voltage), the device switches into conduction. With increasing magnitude of I_G, the forward breakover voltage is reduced. And eventually at I_{G3} , the device behaved like a diode with entire forward blocking region removed. The device will turn on successfully if a minimum current, called a latching current (I_L), is maintained. During conduction, if the gate current is zero and the anode current falls below a critical limit, called the holding current (I_h), the device reverts to the forward blocking state. With revere voltage, the end P-N junction of the device become revere-biased and V-I curve becomes essentially similar to that of a diode rectifier.

Modern thyristors are available with very large voltage (several KV) and current (several KA) ratings.

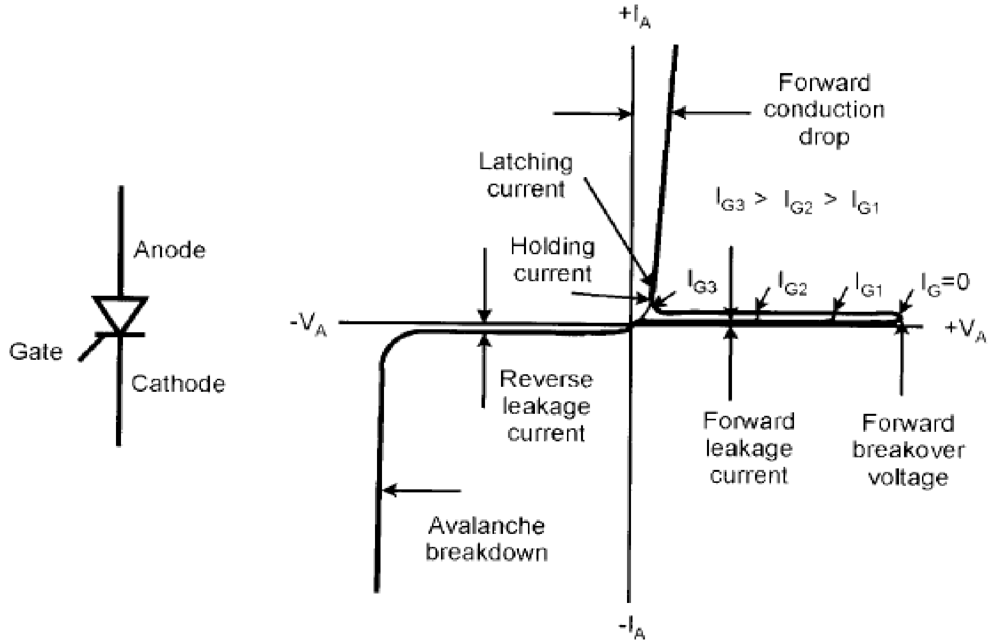


Figure (14) Thyristor symbol and Volt-ampere characteristics.

Switching characteristics:

Initially when forward voltage is applied across a device, the off-state, or static *dv/dt*, must be limited so that it does not switch on spuriously. The *dv/dt* creates displacement current in the depletion layer capacitance of the middle junction, which include emitter current in the component transistors and causes switching action. When the device turn on, the anode current *di/dt* can be excessive, which can destroy the device by heavy current concentration. During conduction, the inner P-N regions remain heavily saturated with minority carries and the middle junction remains forward-biased. To recover the forward voltage blocking capability, a reverse voltage is applied across the device to sweep out the minority carries and the phenomena are middle are similar to that of a diode. However, when the recovery current goes to zero, the middle junction still remain forward-biased. This junction eventually blocks with additional delay when the minority carries die by the recombination process. The forward voltage can then be applied successfully, but the reapplied *dv/dt* will be somewhat less than the static *dv/dt* because of the presence of minority carries. For example, POWEREX SCR/diode module CM4208A2 (800 V, 25 A) has limited *di/dt=100* A/µs and off-state *dv/dt* =500 V/µs permeable limit. A suitably –designed snubber circuit can limit *di/dt & dv/dt* within acceptable limit. In a converter circuit, a thyristor can be turned off (or commutated) by a segment of reverse ac line or load voltage (defined as a line or load commutated, respectively) or by an inductance capacitance circuit-induced transient reverse voltage (defined as forced commutation).

The important points on this characteristic are:

1-Latching Current I_L

This is the minimum anode current required to maintain the thyristor in the on-state immediately after a thyristor has been turned on and the gate signal has been removed. If a gate current, greater than the threshold gate current is applied until the anode current is greater than the latching current I_L then the thyristor will be turned on or triggered.

2-Holding Current I_H

This is the minimum anode current required to maintain the thyristor in the on state. To turn off a thyristor, the forward anode current must be reduced below its holding current for a sufficient time for mobile charge carriers to vacate the junction. If the anode current is not maintained below I_H for long enough, the thyristor will not have returned to the fully blocking state by the time the anode-to-cathode voltage rises again. It might then return to the conducting state without an externally applied gate current.

3-Reverse Current I_R

When the cathode voltage is positive with respect to the anode, the junction J_2 is forward biased but junctions J_1 and J_3 are reverse biased. The thyristor is said to be in the *reverse blocking state* and a reverse leakage current known as reverse current I_R will flow through
the device.

4-Forward Break-over Voltage V_{BO}

If the forward voltage V_{AK} is increased beyond V_{BO}, the thyristor can be turned on. However, such a turn-on could be destructive. In practice, the forward voltage is maintained below V_{BO} and the thyristor is turned on by applying a positive gate signal between gate and cathode.

5-

Once the thyristor is turned on by a gate signal and its anode current is greater than the holding current, the device continues to conduct due to positive feedback even if the gate signal is removed. This is because the thyristor is a latching device and it has been latched to the on state.

<u>TESTING OF A THYRISTOR</u>

TO observe the terminal configuration of a thyristor, thyristor's body is generally connected with anode terminal by the manufacture; hence, the anode terminal can be identified with help of a multimeter. Now, measure the resistance between other two terminals (gate and cathode) of the thyrsitor. The forward-biased p-n junction of a diode shows a low resistance than the reverse-biased junction. When the AVO meter

shows a low resistance then the gate (G) terminal is the one, which connected with positive terminal of the multi-meter battery.

SCR Ratings

A data sheet for a typical thyristor follows this section and includes the following information:

Surge Current Rating (I_{FM})—The surge current rating (I_{FM}) of an SCR is the peak anode current an SCR can handle for a short duration.

Latching Current (I_L)—A minimum anode current must flow through the SCR in order for it to stay ON initially after the gate signal is removed. This current is called the latching current (*IL*).

Holding Current (I_h)—After the SCR is latched on, a certain minimum value of anode current is needed to maintain conduction. If the anode current is reduced below this minimum value, the SCR will turn OFF.

Peak Repetitive Reverse Voltage (*V*RRM)—The maximum instantaneous voltage that an SCR can withstand, without breakdown, in the reverse direction.

Peak Repetitive Forward Blocking Voltage (*V*DRM)—The maximum instantaneous voltage that the SCR can block in the forward direction. If the *V*DRM rating is exceeded, the SCR will conduct without a gate voltage.

Nonrepetitive Peak Reverse Voltage (*V*RSM)—The maximum transient reverse voltage that the SCR can withstand.

Maximum Gate Trigger Current (I_{GTM})—The maximum DC gate current allowed to turn the SCR ON.

Minimum Gate Trigger Voltage (V_{GT})—The minimum DC gate-to-cathode voltage required to trigger
the SCR.

Minimum Gate Trigger Current (I_{GT})—The minimum DC gate current necessary to turn the SCR ON.

6.6 Triacs

A triac has a complex multiple-junction structure, but but functionally, it is an integration of a pair of phase-controlled thyriostors connected in inverse-parallel on the same chip. The three-terminal device can be trigged into conduction in both positive and negative half-cycle of supply voltage by applying gate trigger pulse. In I+ mode, the terminal T2 is positive and the device is switched on by positive gate current pulse. See figure (15)
In III- mode, the terminal T1 is positive and it is switched on by negative gate current pulse. A triac is more economical than a pair of thyriostors in anti-parallel and its control is simpler, but its integrated construction has same disadvantage. The gate

current sensitivity of a traic is poorer and the turn-off time is longer due to the minority carrier storage effect. For the same reason, the reapplied *dv/dt* rating is lower, thus making it difficult to used with inductive load. A well-designed RC snubber is essential for a traic circuit. Traics are used in light dimming, heating control, appliance-type motor drives, and solid-state relays with typically 50/60 Hz supply frequency.

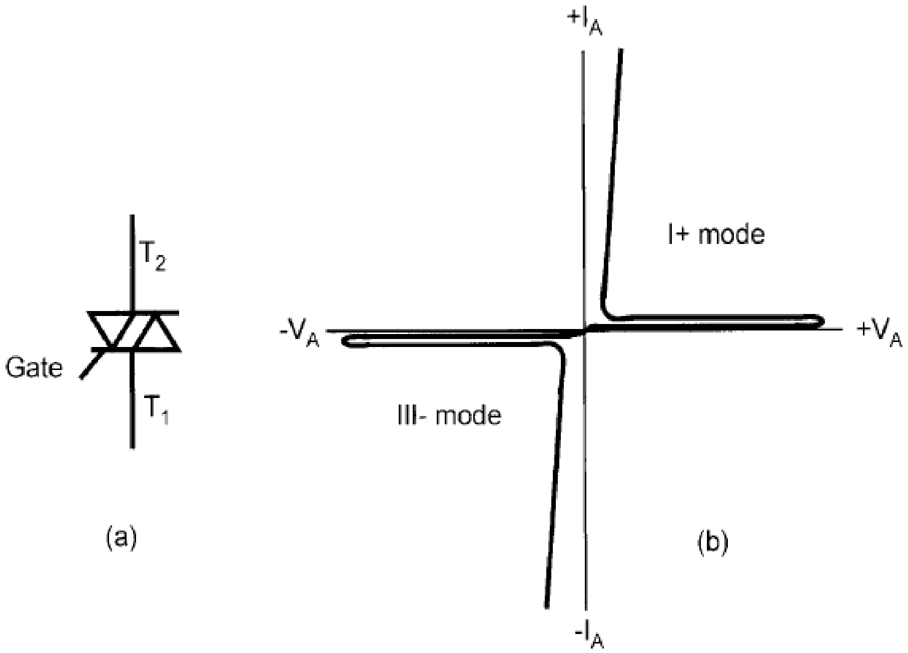


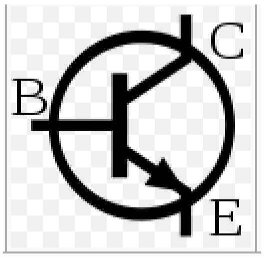
Figure (15) Triac symbol and characteristics.

6.7 GATE TURN-OFF THYRISTORS (GTOs)

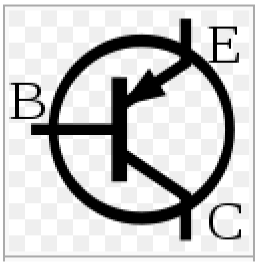
A gate turn-off thyriostors (GTO), as the name indicates, is basically a thyriostor-type device that can be turned by a small positive gate current pulse, but in addition, has a capability of being turned off by a negative gate current pulse. The turn-off capability of a GTO is due to the diversion of P-N-P collector current by the gate, thus breaking the P-N-P/N-P-N regenerative feedback effect. GTOs are available with asymmetric and symmetric voltage-blocking capability, which are used in voltage-fed converter, respectively. The turn-off current gain of a GTO, defined as the ratio of a anode current prior to turn-off to the negative gate current required for turn-off, it is very low, typically 4 or 5. This means that a 6000 A GTO requires as high as-1500 A gate current pulse. However, the duration of the pulsed gate current and the corresponding energy associated with it is small and can easily be supplied by low-voltage power MOSFETs, GTOs are used in motor driver. Static VAR compensator (SVCs). A ac/dc power supplies with high power rating when large-power GTOs became available. They ousted the force-commutated, voltage-fed thyristor inverters.

6.8. The Bipolar Junction Transistor. (BJT).

A **bipolar (junction) transistor** (**BJT**) is a three-terminal electronic device constructed of doped semi conductor material and may be used in amplifying or switching applications. *Bipolar* transistors are so named because their operation involves both electrons and holes.
Charge flow in a BJT is due to bidirectional diffusion of charge carriers across a junction between two regions of different charge concentrations. This mode of operation is contrasted with ***unipolar transistors***. By design, most of the BJT collector current is due to the flow of charges injected from a high-concentration emitter into the base where they are minority carriers that diffuse toward the collector, and so BJTs are classified as *minority-carrier* devices. There are two types of BJT transistor, NPN and PNP, the symbols of which are shown in figure (16).



NPN



PNP

Figure (16) Schematic symbols for PNP- and NPN-type BJTs.

Transistor 'alpha' and 'beta'

The proportion of electrons able to cross the base and reach the collector is a measure of the BJT efficiency. The heavy doping of the emitter region and light doping of the base region causes many more electrons to be injected from the emitter into the base than holes to be injected from the base into the emitter. The *common-emitter current gain* is represented by β_F or h_{FE}; it is approximately the ratio of the DC collector current to the DC base current in forward-active region. It is typically greater than 100 for small-signal transistors but can be smaller in transistors designed for high-power applications. Another important parameter is the common-base current gain, α_F. The common-base current gain is approximately the gain of current from emitter to collector in the forward-active region. This ratio usually has a value close to unity; between 0.98 and 0.998. Alpha and beta are more precisely related by the following identities (NPN transistor):

$$\alpha_F = \frac{I_C}{I_E}$$

$$\beta_F = \frac{I_C}{I_B}$$

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} \iff \alpha_F = \frac{\beta_F}{\beta_F + 1}$$

The output Characteristics

This is the most important characteristics for the power transistor when used in power electronics converters. It is the relationship between the collector current Ic and collector-emitter voltage V_{CE} at a certain value of I_B.(see figure 17). It is clear that the base current controls the collector current.

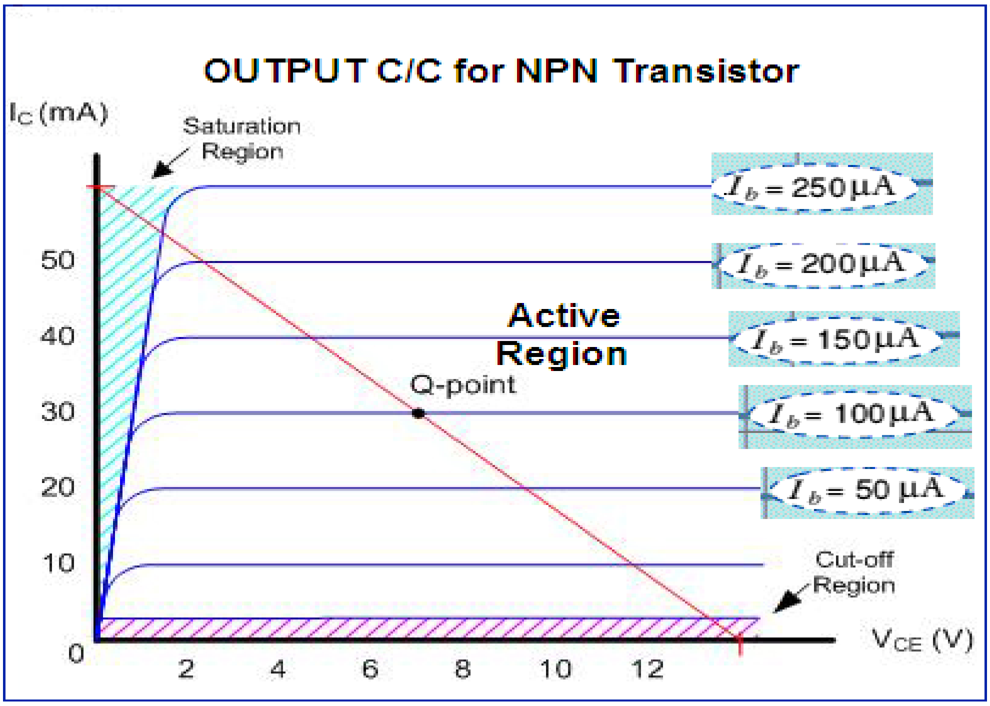


Figure (17) Output characteristics of BJT-NPN transistor.

Regions of Operation

Referring to figure (13), bipolar transistors have three important distinct regions of operation, defined by BJT junction biases, namely:

- **Cut-off region**: This is the case where the transistor is essentially inactive.

In cutoff, the following behavior is noted:

* $I_B = 0$ (no base current)

* Ic = 0 (no collector current)

* $V_{BE} < 0.7V$(emitter-base junction is not forward biased)

In cutoff, the transistor appears as an open circuit between the collector and emitter terminals. In the circuit above, this implies Vout is equal to V_{CC} volts.

- **Saturation Region:** This is where the base current has increased well beyond the point that the emitter-base junction is forward biased. In fact, the base current has increased beyond the point where it can cause the collector current flow to increase. In saturation, the transistor appears as a near short circuit between the collector and emitter terminals.

  In saturation, the following behavior is noted:

  * V_{CE} <= 0.2V. This is known as the saturation voltage, or V_{CE}(sat)

  * I_B = maximum allowable value (according to its specification).

  * V_{BE} >= 0.7V

  Using the two states of cutoff and saturation, the transistor may be used as a switch. The collector and emitter form the switch terminals and the base is the switch handle. In other words, the small base current can be made to control a much larger current between the collector and emitter.

- **Active Region**: In this region the transistor can act as a fairly linear amplfier. In this region, we see that:

  * 0.2 < V_{CE} < Vcc ; where Vcc is the supply voltage

  * I_B > 0 and Ic > 0

  * V_{BE} >= 0.7V

Thus the transistor is on and the collector to emitter voltage is somewhere between the cutoff and saturated states. In this state, the transistor is able to amplify small variations in the voltage present on the base. The output is extracted at the collector. In the forward active state, the collector current is proportional to the base current by a constant multiplier called “beta”, denoted by the symbol β. Thus in the forward active region we will also observe that:

$$Ic = \beta * Ib$$

The transistor as a switch

To illustrate this, the simplest way to use an NPN bipolar transistor as a switch is to insert the load between the positive supply and its collector, with the emitter terminal grounded (as shown in Figure 18). Applying no voltage at the base of the transistor will put it in the cut-off region, preventing current from flowing through it and through the load, which is a resistor in this example. In this state, the load is 'off'.

Applying enough voltage at the base of the transistor will cause it to saturate and become fully conductive, effectively pulling the collector of the transistor to near ground. This causes a collector-to-emitter current to flow through the load that's limited only by the impedance of the load. In this state, the load is 'on'.

One limitation of this simple design is that the switch-off time of the transistor is slower than its switch-on time if the load is a resistor. This is because of the stray capacitance across the collector of the transistor and ground, which needs to charge through the load resistor during switch-off. On the other hand, this stray capacitance is easily discharged to ground by the large collector current flow when the transistor is switched on. There are, of course, other better designs for using the bipolar transistor as a switch.

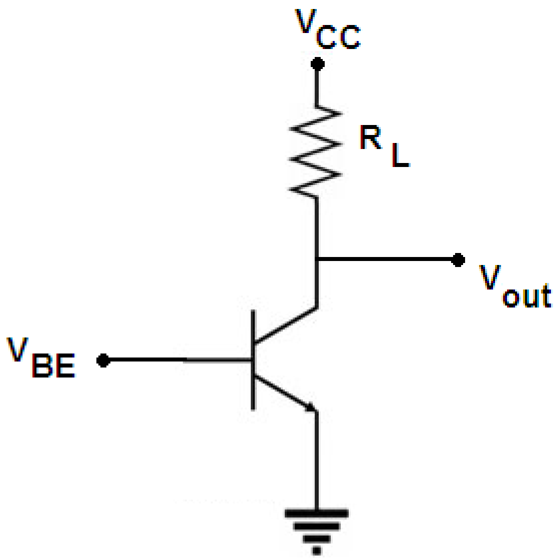


Figure (18) A simple switch of NPN transistor.

The transistor can be damaged if ,

(1) a large positive voltage is applied across the CE junction (breakdown region), or

(2) product of i_C V_{CE} exceed power handling of the transistor, or

(3) a large reverse voltage is applied between any two terminals.

6.9. Metal Oxide Silicon Field Effect Transistor (MOSFET)

MOSFETs come in four different types. They may be *enhancement* or *depletion* mode, and they may be *n-channel* or *p-channel*. The symbol of each is shown in figure (19). It has three terminals : D (drain), S (source), and G (gate). The gate of a MOSFET is isolated electrically from the source by a layer of silicon oxide. The gate draws only a minute leakage current on the order of nanoamperes. Hence, the gate drive circuit is simple and power loss in the gate control circuit is practically negligible.

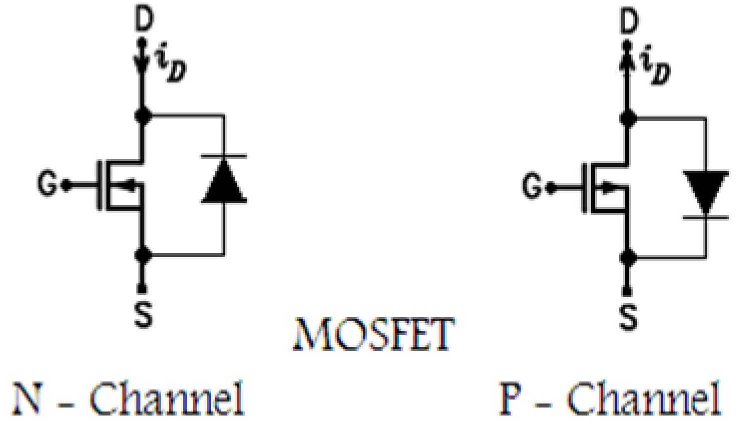


Figure (19) Symbols of a MOSFET.

I-V characteristics (Output characteristics)

It is the relationship between i_D and V_{DS} in many VGS conditions. (Refer to Figure (20). It is divided into the ohmic region, the saturation (=active) region, and the cut-off region.

Ohmic region: A constant resistance region. If the drain-to-source voltage is zero, the drain current also becomes zero regardless of gate–to-source voltage. This region is at the left side of the VGS – VGS(th) = VDS boundary line ($V_{GS} – V_{GS}(th) > V_{DS} > 0$).

Saturation region: A constant current region. It is at the right side of the $V_{GS} – V_{GS}(th) = V_{DS}$ boundary line. Here, the drain current differs by the gate–to source voltage, and not by the drain-to-source voltage. Hence, the drain current is called saturated.

Cut-off region: It is called the cut-off region, because the gate-to-source voltage is lower than the VGS(th) (threshold voltage).

A power MOSFET is a unipolar, majority carrier, "zero junction". Voltage-controlled device.

If the gate voltage is positive and beyond a threshold value (V_{GTH}). An N-type conducting channel will be inducted that will permit current flow by majority carrier (electrons) between the drain and the source. Although the gate impedance is extremely high at steady state. The effective gate-source capacitance will demand a pulse current during turn-on and turn-off. The device has asymmetric voltage-blocking capability. And had an integral body diode. as shown. Which can carry full current in the reserve direction. The diode is characteristics by slow recovery and is often by assed a external fast-recovery diode in high frequency application.
The V-I characteristics of the device have two distinct regions. A constant resistance ($R_{DS(on)}$) region and constant current region. The $R_{DS(ON)}$ of MOSFET is an important parameter which determines the conduction drop of the device. For a high voltage MOSFET . The longer conduction channel makes this drop large ($R_{DS(ON)}$ α $V^{2.5}$). it is interesting to note that modern trench gate technology tends to lower the conduction resistance. The positive temperature coefficient of this resistance makes parallel operation of MOSFET easy. In fact, large MOSFETS are fabricated by parallel connection of many devices.

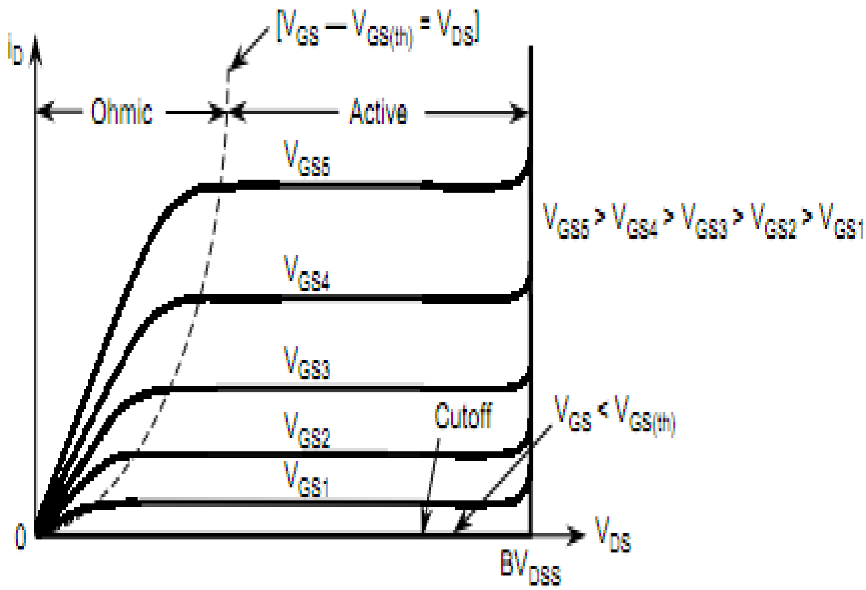


Figure (20) MOSFET Output characteristics.

<u>Advantages of a MOSFET</u>

1. High input impedance - voltage controlled device - easy to drive .To maintain the on-state, a base drive current which is 1/5th or 1/10th of collector current is required for the current controlled device (BJT). And also a larger reverse base drive current is needed for the high speed turn-off of the current controlled device (BJT). Due to these characteristics base drive circuit design becomes complicated and expensive. On the other hand, a voltage controlled MOSFET is a switching device which is driven by a channel at the semiconductor's

surface due to the field effect produced by the voltage applied to the gate electrode، which is isolated from the semiconductor surface. As the required gate current during switching transient as well as the on and off states is small, the drive circuit design is simple and less expensive.

2. Unipolar device - majority carrier device - fast switching speed. As there are no delays due to storage and recombination of the minority carrier, as in the BJT، the switching speed is faster than the BJT by orders of magnitude. Hence, it has an advantage in a high frequency operation circuit where switching power loss is prevalent.

3. Forward voltage drop with positive temperature coefficient - easy to use in parallel. When the temperature increases, the forward voltage drop also increases. This causes the current to flow equally through each device when they are in parallel. Hence, the MOSFET is easier to use in parallel than the BJT, which has a forward voltage drop with negative temperature coefficient .

Disadvantage

In high breakdown voltage devices over 200V, the conduction loss of a MOSFET is larger than that of a BJT, which has the same voltage and current rating due to the on-state voltage drop.

6.10 IGBT (Insulated Gate Bipolar Transistor)

The **insulated gate bipolar transistor** or **IGBT** is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers.
In order to combine the low forward voltage drop of the power BJT and the high input impedance of the power MOSFET, the IGBT is invented as a new power device.
The structure of the IGBT is the combination of the P+ layer added to the MOSFET structure. As such, IGBT is easier to drive, and it combines the advantages of MOSFET's faster switching speed and power BJT's lower conduction loss. IGBT is a useful device in that it overcomes the shortfall of MOSFET in that it is not suitable for high voltage، high current applications due to its high conduction loss, while IGBT has the advantage over power BJT, which has limitations in high frequency applications due to its switching speed.
Symbol and V-I characteristics of an IGBT is shown in figure (21). Referring to its characteristics The IGBT has the high input impedance and high-speed characteristics of a MOSFET with the conductivity characteristic (low saturation

voltage) of a bipolar transistor. The IGBT is turned on by applying a positive voltage between the gate and emitter and, as in the MOSFET, it is turned off by making the gate signal zero or slightly negative. The IGBT has a much lower voltage drop than a MOSFET of similar ratings.

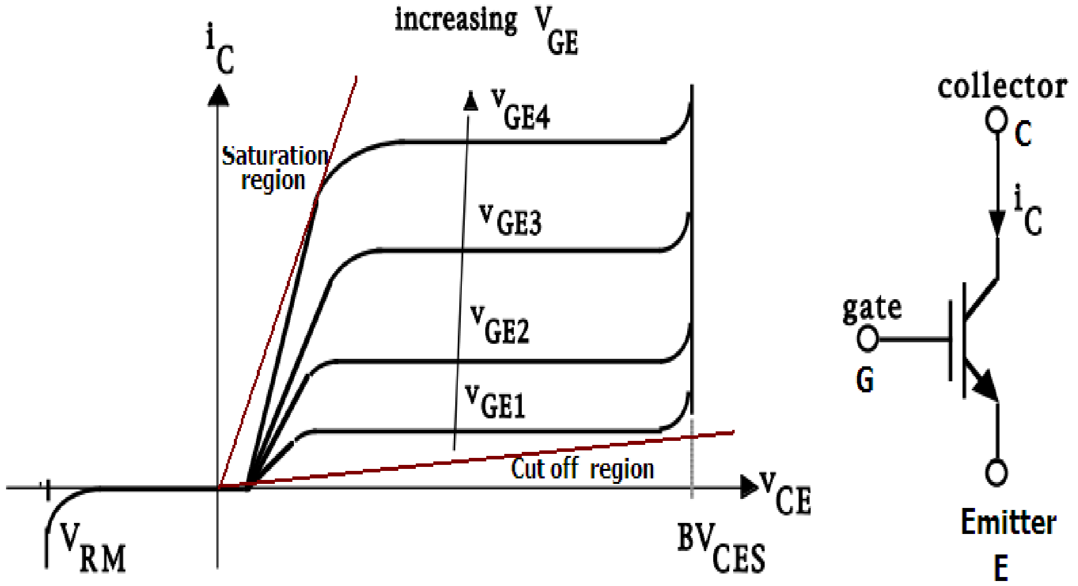


Figure (21) Symbol and characteristics of an IGBT.

6.1 Static Induction Transistor (SIT)

A **SIT(Static Induction Transistor)** is high power, high frequency device. It is a vertical structure device with short multi channels. A SIT has short channel length, low GATE series resistance, low GATE-SOURCE capacitance and small thermal resistance. It has low noise, low distortion and high audio frequency power capability. Turn-on and Turn-off time are very small typically in 0.25µs.

It has more advantages as compared to mosfet. These switches are used in induction heating application where high speed and high current is required.

6.12 SITh (Static Induction Thyristor).

The **static induction thyristor** (**SI-thyristor**, **SITh**) is a thyristor with a buried gate structure in which the gate electrodes are placed in n-base region. Since they are normally on-state, gate electrodes must be negatively biased to hold off-state. It is characterized by :

- short channel length. * Low gate series resistance
- low gate-source capacitance. * small thermal resistance
- low noise and low distortion
- high audio frequency power capability
- short turn-on and turn-off time, typically 0.25 µs

Figure (21) shows SIT and SITh symbols.

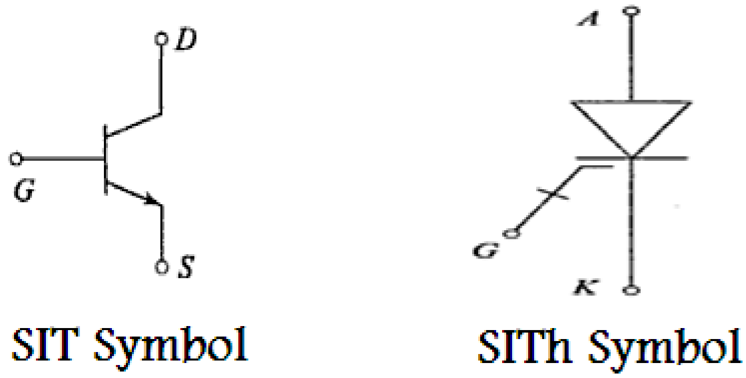


Figure (21) Symbols of SIT and SITh.

6.13 MOS-Controlled Thyristor (MCT)

An MOS-controlled thyristor (MCT), as the name indicates, is a thyristor-like, trigger-into-conduction hybrid device that can be turned on or off by a short voltage pulse on the MOS gate. The device has a microcell construction, where thousands of microdevices are connected in parallel on the same chip. The cell structure is somewhat complex. Figure 22 shows the symbo N-MCT & p-MCT of the device. It is turned on by a negative voltage pulse at the gate with respect to the anode and is turned off by a positive voltage pulse. The MCT has a thyristor-like P-N-P-N structure, where the P-N-P and N-P-N transistor components are connected in regenerative feedback, as shown in the figure. However, unlike a thyristor, it has unipolar (or asymmetric) voltage-blocking capability. If the gate of an MCT is negative with respect to the anode, a P-channel is induced in the P-FET, which causes forward-biasing of the N-P-N transistor. This also forward-biases the P-N-P transistor and the device goes into saturation by positive feedback effect. At conduction, the drop is around one volt (like a thyristor). If the gate is positive with respect to the anode, the N-FET will saturate and short-circuit the emitter-base junction of the P-N-P transistor. This will break the positive feedback loop for thyristor operation and the device will turn off. The turn-off occurs purely by recombination effect and therefore the tail time of the MCT is somewhat large. The device has a limited SOA, and therefore a snubber circuit is mandatory in an MCT converter. Recently, the device has been promoted for "soft-switched" converter applications, where the SOA is not utilized. In spite of complex geometry, the current density of an MCT is high compared to a power MOSFET, BJT, and IGBT, and therefore it needs a smaller die area.

The MCT was commercially introduced in 1992, and currently, medium-power devices are available commercially. The future acceptance of the device remains uncertain at this point.

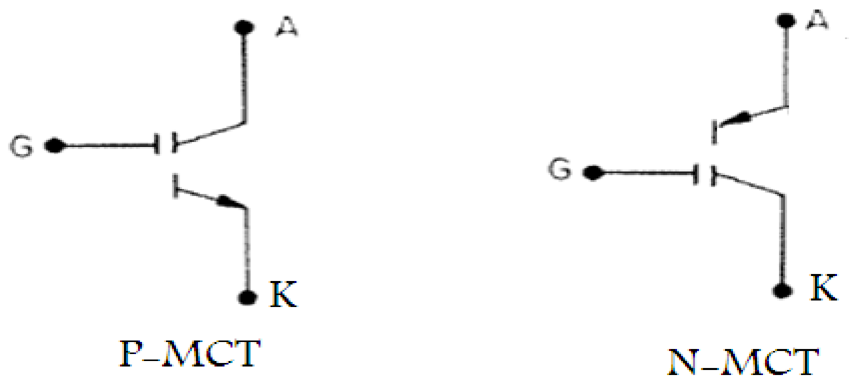


Figure (22) Symbols of MCTs.

TABLE (1) Semiconductor devices used in power electronics

Diode Current ratings from under 1 A to more than 5000 A. Voltage ratings from 10V to 10 kV or more. The fastest power devices switch in less than 20 ns, while the slowest require 100 µs or more. The function of a diode applies in rectifiers and dc–dc circuits.

BJT (Bipolar junction transistor) Conducts collector current (in one direction) when sufficient base current is applied. Power device current ratings from 0.5 to 500 A or more; voltages from 30 to 1200 V. Switching times from 0.5 to 100 µs. The function applies to dc–dc circuits; combinations with diodes are used in inverters.

FETs and IGBTs.

FET (Field effect transistor) Conducts drain current when sufficient gate voltage is applied. Power FETs (nearly always enhancement-mode MOSFETs) have a parallel connected reverse diode by virtue of their construction. Ratings from about 0.5 A to about 150 A and 20V up to 1000 V. Switching times are fast, from 50 ns or less up to 200 ns. The function applies to dc–dc conversion, where the FET is in wide use, and to inverters.

IGBT (Insulated gate bipolar transistor) A special type of power FET that has the function of a BJT with its base driven by an FET. Faster than a BJT of similar ratings, and easy to use. Ratings from 10 A to more than 600 A, with voltages of 600 to 2500 V. The IGBT is popular in inverters from about 1 to 200kW or more. It is found almost exclusively in power electronics applications.

SCR (Silicon controlled rectifier) A thyristor that conducts like a diode after a gate pulse is applied. Turns off only when current becomes zero. Prevents current flow

until a pulse appears. Ratings from 10 A up to more than 5000 A, and from 200V up to 6 kV. Switching requires 1 to 200 µs. Widely used for controlled rectifiers. The SCR is found almost exclusively in power electronics applications, and is the most common member of the thyristor family.

GTO (Gate turn-off thyristor) An SCR that can be turned off by sending a negative pulse to its gate terminal. Can substitute for BJTs in applications where power ratings must be very high. The ratings approach those of SCRs, and the speeds are similar as well. Used in inverters rated above about 100 kW.

TRIAC A semiconductor constructed to resemble two SCRs connected in reverse parallel. Ratings from 2 to 50 A and 200 to 800 V. Used in lamp dimmers, home appliances, and hand tools. Not as rugged as many other device types, but very convenient for many ac applications.

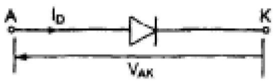
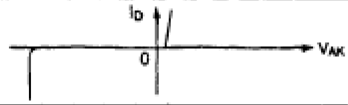
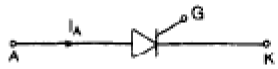
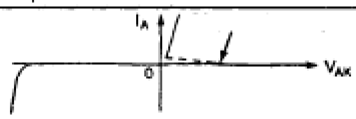
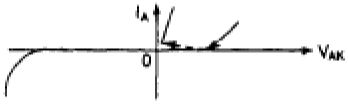
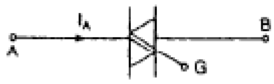
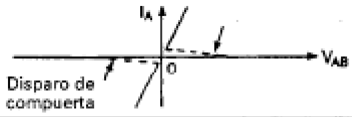
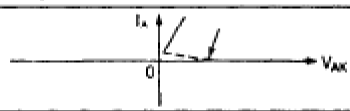
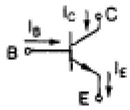
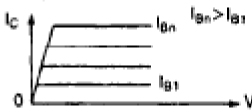
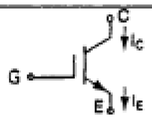
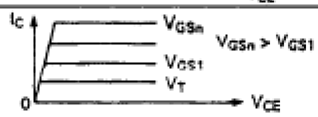
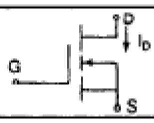
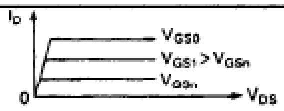
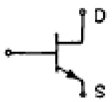
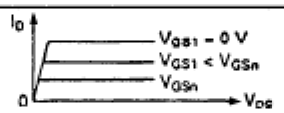
SIT and SITh are used for high voltage high current applications.

MCT (MOSFET controlled thyristor) A special type of SCR that has the function of a GTO with its gate driven from an FET. Much faster than conventional GTOs, and easier to use.

Table (2) Comparison of power semiconductor devices

Device type	Year made available	Rated voltage	Rated current	Rated frequency	Rated power	Forward voltage
Thyristor (SCR)	1957	6 kV	3.5 kA	500 Hz	100's MW	1.5–2.5 V
Triac	1958	1 kV	100 A	500 Hz	100's kW	1.5–2 V
GTO	1962	4.5 kV	3 kA	2 kHz	10's MW	3–4 V
BJT (Darlington)	1960s	1.2 kV	800 A	10 kHz	1 MW	1.5–3 V
MOSFET	1976	500 V	50 A	1 MHz	100 kW	3–4 V
IGBT	1983	1.2 kV	400 A	20 kHz	100'skW	3–4 V
SIT		1.2 kV	300 A	100 kHz	10's kW	10–20 V
SITH		1.5 kV	300 A	10 kHz	10's kW	2–4 V
MCT	1988	3 kV	2 kV	20–100 kHz	10's MW	1–2 V

Table (3) Symbols and characteristics of devices used in power electronics.

Device	Symbol	Characteristics
Diodo		
Tiristor		
SITH		
GTO		
MCT		
TRIAC		
LASCR		
NPN BJT		
IGBT		
MOSFET de canal N.		
SIT		

<u>Table (4) properties of power electronics devices.</u>

Type of switch	Current	Turn-on	Turn-off	Features
Ideal switch	Bidirectional	Instantaneous	Instantaneous	Zero on-state impedance
Diode	Unidirectional	Forward voltage ($V_A > V_K$)	Reverse voltage ($V_A < V_K$)	Voltage activated Low on-state impedance Low on-state volt drop High off-state impedance
Thyristors				
Silicon controlled rectifier (SCR)	Unidirectional	Forward voltage ($V_A > V_K$) Forward gate bias ($V_G > V_K$)	Reverse voltage $V_A < V_K$ to reduce the current	Gate turn-off is not possible
Gate turn-off devices State induction thyristor (SITH)	Unidirectional	Forward voltage ($V_A > V_K$) turn-on is the normal state (without gate drive)	-remove forward voltage -negative gate signal ($V_G < V_K$)	Low reverse blocking voltage
Gate turn-off thyristor (GTO)	Unidirectional	Forward voltage (V_A V_K) And + ve gate pulse ($I_G > 0$)	− By θ ve gate pulse ($I_G < 0$) or by current reduction	When the reverse blocking voltage is low it is known as an *asymmetric GTO*
MOS controlled thyristor (MCT)	Unidirectional	Forward voltage ($V_A > V_K$) − θ ve gate pulse ($V_G < V_K$)	+ve gate pulse ($V_G > V_A$)	Low reverse avalanche voltage
TRIAC	Birectional	Forward or reverse voltage (V_A >< V_K) +ve or θ ve gate pulse	Current reduction by voltage reversal with zero gate signal	Symmetrical forward and reverse blocking Ideally suited to phase angle triggering
Transistors				
Bipolar junction transistor (BJT)	Unidirectional	Forward voltage ($V_C > V_E$) +ve base drive ($V_B > V_B$)	Remove base current (I_B=0)	Cascading 2 or 3 devices produces a Darlington connection with high gain (low base current)
Metal-oxide-semiconductor field-effect transistor (MOSFET)	Unidirectional	Forward voltage ($V_D > V_E$) +ve gate pulse ($V_G > V_S$)	Remove gate drive (V_G=0)	Very fast turn-on and turn-off
Insulated gate bipolar transistor (IGBT)	Unidirectional	Forward voltage ($V_C > V_E$) +ve gate pulse ($V_G > V_S$)	Remove gate drive (V_G=0)	Low on-state losses, very fast turn-on/turn-off, low reverse blocking
Static induction transistor (SIT)	Unidirectional	Forward voltage ($V_D > V_X$) normally on ($V_G = 0$)	+ve gate pulse ($V_G > V_S$)	Also called the *power JFET high on-state voltage drop*

7. Uni Junction Transistor (UJT)

THEORY

UJT is the Uni Junction Transistor. It is a three terminal device. They are: a) emitter b) base1 c) base2. The equivalent circuit is shown with the circuit diagram in figure (23). So there are two resistors. One is a variable resistor and other is a fixed resistor.

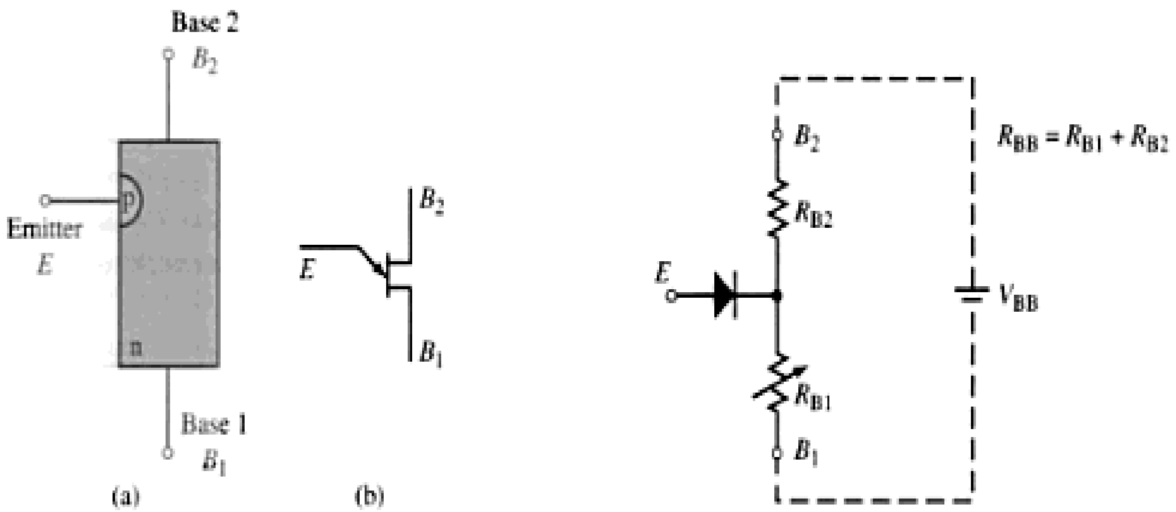


Figure (23) Construction, symbol, and equivalent circuit of a UJT.

The ratio of internal resistances is referred as intrinsic standoff ratio (η).It is defined as the ratio of the variable resistance to the total resistance. Due to the existing p-n junction, there will be a voltage drop. If we apply a voltage to the emitter, the device will not turn on until the input voltage is less than the drop across the diode plus the drop at the variable resistance R1. When the device is turned on holes moves from emitter to base resulting in a current flow. Due to this sudden increase in charge concentration in base1 region conductivity increases. This causes a drop at base1. This region in the graph is known as negative resistance region. If we further increase the emitter voltage the device undergoes saturation. So a UJT has 3 operating regions:

1. Cut off region.
2. Negative resistance region.
3. Saturation region.

In a relaxation circuit there is an RC timing circuit. When the supply is turned on, the capacitor starts charging. When the voltage across the capacitor reaches the

pinch off voltage, the UJT turns on. After discharging of capacitor, again it starts charging, and this process continues till power supply is turned off.

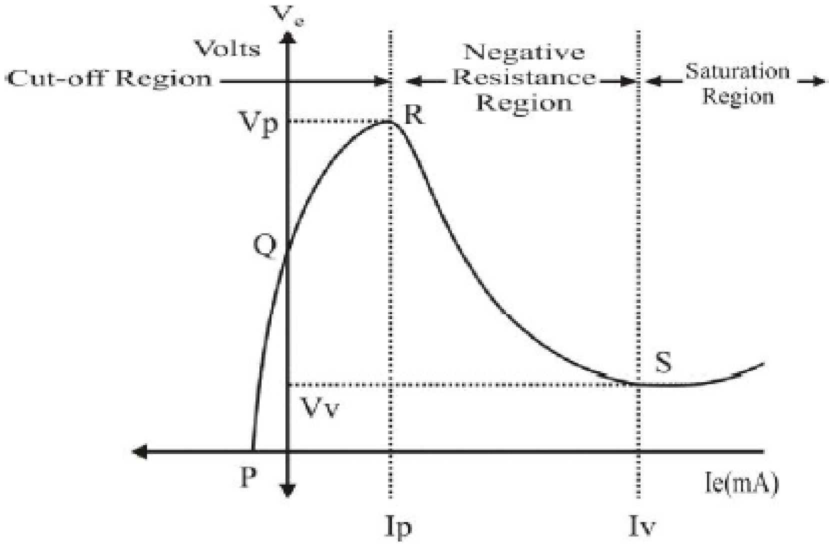


Figure (24) Characteristics of a UJT.

When an external voltage source VBB is applied between the base terminals (with the emitter open), an internal voltage will be developed across the resistance RB1, in accordance with the voltage divider rule and is expressed as

$$V_{RB1} = RB1/(RB2+RB1) * VBB = VBB * RB1/RBB$$

(where RBB=RB1+RB2)

The intrinsic standoff ratio (η) of the UJT is defined as the following resistance ratio

$$(\eta) = R_{B1} / R_{BB}$$

The typical values of (η) are in the range of 0.5 → 0.9. The operation of the UJT can be explained as follows:

1. When VEE=0 , the p-n junction (represented by the diode) will be reverse-biased. The current in the emitter circuit will be the result of the leakage current through this junction (Typically in the order of a few microampere)
2. As the applied emitter voltage is increased to a point where VEE=VBB, the diode will begin to conduct. The emitter voltage at this point will represents the peak voltage of the UJT (Vp) and is expressed as

$$Vp = \eta \; VBB + VD$$

3. Since the emitter region of the UJT is heavily doped, the forward-biased p-n junction will allow holes to be injected into the base junction and reducing the resistance RB1, effectively reducing the resistance of this region. Consquently, the value of VE decreases, while at the same time as the current through the emitter circuit increases.
4. The reduction in resistance causes a further increase in current. The increase current results in the injection of even more carriers into the base region of RB1, with a corresponding reduction in the value of RB1.
5. Eventually a point is reached where further increase in current does not inject any more holes the lower base region. The resistance RB1 has reached its minimum value. This point is reffered to as vally point of the UJT (Vv).
6. Further increases in the emitter current, IE, cause VE to also increase. At this point the UJT is saturated.

Relaxation oscillator.

If a circuit is designed with an emitter resistance, R_E, that ensures the UJT operates in the negative resistance region, so in this situation we can use the UJT as a relaxation oscillator. The frequency of the oscillation is dependent on the rate at which an emitter capacitor, C_E charges and the resistance RE. Figure (3) shows a simple UJT relaxation oscillator and the corresponding emitter voltage.

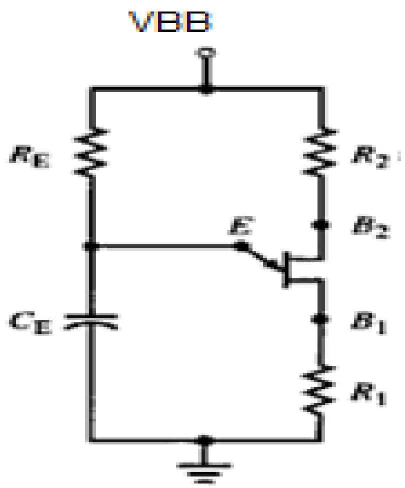


Figure (3) Relaxation oscillator circuit.

In order for the UJT oscillator to maintain its oscillation, it must operate in the negative resistance region. This means that the operating point must be lie between the peak and valley points of the emitter characteistic curve. In order for the circuit to have enough current to cause the UJT to fire, the emitter resistance must have a

value that is less than a value $R_{E(max)}$ detrmined from the peak point volatge and current as

$$R_{E(max)} = (VBB – Vp) / Ip$$

Additionally, the value of RE must be greater than the minimu value $R_{E(min)}$ determined from the point and current as

$$R_{E(min)} = (VBB – Vv) / Iv$$

The peak point voltage can be calculated as

$$Vp = \eta V_{BB} + V_D$$

The intrinsic standoff ratio

$$\eta = \frac{V_p - V_D}{V_{BB}}$$

The oscillation frequency can be found from the following expression,

$$f = \frac{1}{R_E C_E \ln(\frac{1}{1-\eta})} \quad \text{or} \quad T = R_E C_E \ln(\frac{1}{1-\eta})$$

EX.1

Take Vp = 10 V and f =1 KHZ η = 0.62 VBB=15V

Vp= η VBB+ V_D (V_D can be neglected) = 0.62 * 15 = 9.3 V

From data sheet valley point specifications are Vv=1.5 V and Iv = 4 mA and Ip = 5µA

$RE_{(max)}$= (VBB - Vp) / Ip = 1.14 M

$RE_{(min)}$ = (VBB - Vv) / Iv =3.37 K

For this use a 100 K pot in series with 10 K

Now

$$f = \frac{1}{R_E C_E \ln(\frac{1}{1-\eta})}$$

So

C_E =0.0103 uF (use 0.01 uF)

Use 100 Ω resistors at the two bases to provide low discharging path

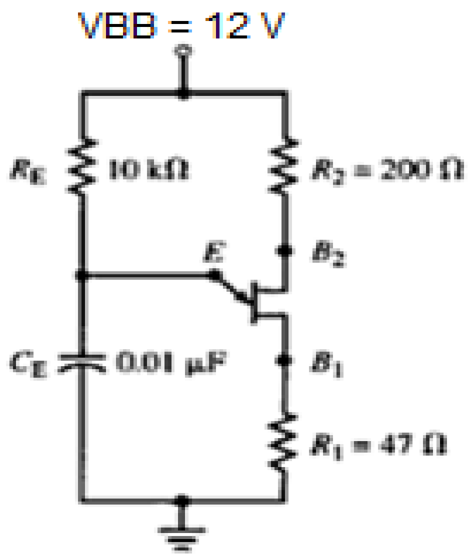
EX.2

Given that the UJT in the circuit below and has the following parameters:

Valley Point V_v=1.5 V I_v = 2mA VBB=12 V R_E= 10 K

Peak Point V_p = 8.0 V I_p = 2.0 μA V_D = 0.6 V C_E = 0.01μF

Find the frequency of oscillation, and sketch the waveforms.



Sol.

We have

Vp = η VBB + VD

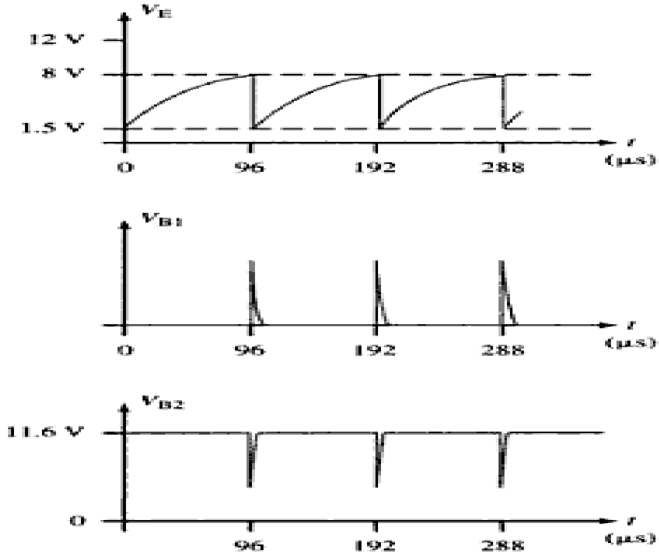
And η can be determined as

η = (V_p – V_D) / VBB = (8 – 0.6) / 12 = **0.617**

a) The frequency of oscillation is

$$f = \frac{1}{R_E C_E \ln(\frac{1}{1-\eta})} = \frac{1}{(10\ K\ )(0.01\ \mu F)\ln(\frac{1}{1-0.617})} = 10.5 \text{ KHz.}$$

b) The waveforms shown in figure below.



v_E
12 V
8 V
1.5 V
0
96
192
288
t (μs)
v_{B1}
0
96
192
288
t (μs)
v_{B2}
11.6 V
0
96
192
288
t (μs)

DATA SHEET OF 2N2646 UJT

ASI **2N2646**

SILICON PN UNIJUNCTION TRANSISTOR

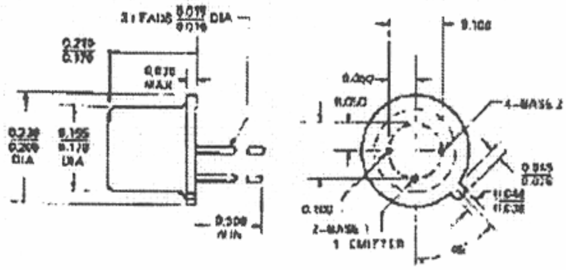
DESCRIPTION:

The **2N2646** is a Unijunction Transistor Used in General Purpose Pulse, Timing, Sense and Trigger Applications.

MAXIMUM RATINGS

I_C	2.0 A (PULSED)
V_{CE}	30 V
P_{DISS}	300 mW @ T_C = 25 °C
T_J	-65 °C to +125 °C
T_{STG}	-65 °C to +150 °C
θ_{JC}	33 °C/W

PACKAGE STYLE TO-18 (MOD)



CHARACTERISTICS T_C = 25 °C

SYMBOL	TEST CONDITIONS	MINIMUM	TYPICAL	MAXIMUM	UNITS
η	V_{B2B1} = 10 V	0.56		0.75	--
r_{BB}	V_{B2B1} = 3.0 V	4.7		9.1	KΩ
α_{rBB}	V_{B2B1} = 3.0 V T_A = -55 to 125°C	0.1		0.9	%/°C
$V_{EB1(SAT)}$	V_{B2B1} = 10 V I_E = 50 mA		3.0		V
$I_{B2(MOD)}$	V_{B2B1} = 10 V I_E = 50 mA		20		mA
I_{B2EO}	V_{B2E} = 30 V I_{B1} = 0			12	µA
I_P	V_{B2B1} = 25 V			5.0	µA
I_V	V_{B2B1} = 20 V R_{B2} = 100 Ω	4.0			mA
V_{OB1}	V_{B2B1} = 20 V R_{B1} = 20 Ω	3.0	5.0		V

ADVANCED SEMICONDUCTOR, INC. REV. A

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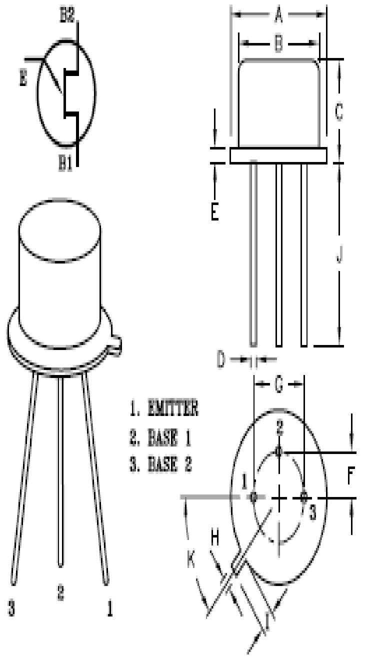
SPC-F005.DWG

REVISIONS			DOC. NO. SPC-F005 • Effective: 7/8/02 • DCP No: 1398					
DCP #	REV	DESCRIPTION	DRAWN	DATE	CHECKD	DATE	APPRVD	DATE
1262	A	RELEASED	HO	9/5/02	JWM	9/5/02	DJC	9/6/06

Description: A PN Unijunction Transistor designed for use in pulse and timing circuits, sensing circuits, and thyristor trigger circuits.

Electrical Characteristics: (T_A = +25°C Unless otherwise specified)

Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
OFF Characteristics						
Intrinsic Standoff Ratio		V_{B2B1}= 10V, Note 3	0.56	-	0.75	-
Interbase Resistance	r_{BB}	V_{B2B1}= 3V, I_E=0	4.7	7.0	9.1	k Ohms
Interbase Resistance Temperature Coefficient			0.1	-	0.9	%/°C
Emitter Saturation Voltage	$V_{EB1(sat)}$	V_{B2B1}= 10V, I_E= 50mA, Note 4	-	3.5	-	V
Modulated Interbase Current	$I_{B2(mod)}$	V_{B2B1}= 10V, I_E= 50mA	-	15	-	mA
Emitter Reverse Current	I_{EB2O}	V_{B2E}= 30V, I_{B1}= 0	-	0.005	12	µA
Peak Point Emitter Current	I_P	V_{B2B1}= 25V	-	1	5	µA
Valley Point Current	I_V	V_{B2B1}= 20V, R_{B2}= 100 Ohms	4	6	-	mA
Base-One Peak Pulse Voltage	V_{OB1}		3	5	-	V



Features:
- low peak point current: 5µA (Max.)
- Low emitter reverse current: 0.005 µA (Max.)
- Passivated surface for reliability and uniformity

ABSOLUTE MAXIMUM RATINGS: (T_A = 25°C Unless otherwise specified)
- Power Dissipation (Note 1) P_D: 300 mW
- RMS Emitter Current $I_{E(RMS)}$: 50mA
- Peak Pulse Emitter Current (Note 2), i_E: 2 Amps
- Emitter Reverse Voltage V_{B2E}: 30 Volts
- Interbase Voltage V_{B2B1}: 35 Volts
- Operating Junction Temperature Range T_J: -65°C ~ +125°C
- Storage Temperature Range T_{stg}: -65°C ~ +150°C

Dimensions	A	B	C	D	E	F	G	H	I	J	K
Min.	5.24	4.52	4.31	0.40	-	-	-	0.91	0.71	12.7	45°
Max.	5.84	4.97	5.33	0.53	0.76	1.27	2.97	1.17	1.21	-	

Notes:
1. Derate 3mW/°C increase in ambient temperature. The total power dissipation (available power to Emitter and Base-Tow) must be limited by the external circuitry.
2. Capacitor discharge -10µF or less, 30V or less.
3. Intrinsic standoff ration is defined by the equation: $V_P = V_F / V_{B2B1}$
   Where: V_P = peak Point Emitter Voltage; V_{B2B1} = Interbase Voltage; V_F = Emitter to Base-One Junction Diode Drop (~0.45V @ 10 µA)
4. Use pulse techniques: Pulse Width ~ 300µS, Duty Cycle ≤2% to avoid internal heating due to interbase modulation which may result in erroneous readings.

TOLERANCES:
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE FOR REFERENCE PURPOSES ONLY.

DRAWN BY:	DATE:
HISHAM ODISH	9/5/02
CHECKED BY:	DATE:
JEFF MCVICKER	9/5/02
APPROVED BY:	DATE:
DANIEL CAREY	9/6/02

DRAWING TITLE: Transistor, Unijunction, TO-18, PN

SIZE	DWG. NO.	ELECTRONIC FILE	REV
A	2N2646	35C0693.DWG	A

SCALE: NTS U.O.M.: Millimeters SHEET: 1 OF 1

8. Power Electronics converters.

7.1. AC to DC uncontrolled rectifier.
7.2. AC to DC controlled rectifier.
7.3. DC to DC chopper.
7.4. DC to AC inverter.
7.5. AC to AC regulator.
7.6. AC to AC cycloconverter.