$$I_{C\,(sat)} \simeq \frac{V_{CC}}{R_C}\;; \quad V_{CE} = V_{CE(sat)} = V_{knee}$$

If base current is greater than $I_{B(sat)}$, then collector current cannot increase because collector-base junction is no longer reverse-biased.

(*iii*) Active region. The region between cut off and saturation is known as *active region*. In the active region, collector-base junction remains reverse biased while base-emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

Note. We provide biasing to the transistor to ensure that it operates in the active region. The reader may find the detailed discussion on transistor biasing in the next chapter.

Summary. A transistor has two *pn* junctions *i.e.*, it is like two diodes. The junction between base and emitter may be called *emitter diode*. The junction between base and collector may be called *collector diode*. We have seen above that transistor can act in one of the three states : **cut-off, saturated** and **active**. The state of a transistor is entirely determined by the states of the emitter diode and collector diode [See Fig. 8.50]. The relations between the diode states and the transistor states are :

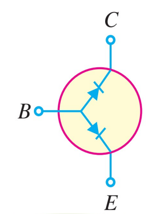


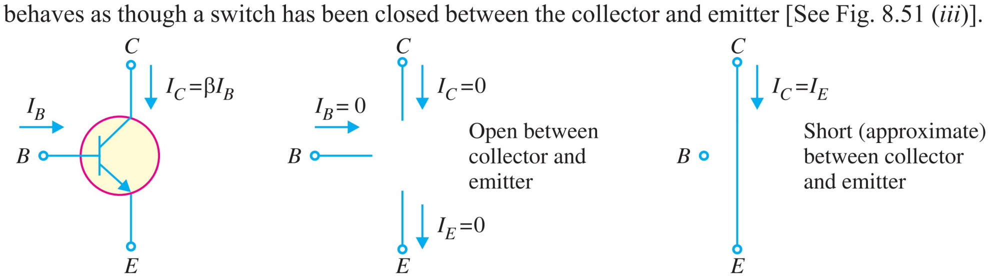
Fig. 8.50

CUT-OFF : Emitter diode and collector diode are **OFF.**

ACTIVE : Emitter diode is **ON** and collector diode is **OFF.**

SATURATED : Emitter diode and collector diode are **ON.**

In the **active state**, collector current [See Fig 8.51 (*i*)] is β times the base current (*i.e.* $I_C = \beta I_B$). If the transistor is **cut-off,** there is no base current, so there is no collector or emitter current. That is collector emitter pathway is open [See Fig. 8.51 (*ii*)]. In **saturation,** the collector and emitter are, in effect, shorted together. That is the transistor behaves as though a switch has been closed between the collector and emitter [See Fig. 8.51 (*iii*)].



(*i*) ACTIVE (*ii*) CUT-OFF (*iii*) SATURATED

Fig. 8.51

Note. When the transistor is in the active state, $I_C = \beta I_B$. Therefore, a transistor acts as an amplifier when operating in the active state. Amplification means *linear amplification*. In fact, small signal amplifiers are the most common *linear devices*.

Example 8.31. *Find $I_{C(sat)}$ and $V_{CE(cut\ off)}$ for the circuit shown in Fig. 8.52 (i).*

Solution. As we decrease R_B, base current and hence collector current increases. The increased collector current causes a greater voltage drop across R_C; this decreases the collector-emitter voltage. Eventually at some value of R_B, V_{CE} decreases to V_{knee}. At this point, collector-base junction is no longer reverse biased and transistor action is lost. Consequently, further increase in collector current is not possible. The transistor conducts maximum collector current ; we say the transistor is saturated.

$$I_{C(sat)} = \frac{V_{CC} - {}^{*}V_{knee}}{R_C} = \frac{V_{CC}}{R_C} = \frac{20\text{ V}}{1\text{ k}\Omega} = \mathbf{20mA}$$

* V_{knee} is about 0.5 V for Ge transistor and about 1V for Si transistor. Consequently, V_{knee} can be neglected as compared to V_{CC} (= 20 V in this case).

As we increase R_B, base current and hence collector current decreases. This decreases the voltage drop across R_C. This increases the collector-emitter voltage. Eventually, when $I_B = 0$, the emitter-base junction is no longer forward biased and transistor action is lost. Consequently, further increase in V_{CE} is not possible. In fact, V_{CE} now equals to V_{CC}.

$$V_{CE(cut\text{-}off)} = V_{CC} = \mathbf{20\ V}$$

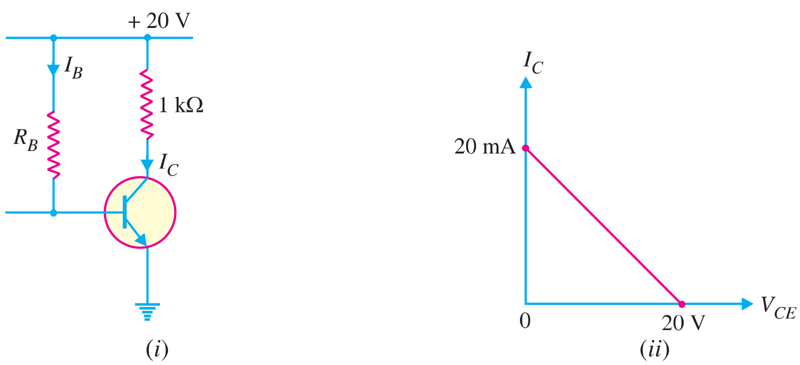


Fig. 8.52

Figure 8.52 (*ii*) shows the saturation and cut off points. Incidentally, they are end points of the d.c. load line.

Note. The exact value of $V_{CE(cut\text{-}off)} = V_{CC} - I_{CEO}\,R_C$. Since the collector leakage current I_{CEO} is very small, we can neglect $I_{CEO}\,R_C$ as compared to V_{CC}.

Example 8.32. *Determine the values of* $V_{CE\,(off)}$ *and* $I_{C\,(sat)}$ *for the circuit shown in Fig. 8.53.*

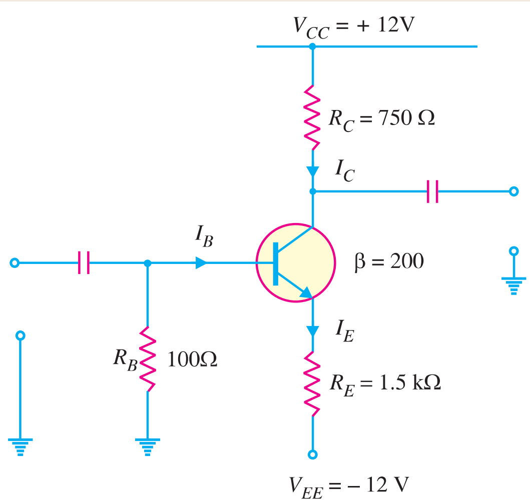


Fig. 8.53

Solution. Applying Kirchhoff's voltage law to the collector side of the circuit in Fig. 8.53, we have,

$$V_{CC} - I_C\,R_C - V_{CE} - {}^{*}I_C\,R_E + V_{EE} = 0$$

or $$V_{CE} = V_{CC} + V_{EE} - I_C\,(R_C + R_E) \qquad \text{... (i)}$$

* Voltage across $R_E = I_E\,R_E$. Since $I_E \simeq I_C$, voltage across $R_E = I_C\,R_E$.

We have $V_{CE\,(off)}$ when $I_C = 0$. Therefore, putting $I_C = 0$ in eq. (*i*), we have,

$$V_{CE\,(off)} = V_{CC} + V_{EE} = 12 + 12 = \mathbf{24V}$$

We have $I_{C\,(sat)}$ when $V_{CE} = 0$.

$$\therefore \quad I_{C\,(sat)} = \frac{V_{CC} + V_{EE}}{R_C + R_E} = \frac{(12+12)\,V}{(750+1500)\,\Omega} = \mathbf{10.67\ mA}$$

Example 8.33. *Determine whether or not the transistor in Fig. 8.54 is in stauration. Assume $V_{knee} = 0.2V$.*

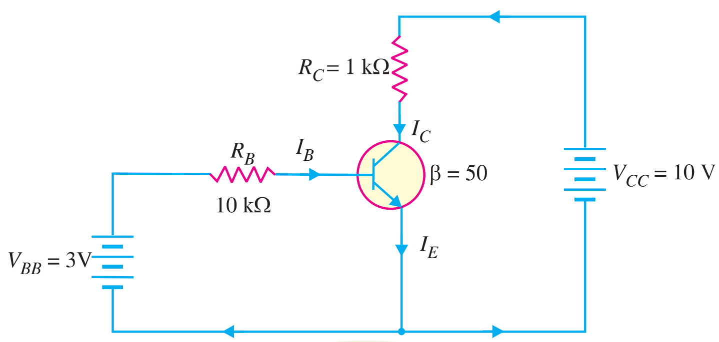


Fig. 8.54

Solution.

$$I_{C\,(sat)} = \frac{V_{CC} - V_{knee}}{R_C} = \frac{10\,V - 0.2\,V}{1\,k\Omega} = \frac{9.8\,V}{1\,k\Omega} = 9.8\ \text{mA}$$

Now we shall see if I_B is large enough to produce $I_{C\,(sat)}$.

$$\text{Now} \quad I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3V - 0.7V}{10\,k\Omega} = \frac{2.3\,V}{10\,k\Omega} = 0.23\ \text{mA}$$

$$\therefore \quad I_C = \beta I_B = 50 \times 0.23 = 11.5\ \text{mA}$$

This shows that with specified β, this base current (= 0.23 mA) is capable of producing I_C greater than $I_{C\,(sat)}$. Therefore, the transistor is **saturated.** In fact, the collector current value of 11. 5 mA is never reached. If the base current value corresponding to $I_{C\,(sat)}$ is increased, the collector current remains at the saturated value (= 9.8 mA).

Example 8.34. *Is the transistor in Fig. 8.55 operating in saturated state ?*

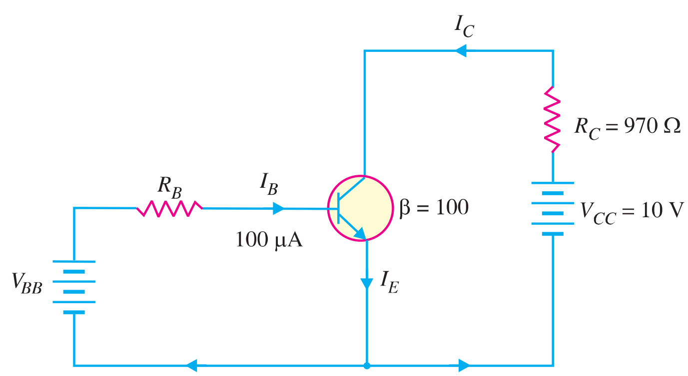


Fig. 8.55

Solution.

$$I_C = \beta I_B = (100)(100\ \mu A) = 10\ mA$$
$$V_{CE} = V_{CC} - I_C R_C$$
$$= 10V - (10\ mA)(970\Omega) = 0.3V$$

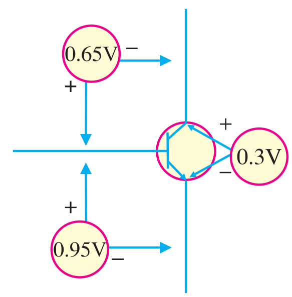


Fig. 8.56

Let us relate the values found to the transistor shown in Fig. 8.56. As you can see, the value of V_{BE} is 0.95V and the value of $V_{CE} = 0.3V$. This leaves V_{CB} of 0.65V (Note that $V_{CE} = V_{CB} + V_{BE}$). In this case, collector – base junction (*i.e.*, collector diode) is forward biased as is the emitter-base junction (*i.e.*, emitter diode). Therefore, the transistor is operating in the **saturation region.**

Note. When the transistor is in the saturated state, the base current and collector current are independent of each other. The base current is still (and always is) found only from the base circuit. The collector current is found apporximately by closing the imaginary switch between the collector and the emitter in the collector circuit.

Example 8.35. *For the circuit in Fig. 8.57, find the base supply voltage (V_{BB}) that just puts the transistor into saturation. Assume $\beta = 200$.*

Solution. When transistor first goes into saturation, we can assume that the collector shorts to the emitter (*i.e.* $V_{CE} = 0$) but the collector current is still β times the base current.

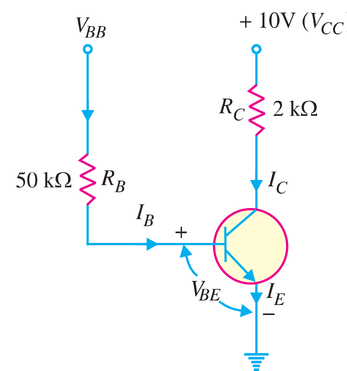


Fig. 8.57

$$I_{C(sat)} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC} - 0}{R_C}$$
$$= \frac{10\ V - 0}{2\ k\Omega} = 5\ mA$$

The base current I_B corresponding to $I_{C\ (sat)}$ (=5 mA) is

$$I_B = \frac{I_{C\ (sat)}}{\beta} = \frac{5\ mA}{200} = 0.025\ mA$$

Applying Kirchhoff's voltage law to the base circuit, we have,

$$V_{BB} - I_B R_B - V_{BE} = 0$$

or $$V_{BB} = V_{BE} + I_B R_B$$
$$= 0.7V + 0.025\ mA \times 50\ k\Omega = 0.7 + 1.25 = 1.95V$$

Therefore, for $V_{BB} \geq 1.95$, the transistor will be in *saturation.*

Example. 8.36. *Determine the state of the transistor in Fig. 8.58 for the following values of collector resistor :*

(i) $R_C = 2\ k\Omega$ (ii) $R_C = 4\ k\Omega$ (iii) $R_C = 8\ k\Omega$

Solution. Since I_E does not depend on the value of the collector resistor R_C, the emitter current (I_E) is the same for all three parts.

Emitter voltage, $V_E = V_B - V_{BE} = V_{BB} - V_{BE}$
$$= 2.7V - 0.7\ V = 2V$$

Also $$I_E = \frac{V_E}{R_E} = \frac{2V}{1\ k\Omega} = 2\ mA$$

(*i*) When $R_C = 2\ k\Omega$. Suppose the transistor is active.

∴ $$I_C = I_E = 2\ mA$$

∴ $$I_B = I_C/\beta = 2\ mA/100 = 0.02\ mA$$

Collector voltage, $V_C = V_{CC} - I_C R_C$

$= 10V - 2\ mA \times 2\ k\Omega = 10V - 4V = 6V$

Since V_C (= 6V) is greater than V_E (= 2V), the transistor is **active.** Therefore, our assumption that transistor is active is correct.

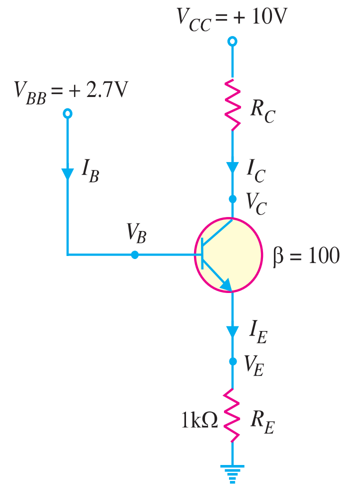


Fig. 8.58

(ii) When $R_C = 4\ k\Omega$. Suppose the transistor is active.

$\therefore \quad I_C = 2mA$ and $I_B = 0.02$ mA ... as found above

Collector voltage, $V_C = V_{CC} - I_C R_C$

$= 10V - 2\ mA \times 4\ k\Omega = 10V - 8V = 2V$

Since $V_C = V_E$, the transistor is just at the edge of **saturation.** We know that at the edge of saturation, the relation between the transistor currents is the same as in the **active state.** Both answers are correct.

(iii) When $R_C = 8\ k\Omega$. Suppose the transistor is active.

$\therefore \quad I_C = 2mA$; $I_B = 0.02$ mA ... as found earlier.

Collector voltage, $V_C = V_{CC} - I_C R_C$

$= 10V - 2\ mA \times 8\ k\Omega = 10V - 16V = -6V$

Since $V_C < V_E$, the transistor is **saturated** and our assumption is not correct.

Example 8.37. *In the circuit shown in Fig. 8.59, V_{BB} is set equal to the following values :*
(i) $V_{BB} = 0.5V$ (ii) $V_{BB} = 1.5V$ (iii) $V_{BB} = 3V$

Determine the state of the transistor for each value of the base supply voltage V_{BB}.

Solution. The state of the transistor also depends on the base supply voltage V_{BB}.

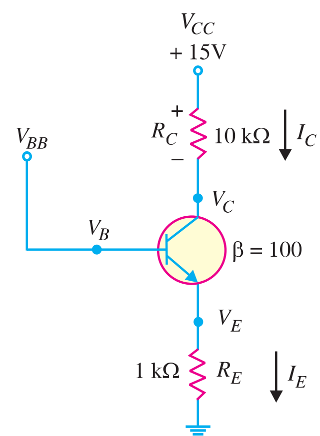


Fig. 8.59

(i) For $V_{BB} = 0.5V$

Because the base voltage V_B (= V_{BB} = 0.5V) is less than 0.7V, the transistor is **cut-off.**

(ii) For $V_{BB} = 1.5V$

The base voltage V_B controls the emitter voltage V_E which controls the emitter current I_E.

Now $\quad V_E = V_B - 0.7V = 1.5V - 0.7V = 0.8V$

$$\therefore \quad I_E = \frac{V_E}{R_E} = \frac{0.8\,V}{1\,k\Omega} = 0.8\ mA$$

If the transistor is active, we have,

$I_C = I_E = 0.8$ mA and $I_B = I_C/\beta = 0.8/100 = 0.008$ mA

$\therefore$ Collector voltage, $V_C = V_{CC} - I_C R_C$

$= 15V - 0.8\ mA \times 10\ k\Omega = 15V - 8V = 7V$

Since $V_C > V_E$, the transistor is **active** and our assumption is correct.

(iii) For $V_{BB} = 3V$

$V_E = V_B - 0.7V = 3V - 0.7V = 2.3V$

$$\therefore \quad I_E = \frac{V_E}{R_E} = \frac{2.3\,V}{1\,k\Omega} = 2.3\ mA$$

Assuming the transistor is active, we have,

$I_C = I_E = 2.3$ mA ; $I_B = I_C/\beta = 2.3/100 = 0.023$ mA

Collector voltage, $V_C = V_{CC} - I_C R_C$

$= 15\text{V} - 2.3 \text{ mA} \times 10 \text{ k}\Omega = 15\text{V} - 23\text{V} = -8\text{V}$

Since $V_C < V_E$, the transistor is **saturated** and our assumption is not correct.

8.23 Power Rating of Transistor

The maximum power that a transistor can handle without destruction is known as **power rating** *of the transistor.*

When a transistor is in operation, almost all the power is dissipated at the reverse biased *collector-base junction. The power rating (or maximum power dissipation) is given by :

$$P_{D\ (max)} = \text{Collector current} \times \text{Collector-base voltage}$$
$$= I_C \times V_{CB}$$
$$\therefore \quad P_{D\ (max)} = I_C \times V_{CE}$$
$$[\because V_{CE} = V_{CB} + V_{BE}. \text{ Since } V_{BE} \text{ is very small, } V_{CB} \simeq V_{CE}]$$

While connecting transistor in a circuit, it should be ensured that its power rating is not exceeded otherwise the transistor may be destroyed due to excessive heat. For example, suppose the power rating (or maximum power dissipation) of a transistor is 300 mW. If the collector current is 30 mA, then maximum V_{CE} allowed is given by ;

$$P_{D\ (max)} = I_C \times V_{CE\ (max)}$$
or
$$300 \text{ mW} = 30 \text{ mA} \times V_{CE\ (max)}$$
or
$$V_{CE\ (max)} = \frac{300 \text{ mW}}{30 \text{ mA}} = 10\text{V}$$

This means that for $I_C = 30$ mA, the maximum V_{CE} allowed is 10V. If V_{CE} exceeds this value, the transistor will be destroyed due to excessive heat.

Maximum power dissipation curve. For **power transistors, it is sometimes necessary to draw maximum power dissipation curve on the output characteristics. To draw this curve, we should know the power rating (*i.e.* maximum power dissipation) of the transistor. Suppose the power rating of a transistor is 30 mW.

$$P_{D\ (max)} = V_{CE} \times I_C$$
or
$$30 \text{ mW} = V_{CE} \times I_C$$

Using convenient V_{CE} values, the corresponding collector currents are calculated for the maximum power dissipation. For example, for $V_{CE} = 10\text{V}$,

$$I_C\ (max) = \frac{P_{D\ (max)}}{V_{CE}} = \frac{30 \text{ mW}}{10 \text{ V}} = 3\text{mA}$$

This locates the point *A* (10V, 3 mA) on the output characteristics. Similarly, many points such as *B, C, D etc.* can be located on the output characteristics. Now draw a curve through the above points to obtain the maximum power dissipation curve as shown in Fig. 8.60.

In order that transistor may not be destroyed, the transistor voltage and current (*i.e.* V_{CE} and I_C) conditions must at all times be maintained in the portion of the characteristics below the maximum power dissipation curve.

* The base-emitter junction conducts about the same current as the collector-base junction (*i.e.* $I_E \simeq I_C$). However, V_{BE} is very small (0.3 V for *Ge* transistor and 0.7 V for *Si* transistor). For this reason, power dissipated at the base-emitter junction is negligible.

** A transistor that is suitable for large power amplification is called a *power transistor.* It differs from other transistors mostly in size ; it is considerably larger to provide for handling the great amount of power.