1.9 Bias Compensation

May-03, 10, Dec.-04, 09, 10

The biasing circuits so far discussed provide stability of operating point in case of variations in the transistor parameters such as I_{CO}, V_{BE} and β. The collector to base bias and the voltage follower bias use the negative feedback to do the stabilization action. This negative feedback reduces the amplification of the signal. If this loss in signal amplification is intolerable and extremely stable biasing conditions are required, then it is necessary to use compensation techniques.

As mentioned earlier, compensation techniques use temperature sensitive devices such as diodes, transistors, thermistors, etc. to maintain operating point constant. In this section we are going to study some compensation techniques.

1.9.1 Diode Compensation Techniques

Compensation for V_{BE} :

a) Diode in Emitter Circuit

Fig. 1.9.1 shows the voltage divider bias with bias compensation technique. Here, separate supply V_{DD} is used to keep diode in forward biased condition. If the diode used in the circuit is of same material and type as the transistor, the voltage across the diode will have the same temperature coefficient (-2.5 mV/°C) as the base to emitter voltage V_{BE}. So when V_{BE} changes by ∂V_{BE} with change in temperature, V_D changes by ∂V_D and $\partial V_D' \approx \partial V_{BE}$, the changes tend to cancel each other.

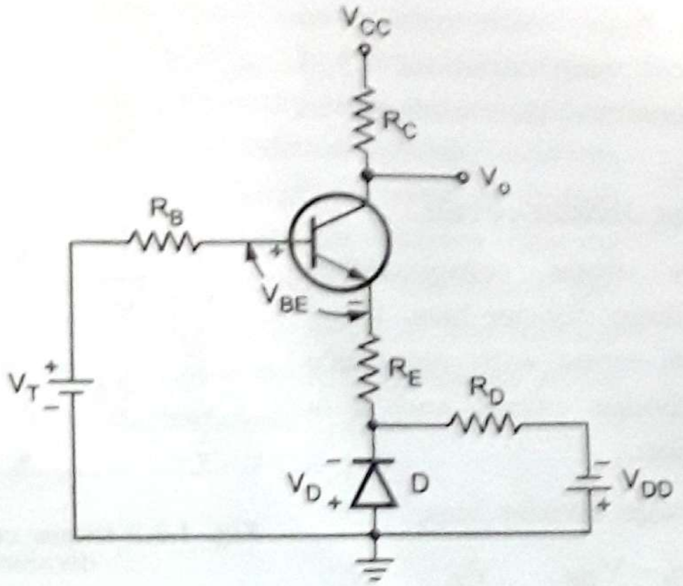

Fig. 1.9.1 Stabilization by means of voltage divider bias and diode compensation technique

Applying KVL to the base circuit of Fig. 1.9.1 we have

$$\begin{aligned} V_{TH} &= I_B R_B + V_{BE} + (I_B + I_C) R_E - V_D \\ &= I_B (R_B + R_E) + I_C R_E + V_{BE} - V_D \qquad \text{... (1.9.1)} \end{aligned}$$

Considering leakage current we have,

$$I_C = \beta I_B + (1+\beta) I_{CO}$$

$$\therefore \quad I_B = \frac{I_C}{\beta} + \frac{(1+\beta) I_{CO}}{\beta}$$

Substituting the value of I_B in equation (1.9.1) we have

$$\begin{aligned} V_{TH} &= \left[\frac{I_C}{\beta} + \frac{(1+\beta) I_{CO}}{\beta}\right] (R_B + R_E) + I_C R_E + V_{BE} - V_D \\ &= \frac{I_C}{\beta}(R_B + R_E) + \frac{\beta I_C R_E}{\beta} + \frac{(1+\beta) I_{CO} (R_B + R_E)}{\beta} + V_{BE} - V_D \\ &= \frac{I_C}{\beta}[R_B + (1+\beta) R_E] + \frac{(R_B + R_E)(1+\beta) I_{CO}}{\beta} + V_{BE} - V_D \end{aligned}$$

$$\therefore \quad \frac{I_C}{\beta}[R_B + (1+\beta) R_E] = V_{TH} - V_{BE} + V_D + \frac{(R_B + R_E)(1+\beta) I_{CO}}{\beta}$$

$$\therefore \quad I_C = \frac{\beta[V_{TH} - (V_{BE} - V_D)] + (R_B + R_E)(1+\beta) I_{CO}}{R_B + (1+\beta) R_E} \qquad \text{... (1.9.2)}$$

Since V_D tracks V_{BE} with respect to temperature, it is clear from equation (1.9.2) that I_C will be insensitive to variations in V_{BE}.

b) Diode in voltage divider circuit

Fig. 1.9.2 shows diode compensation technique used in voltage divider bias. Here, diode is connected in series with resistance R_2 in the voltage divider circuit and it is forward biased condition.

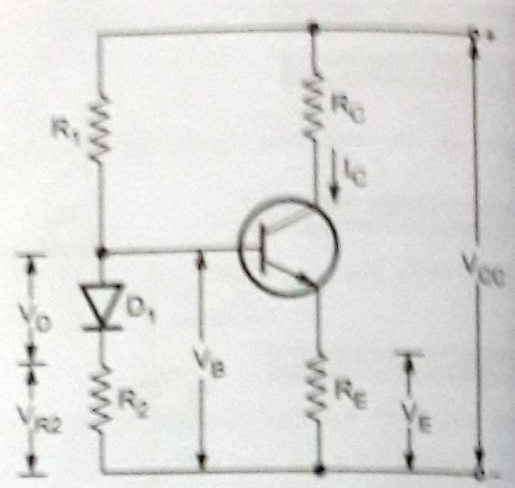

Fig. 1.9.2 Diode compensation in voltage divider bias circuit

We derived for voltage divider bias,

$$I_E = \frac{V_B - V_{BE}}{R_E} = \frac{V_E}{R_E}$$

$$\therefore \quad I_C \approx \frac{V_B - V_{BE}}{R_E} \qquad \because I_C \approx I_E \qquad \ldots (1.9.3)$$

When V_{BE} changes with temperature, I_C also changes. To cancel the change in I_C one diode is used in this circuit for compensation as shown in Fig. 1.9.2. The voltage at the base V_B is now,

$$V_B = V_{R2} + V_D$$

Substituting in equation (1.9.3), we get,

$$I_C \approx \frac{V_{R2} + V_D - V_{BE}}{R_E} \qquad \ldots (1.9.4)$$

If the diode which is used in this circuit is of same material and type as the transistor, the voltage across the diode will have the same temperature coefficient $(-2.5\ mV/^\circ C)$ as the base to emitter voltage V_{BE}. So when V_{BE} changes by ∂V_{BE} with change in temperature, V_D changes by ∂V_D and $\partial V_D \approx \partial V_{BE}$, the changes tend to cancel each other and leave the collector current as

$$I_C \approx \frac{V_{R2}}{R_E}$$

Which is unaffected due to change in V_{BE}. From Fig. 1.9.2 we can see that biasing is provided by R_1, R_2 and R_E. The changes in V_{BE} due to temperature are compensated by changes in the diode voltage which keeps I_C stable at Q point.

Compensation for I_{CO}

In case of germanium transistors, changes in I_{CO} with temperature are comparatively larger than silicon transistor. Thus, in germanium transistor changes in I_{CO} with temperature play the more important role in collector current stability than the changes in the V_{BE}. The Fig. 1.9.3 shows diode compensation technique commonly used for stabilizing germanium transistors. It offers stabilization against variation in I_{CO}. In this circuit diode is kept in reverse biased condition. In reverse biased condition the current flowing through diode is only the leakage current. If the diode and the transistor are of the same type and material, the leakage current I_O of the diode will increase with temperature at the same rate as the collector leakage current I_{CO}.

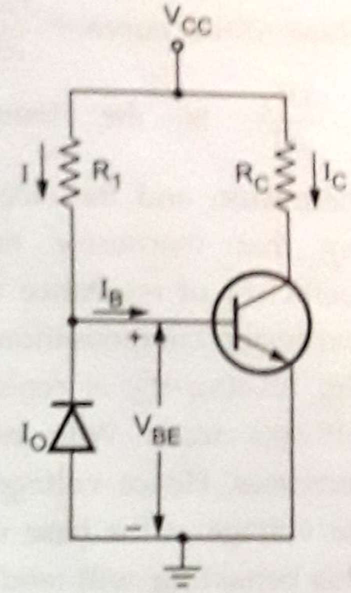

Fig. 1.9.3 Diode compensation for a germanium transistor

From Fig. 1.9.3 we have

$$I = \frac{V_{CC} - V_{BE}}{R_1}$$

and $\quad I = I_B + I_O \qquad \therefore \; I_B = I - I_O$

For germanium transistor $V_{BE} = 0.2$ V, which is very small and neglecting change in V_{BE} with temperature we can write,

$$I \cong \frac{V_{CC}}{R_1} \cong \text{constant}$$

We know, $\quad I_C = \beta I_B + (1+\beta) I_{CO}$

Substituting value of I_B in above equation we get,

$$I_C = \beta I - \beta I_O + (1+\beta) I_{CO}$$

if $\beta >> 1$ we get,

$$I_C = \beta I - \beta I_O + \beta I_{CO} \qquad \dots (1.9.5)$$

Now if $\quad I_O = I_{CO}$ we get,

$$I_C = \beta I \qquad \dots (1.9.6)$$

As I is constant, I_C remains fairly constant. In other words we can say that changes by I_{CO} with temperature are compensated by diode and thus collector current remains fairly constant.

1.9.2 Thermistor Compensation

This method of transistor compensation uses temperature sensitive resistive elements, thermistors rather than diodes or transistors. It has a negative temperature coefficient, its resistance decreases exponentially with increasing temperature as shown in the Fig. 1.9.4.

Slope of this curve = $\frac{\partial R_T}{\partial T}$

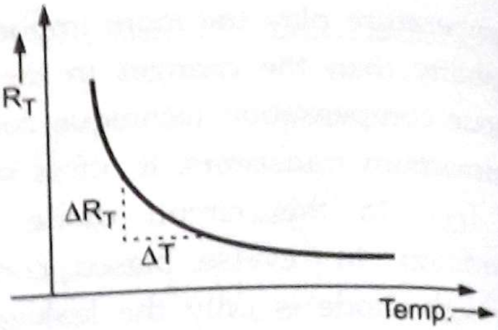

Fig. 1.9.4 Temperature Vs R_T resistance of thermistor

$\frac{\partial R_T}{\partial T}$ is the temperature coefficient for thermistor, and the slope is negative. So we can say that thermistor has negative temperature coefficient of resistance (NTC). Fig. 1.9.4(a) shows thermistor compensation technique. As shown in Fig. 1.9.4(a), R_2 is replaced by thermistor R_T in self bias circuit. With increase in temperature, R_T decreases. Hence voltage drop across it also decreases. This voltage drop is nothing but the voltage at the base with respect to ground. Hence, V_{BE} decreases which reduces I_B. This behaviour will tend to offset the increase in collector current with temperature.

We know, $\quad I_C = \beta I_B + (1+\beta) I_{CO}$

In this equation, there is increase in I_{CO} and decrease in I_B which keeps I_C almost constant.

Fig. 1.9.4 (b) shows another thermistor compensation technique. Here, thermistor is connected between emitter and V_{CC} to minimize the increase in collector current due to changes in I_{CO}, V_{BE}, or β with temperature.

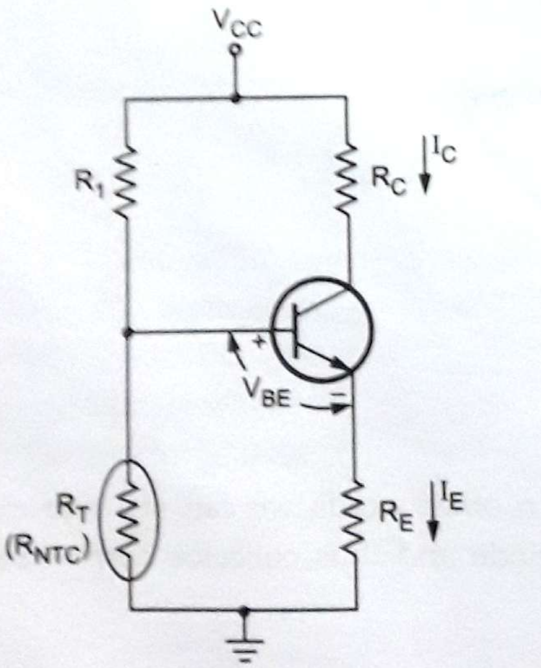

Fig. 1.9.4 (a) Thermistor compensation technique

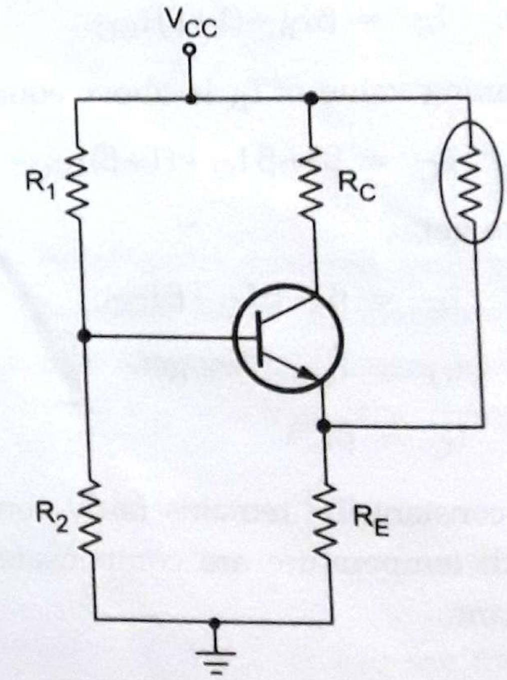

Fig. 1.9.4 (b) Thermistor compensation technique

I_C increases with temperature and R_T decreases with increase in temperatur Therefore, current flowing through R_E increases, which increases the voltage drop acros it. E - B junction is forward biased. But due to increase in voltage drop across R emitter (N-type for NPN transistor) is made more positive, which reduces the forward bias voltage V_{BE}. Hence, base current reduces.

I_C is given by,

$$I_C = \beta I_B + (\beta + 1) I_{CO}$$

As I_{CO} increases with temperature, I_B decreases and hence I_C remains fairly constant.

1.9.3 Sensistor Compensation Technique

This method of transistor compensation uses temperature sensitive resistive element, sensistors rather than diodes or transistors. It has a positive temperature coefficient, its resistance increases exponentially with increasing temperature as shown in the Fig. 1.9.5.

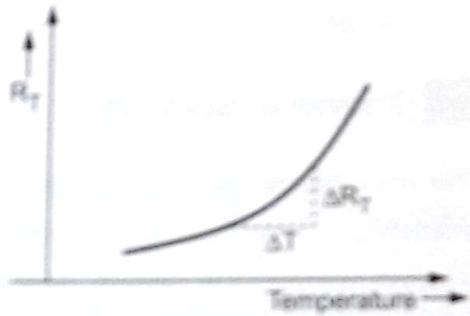

Fig. 1.9.5 Temperature Vs resistance of sensistor, R_T

$$\text{Slope of this curve} = \frac{\partial R_T}{\partial T}$$

$\frac{\partial R_T}{\partial T}$ is the temperature coefficient for thermistor, and the slope is positive.

So we can say that sensistor has positive temperature coefficient of resistance (PTC).

Fig. 1.9.6 shows sensistor compensation technique.

As shown in Fig. 1.9.6, R_1 is replaced by sensistor R_T in self bias circuit. Now, R_T and R_2 are the two resistors of the potential divider.

As temperature increases, R_T increases which decreases the current flowing through it. Hence current through R_2 decreases which reduces the voltage drop across it. Voltage drop across R_2 is the voltage between base and ground. So V_{BE} reduces which decreases I_B. It means, when I_{CBO} increases with increase in temperature, I_B reduces due to reduction in V_{BE}, maintaining I_C fairly constant.

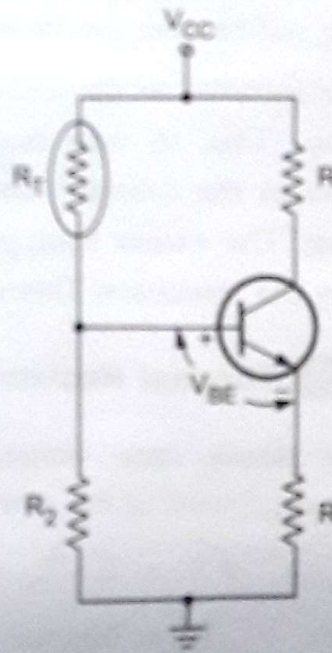

Fig. 1.9.6 Sensistor compensation technique

May-03, Dec.-07

1.10 Thermal Stability

The maximum average power $P_{D(max)}$ which a transistor can dissipate depends upon the transistor construction and may lie in the range from a few milliwatts to 200 W. As mentioned earlier, the power dissipated within a transistor is predominantly the power dissipated at its collector base junction. Thus maximum power is limited by the temperature that the collector-base junction can withstand. For silicon transistor this temperature is in the range 150 to 225 °C, and for germanium it is between 60 to 100 °C. The collector-base junction temperature may rise because of two reasons :

- Due to rise in ambient temperature
- Due to self heating.

The self heating can be explained as follows :

The increase in the collector current increases the power dissipated at the collector junction. This, in turn further increases the temperature of the junction and hence increase in the collector current. The process is cumulative and it is referred to as **self heating**. The excess heat produced at the collector base junction may even burn and destroy the transistor. This situation is called '**Thermal runaway**' of the transistor.

1.10.1 Thermal Resistance

The steady state temperature rise at the collector junction is proportional to the power dissipated at the junction. It is given as

$$\partial T = T_j - T_A = \theta P_D \qquad \text{... (1.10.1)}$$

where T_j = Junction temperature in °C.

T_A = Ambient temperature in °C.

and P_D = Power in watts dissipated at the collector junction.

θ = Constant of proportionality.

The θ, which is constant of proportionality is referred to as thermal resistance.

$$\theta = \frac{T_j - T_A}{P_D} \quad \text{... (1.10.2)}$$

The unit of θ, the thermal resistance, is °C/watt. The typical values of θ for various transistors vary from 0.2 °C/W for a high power transistor with an efficient heat sink to 1000 °C/W for a low power transistor. The maximum collector power P_C allowed for safe operation is specified at 25 °C.

Fig. 1.10.1 shows power-temperature derating curve for a germanium transistor.

It shows that above 25 °C, collector power must be decreased, and at the extreme temperature at which the transistor may operate, P_C is reduced to zero.

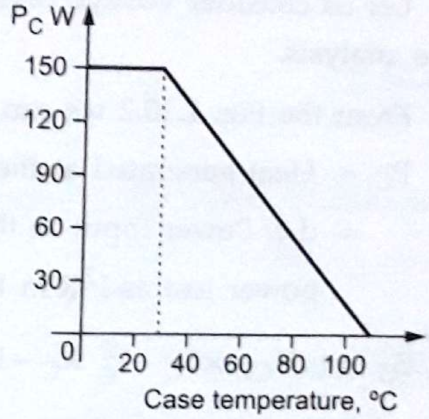

Fig. 1.10.1 Power temperature derating curve

1.10.2 The Condition for Thermal Stability

As we know, the thermal runaway may even burn and destroy the transistor, it is necessary to avoid thermal runaway. The required condition to avoid thermal runaway is that the rate at which heat is released at the collector junction must not exceed the rate at which the heat can be dissipated.

It is given by,

$$\frac{\partial P_C}{\partial T_j} < \frac{\partial P_D}{\partial T_j} \quad \text{... (1.10.3)}$$

If we differentiate equation (1.10.1)

$T_j - T_A = \theta P_D$ with respect to T_j we get,

$$1 = \theta \frac{\partial P_D}{\partial T_j}$$

$$\therefore \quad \frac{\partial P_D}{\partial T_j} = \frac{1}{\theta} \quad \text{... (1.10.4)}$$

Now substituting equation (1.10.4) in equation (1.10.3) we get

$$\frac{\partial P_C}{\partial T_j} < \frac{1}{\theta} \quad \text{... (1.10.5)}$$

This condition must be satisfied to prevent thermal runaway. By proper design of biasing circuit it is possible to ensure that the transistor cannot runaway below a specified ambient temperature or even under any condition.

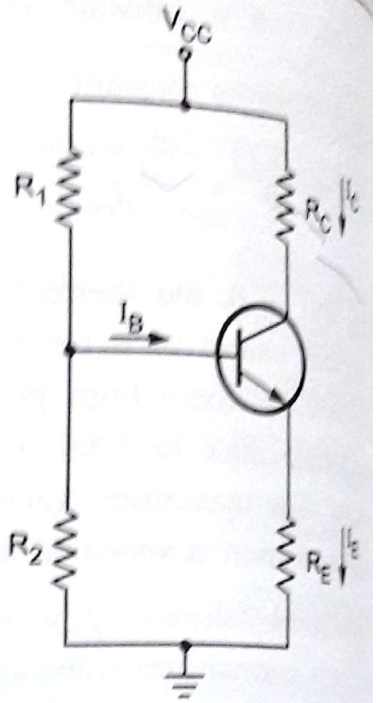

Fig. 1.10.2 Voltage divider bias circuit

Let us consider voltage divider bias circuit for the analysis.

From the Fig. 1.10.2 we can say that,

P_C = Heat generated at the collector junction

= d.c. Power input to the circuit – The power lost as I^2R in R_C and R_E

$$\therefore P_C = V_{CC} \times I_C - I_C^2 R_C - I_E^2 R_E \quad ... (1.10.6)$$

If we consider $I_C \cong I_E$ we get,

$$P_C = V_{CC} \times I_C - I_C^2 (R_C + R_E) \quad ... (1.10.7)$$

Differentiating equation (1.10.7) with respect to I_C we get,

$$\frac{\partial P_C}{\partial I_C} = V_{CC} - 2 I_C (R_C + R_E) \quad ... (1.10.8)$$

Referring and rewriting condition equation (1.8.5) to avoid thermal runaway we get

$$\frac{\partial P_C}{\partial I_C} \cdot \frac{\partial I_C}{\partial T_j} < \frac{1}{\theta} \quad ... (1.10.9)$$

In the above equation $\frac{\partial I_D}{\partial T_j}$ can be written as,

$$\frac{\partial I_D}{\partial T_j} = S \frac{\partial I_{CO}}{\partial T_j} + S' \frac{\partial V_{BE}}{\partial T_j} + S'' \frac{\partial \beta}{\partial T_j} \quad ... (1.10.10)$$

Since junction temperature affects collector current by affecting I_{CO}, V_{BE}, and β as we are doing analysis for thermal runaway the affect of I_{CO} dominates. Thus we write

$$\frac{\partial I_C}{\partial T_j} = \frac{\partial I_{CO}}{\partial T_j} \quad ... (1.10.11)$$

As the reverse saturation current for both silicon and germanium increases about 7 percent per °C, we can write

$$\frac{\partial I_{CO}}{\partial T_j} = 0.07\, I_{CO} \qquad \text{... (1.10.12)}$$

Now substituting value of $\frac{\partial I_C}{\partial T_j}$ and $\frac{\partial P_C}{\partial I_C}$ in equation (1.10.11) we get,

$$\frac{\partial I_C}{\partial T_j} = S \times 0.07\, I_{CO} \qquad \text{... (1.10.13)}$$

Now substituting value of $\frac{\partial I_C}{\partial T_j}$ and $\frac{\partial P_C}{\partial I_C}$ from equations (1.10.13) and (1.10.8) into equation (1.10.9) we get,

$$[V_{CC} - 2\, I_C\, (R_C + R_E)]\, (S)\, (0.07\, I_{CO}) < \frac{1}{\theta} \qquad \text{... (1.10.14)}$$

As S, I_{CO} and θ are positive, we see that the inequality in equation (1.10.14) is always satisfied provided that the quantity in the square bracket is negative.

$$\therefore \quad V_{CC} < 2\, I_C\, (R_C + R_E)$$

$$\therefore \quad \frac{V_{CC}}{2} < I_C\, (R_C + R_E) \qquad \text{... (1.10.15)}$$

Applying KVL to the collector circuit of Fig. 1.10.2 we get,

$$V_{CE} = V_{CC} - I_C\, (R_E + R_C) \qquad \because \quad I_C \cong I_E$$

$$\therefore \quad I_C\, (R_E + R_C) = V_{CC} - V_{CE}$$

Substituting value of $I_C\, (R_E + R_C)$ in equation (1.10.15) we get,

$$\frac{V_{CC}}{2} < V_{CC} - V_{CE}$$

$$\therefore \quad V_{CE} < V_{CC} - \frac{V_{CC}}{2}$$

$$\therefore \quad V_{CE} < \frac{V_{CC}}{2}$$

Thus if $V_{CE} < \frac{V_{CC}}{2}$, the stability is ensured. But in transformer coupled circuit, R_C and R_E are quite small and $V_{CE} \cong V_{CC}$. Hence it is necessary to design transformer coupled circuits with stability factor as close to 1 as possible to avoid thermal runaway.

Example 1.10.1 *Calculate the value of thermal resistance θ for the transistor in the circuit shown in Fig. 1.10.3 in order to make circuit thermally stable. Assume that I_{CO} = 1 nA 25 °C.*

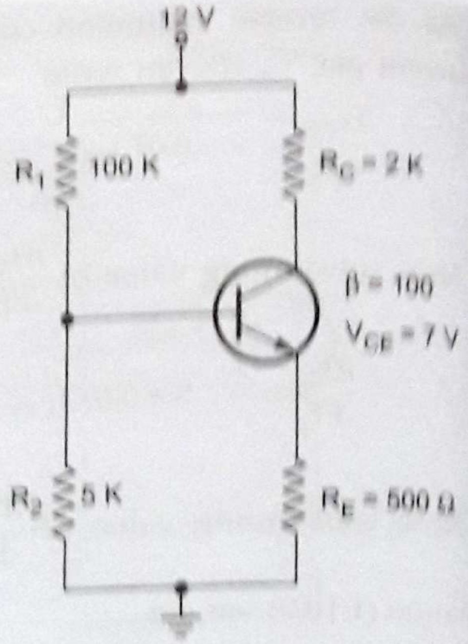

Fig. 1.10.3

Solution : Stability factor for the above circuit (voltage divider bias) is given from equation (1.8.19)

$$S = 1+\beta \times \frac{1+\frac{R_B}{R_E}}{(1+\beta)+\frac{R_B}{R_E}}$$

and
$$R_B = \frac{R_1 R_2}{R_1+R_2} = \frac{100\times10^3 \times 5\times10^3}{100\times10^3+5\times10^3}$$

$$= 4762\ \Omega$$

$$\therefore \quad S = (1+100)\times\frac{1+\frac{4762}{500}}{(1+100)+\left(\frac{4762}{500}\right)} = 9.617$$

Applying KVL to the collector circuit we get,

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E = \beta I_B R_C + V_{CE} + (1+\beta) I_B R_E$$

$$I_B = \frac{V_{CC}-V_{CE}}{\beta R_C + (1+\beta) R_E} = \frac{12-7}{100\times2\times10^3+(100+1)\times500} = 20\ \mu A$$

$$I_C = \beta I_B$$

$$\therefore \quad I_C = 2\ mA$$

From equation (1.10.14) we can write,

$$[V_{CC} - 2I_C (R_C + R_E)](S)(0.07\, I_{CO}) < \frac{1}{\theta}$$

Now substituting values in the above equation we get,

$$[12-2\times2\times10^{-3}(2\times10^3+500)](9.617)(0.07\times1\times10^{-9}) < \frac{1}{\theta}$$

$$1.346\times10^{-9} < \frac{1}{\theta}$$

or $\theta < 7.427\times10^{8}$ °C/W to make circuit thermally stable.