XMUT204 Electronic Design

Note 3d: BJT DC Analysis

1. BJT as Current and Voltage Amplifiers

Transistor has been viewed as a current amplifier as the collector current is much larger than the base current:

$$I_C = \beta_{DC} I_B$$

In the active region of operation, this value of β will be a constant and any increase or decrease in I_B will lead to a proportional increase or decrease in I_C.

We will now look at the transistor as a voltage amplifier where the signals are small AC voltages compared to the DC bias voltages. We need to distinguish between DC and AC quantities in our analysis.

2. Amplification

Amplification is the process of (linear) increase in the amplitude of a signal. This can be achieved when BJT is operating in the active mode. We now must deal with both DC voltage and currents (the bias) and AC voltages and currents (the signal) and must distinguish between them.

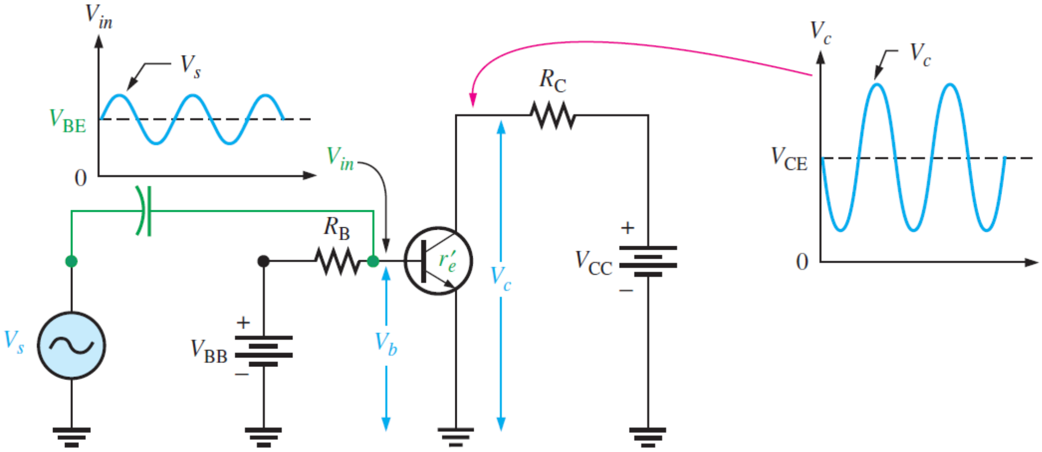


Figure 1: Signals in the input and output of the BJT amplifier

We will normally use capital letters (I and V) for both AC and DC currents and voltages.

For *DC quantities*, we will use a capital subscript:

- V_{BE} : base – emitter DC voltage.
- I_C : DC Collector current.
- V_B : The DC voltage between base and ground.

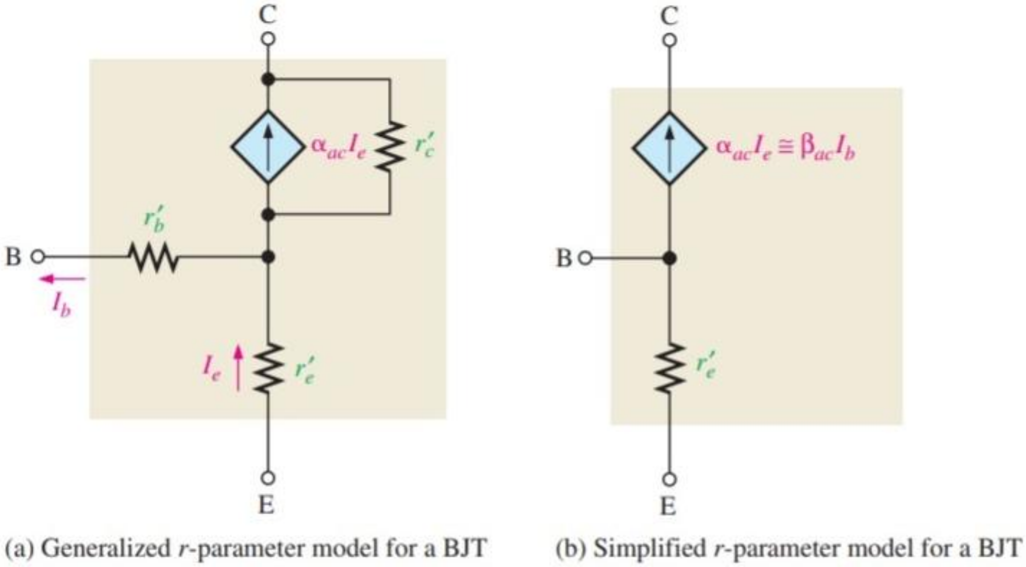
For *AC quantities*, we use a lowercase italic subscript:

- V_{be} : AC voltage over the base – emitter.
- I_c : AC collector current.
- V_b : AC voltage from transistor base terminal to ground.

We also must distinguish between internal transistor resistances and external resistances in the circuit.

Internal transistor resistances are indicated by a lowercase r' with a subscript e.g. r_e' is the internal emitter AC resistance.

External circuit resistances are indicated by capital R with appropriate subscript e.g. R_E is the external DC emitter resistance and R_e is the external AC emitter resistance.



(a) Generalized r-parameter model for a BJT (b) Simplified r-parameter model for a BJT

Figure 2: Internal emitter resistance of the BJT

Now, we superimpose a small AC on top of the DC bias voltage V_{BB}. We will thus have a variation in the base current, which will lead to a much larger variation in the collector current. This AC collector current will then also produce an AC voltage over R_C so that V_c will be amplified but inverted from V_s.

The forward biased base-emitter junction has a very low resistance to the AC signal. This resistance is indicated by r_e'.

The AC voltage at the base is then given by:

$$V_b = I_e r_e'$$

The AC collector voltage V_c equals the AC voltage drop over R_C:

$$V_c = I_c R_C$$

But, since $I_c \approx I_e$, we can write:

$$V_c \approx I_e R_C$$

The V_b can be considered the transistor input voltage with:

$$V_b = V_s - I_b R_B$$

Then, the voltage gain can be defined as the ratio of output voltage to the input voltage, so that for AC voltages we can write:

$$A_v = \frac{V_c}{V_b}$$

Insert values for V_c and V_b

$$A_v = \frac{I_c R_c}{I_c r_e'}$$

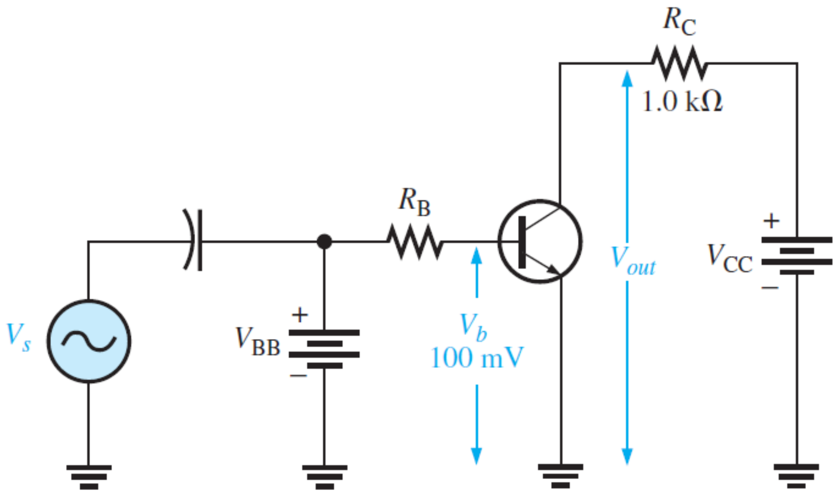
So, that the voltage gain can be written as

$$A_v \cong \frac{R_c}{r_e'}$$

The transistor thus provides voltage gain which depends on the values of R_c and r_e'.

Example 1 – Parameters in BJT Amplifier

For the circuit below, voltage at the base, V_b is 100 mV and output voltage, V_{out} is taken at the collector of the BJT. Calculate the voltage gain and the AC output voltage if internal emitter resistance, r_e' = 50 Ω. [4 marks]



Answer

Given that the circuit is a common emitter BJT amplifier circuit, the voltage amplification factor is calculated from values of the R_c and r_e'.

$$A_v \approx \frac{R_c}{r_e'} = \frac{1\ \text{k}\Omega}{50\ \Omega} = 20$$

The output voltage in the circuit is calculated from:

$$V_{out} = A_v V_{in} = (20)(100\ \text{mV}) = 2\ \text{V}$$

3. Design Procedure

We will first analyse and design the DC bias of BJTs to ensure that they operate efficiently as amplifiers. Look at a common-emitter circuit using two voltage sources:

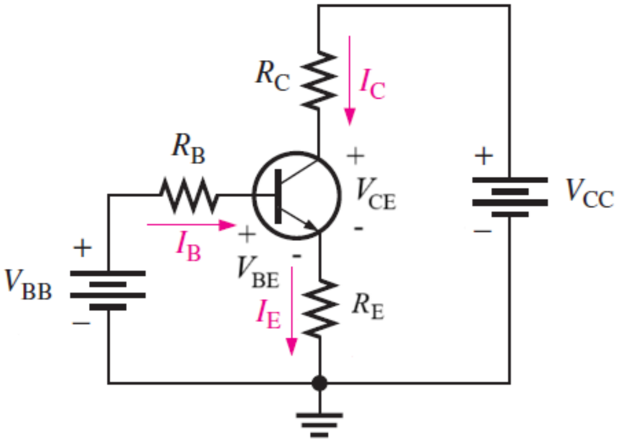


Figure 3: Common emitter BJT amplifier circuit

We can model the transistor in the active region by a forward biased diode the represents the BE junction and a constant current source with current $\beta_{DC} I_B$ that represents the collector current.

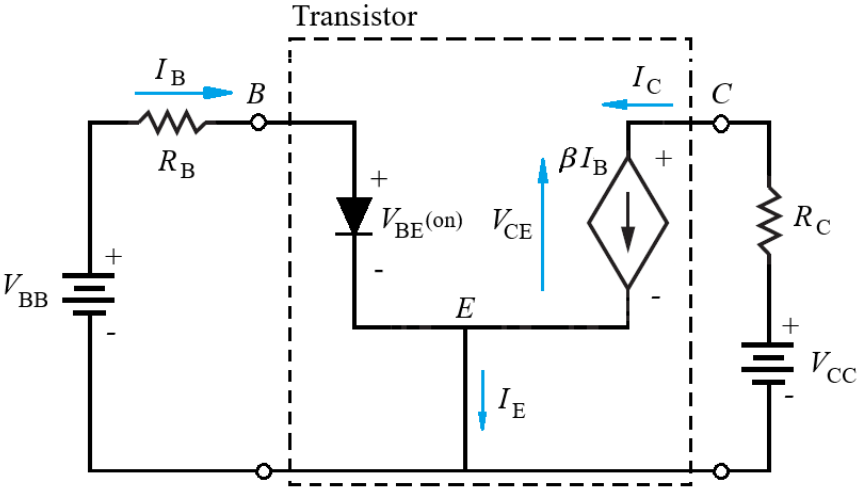


Figure 4: A model of common emitter BJT amplifier circuit

Assuming forward bias for BE junction, the turn-on voltage needed is $V_{BE(\text{on})}$. The collector current is now a dependant current source – controlled by the base current. The base current is:

$$I_B = \frac{V_{BB} - V_{BB(\text{on})}}{R_B}$$

And

$$I_C = \beta I_B$$

For the CE portion of the circuit, we have:

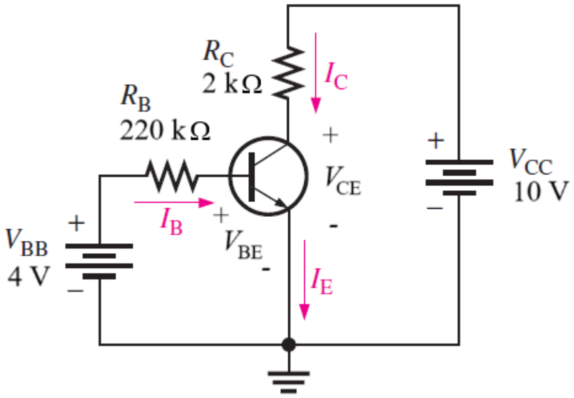
$$V_{CC} = I_C R_C + V_{CE}$$

or

$$V_{CE} = V_{CC} - I_C R_C$$

Example 2 – BJT Amplifier Design

For common-emitter amplifier circuit shown below, given that: V_{BB} = 4 V, R_B = 220 kΩ, R_C = 2 kΩ, V_{CC} = 10 V, $V_{BE(\text{on})}$ = 0.7 V, and β_{DC} = 200.



a. Calculate the base, emitter and collector currents and the voltage across the collector and emitter. [6 marks]

b. Show that the BJT is biased in the forward-active mode if $V_{CE(\text{sat})}$ = 0.2 V. [4 marks]

Answer

a. The currents in the transistor are calculated as follows:

Base current:

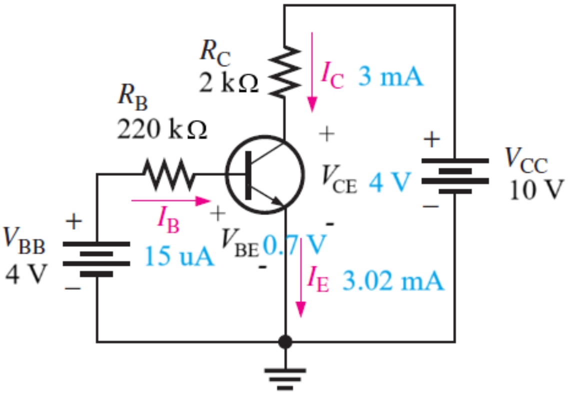
$$I_B = \frac{V_{BB} - V_{BE(\text{on})}}{R_B} = \frac{4\text{ V} - 0.7\text{ V}}{220\text{ k}\Omega} = 15\ \mu\text{A}$$

Collector current:

$$I_C = \beta_{DC} I_B = (200)(15\ \mu\text{A}) = 3\text{ mA}$$

Emitter current:

$$I_E = (\beta_{DC} + 1)I_B = (201)(15\ \mu\text{A}) = 3.02\text{ mA}$$



The voltage across the collector and emitter is calculated from:

$$V_{CE} = V_{CC} - I_C R_C = 10 - (3\text{ mA})(2\text{ k}\Omega) = 4\text{ V}$$

b. Referring to result in part (a), since $V_{CE} > 0.2$ V, transistor is in active region.

4. Load Lines for BJT Transistors

Load lines can again help us visualise transistor characteristics. The input load line is obtained from Kirchhoff's voltage law around the base-emitter loop:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

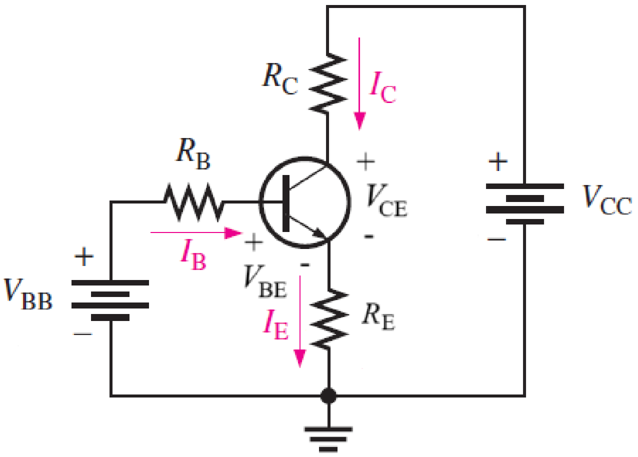


Figure 5: Common emitter BJT amplifier circuit

This is essentially same as for diode. The output load line around the CE loop:

$$V_{CE} = V_{CC} - I_C R_C$$

This equation can be written as:

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

This last equation is the load line equation, showing a linear relationship between I_C and V_{CE}.

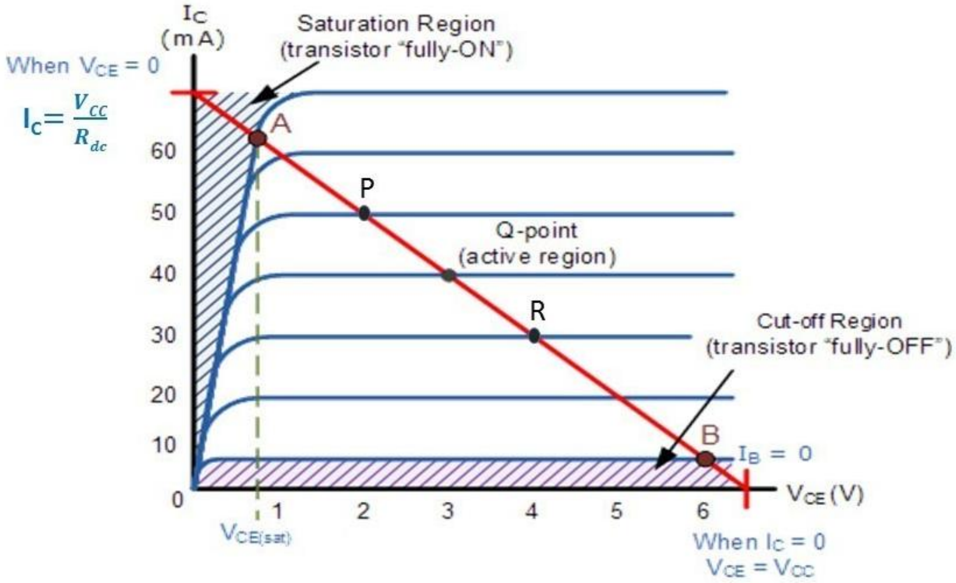


Figure 6: Load line of a common emitter BJT amplifier circuit

4.1. Load Line of Common Emitter BJT Amplifier Circuit

The following example is a load line set up of a given BJT amplifier circuit.

Extreme endpoints of load line are at:

- When I_C = 0, the cut-off voltage across the collector is:

$$V_{CE} = V_{CC} = 10 \text{ V}$$

- When V_{CE} = 0, the saturation current that flows in the collector is:

$$I_C = \frac{V_{CC}}{R_C} = \frac{10}{2\ \text{k}\Omega} = 5\ \text{mA}$$

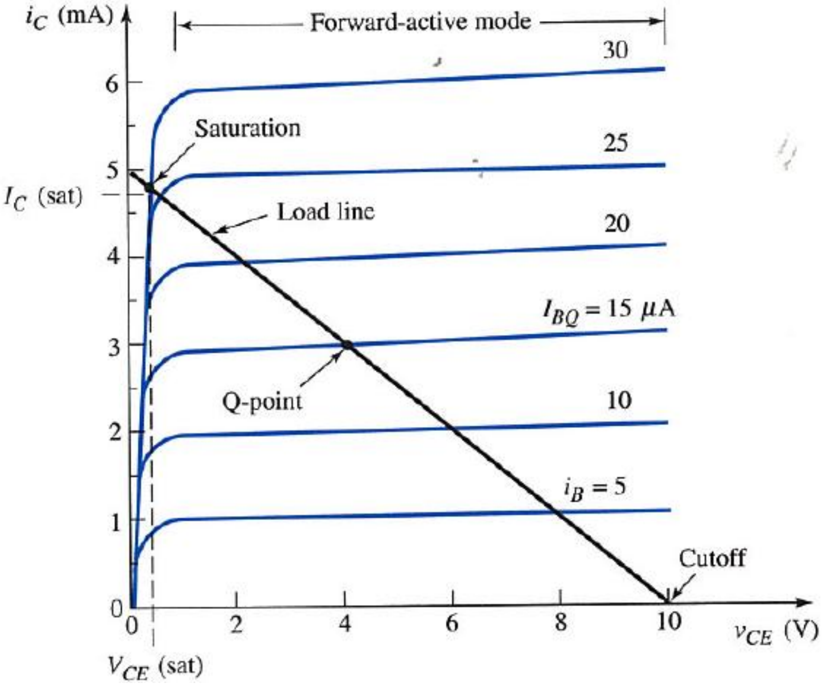


Figure 7: Load line of a common emitter BJT amplifier circuit for various values of I_b

Note:

- If $V_{BB} < V_{BE(\text{on})}$, then $I_B = I_C = 0$ and transistor in cut-off mode. At this point, $V_{CE} = V_{CC} = 10\ V$.
- As V_{BB} increases to $V_{BB} > V_{BE(\text{on})}$, the base current increases and the Q point move up the load line.
- A point will be reached where I_C can no longer increase i.e. the transistor is now in saturation (both junctions of the transistor acting as short circuits).
- The BC junction is now forward biased and I_B and I_C are no longer linear.

4.2. Analysis of Points in Load Line

In this section, we will be deriving $I_{C(\text{max})}$ and $V_{CE(\text{cutoff})}$ and the Q-point in the load line of a typical common emitter BJT amplifier circuit.

4.2.1. DC Operating Point Improvement with Feedback Resistor (R_E)

Feedback resistor at the emitter improves stability at the output of the amplifier.

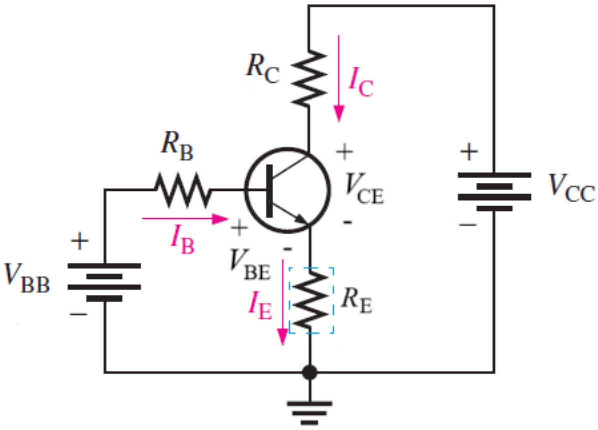


Figure 8: BJT amplifier circuit with feedback resistor (R_E)

Any increase of voltage or current at the collector will be compensated by any increase of voltage or current at the emitter. For fixed V_{CC}, this increase will be minimised.

4.2.2. The $I_{C(\max)}$ and $V_{CE(\text{cutoff})}$ in the Load Line

First, we calculate the saturation collection current, I_C first and then find the cut-off voltage drop across the common-emitter junction of the BJT.

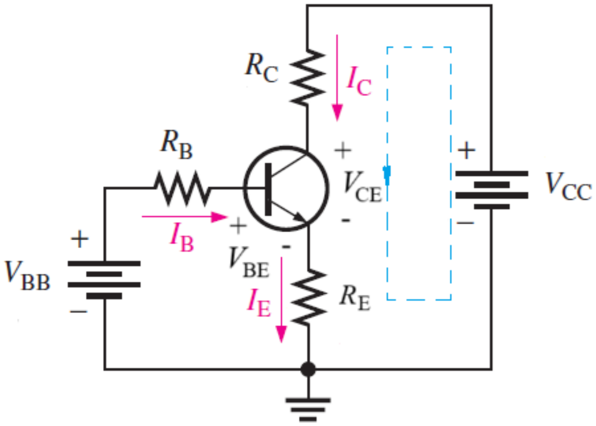


Figure 9: KVL around collector-emitter loop of the BJT

Take KVL around collector-emitter loop of the BJT:

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0 \qquad (Eq. 1)$$

The BJT is saturated when V_{CE} = 0, so the current in the collector I_{CQ} is calculated from:

$$I_{C(\max)} = \frac{V_{CC} - I_E R_E}{R_C} \qquad (Eq. 2)$$

From previous relevant topics in the BJT, we can show that:

$$I_C = \left(\frac{\beta_{DC}}{\beta_{DC} + 1}\right) I_E$$

Thus

$$I_E = \frac{I_C(\beta_{DC} + 1)}{\beta_{DC}} \qquad (Eq. 3)$$

Substitute I_E in equation (2) with equation (3) at saturation condition, the saturation collector current is calculated from.

$$I_{C(\max)} = \frac{V_{CC} - \left[\frac{I_{C(\max)}(\beta_{DC} + 1)}{\beta_{DC}}\right] R_E}{R_C}$$

Rearrange the equation given above, the saturation current that flow in the collector is:

$$I_{C(\max)} = \frac{V_{CC}}{R_C + \left(\frac{\beta_{DC} + 1}{\beta_{DC}}\right) R_E}$$

For calculating the cut-off voltage across the collector emitter V_{CE}, at cut-off condition, collector current $I_C = 0$.

By considering the equation (3), when $I_C = 0$, the current in the emitter I_E is also zero. Thus, the equation (1) becomes:

$$V_{CC} - 0 - V_{CE(\text{cutoff})} - 0 = 0$$

As a result, the cut-off voltage drop across the collector emitter junction is:

$$V_{CE(\text{cutoff})} = V_{CC} = 12 \text{ V}$$

4.2.3. Determining Q Points in the Load Line

For calculating the operating (Q) point of the amplifier circuit, we need to find the quiescent base current first. Then, we can calculate the quiescent collector current and collector-emitter voltage.

Applying KVL around the base-emitter loop of the BJT, the equation for the loop is:

$$V_{BB} - I_B R_B - V_{BE(\text{on})} - I_E R_E = 0 \qquad (Eq.4)$$

Assuming the BE junction is on for active mode, from previous relevant topics in the BJT, the current in the emitter is found from:

$$I_E = (\beta_{DC} + 1) I_B \qquad (Eq.5)$$

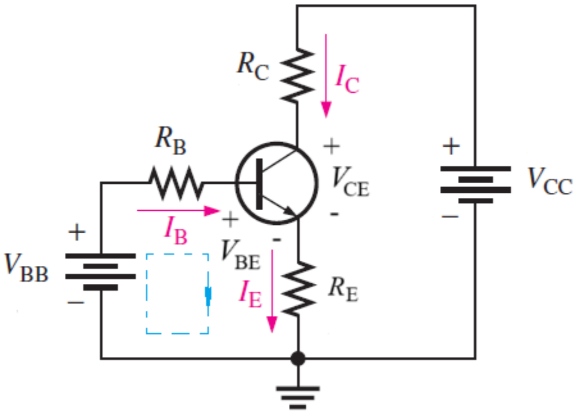


Figure 10: KVL around the base-emitter loop of the BJT

Substitute I_E in equation (4) with (5), it becomes:

$$V_{BB} - I_B R_B - V_{BE(\text{on})} - [(\beta_{DC} + 1) I_B] R_E = 0$$

Rearrange the equation above and solve for the current in the base of BJT, it is now:

$$I_B = \frac{V_{BB} - V_{B(\text{on})}}{R_B + (\beta_{DC} + 1) R_E}$$

Thus, entering values into equation below, the quiescent collector current is:

$$I_{CQ} = \beta_{DC} I_{BQ}$$

The quiescent current in the emitter is calculated from:

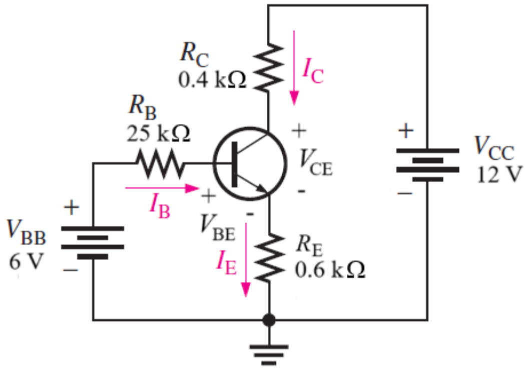
$$I_{EQ} = (\beta_{DC} + 1) I_{BQ}$$

Rearranging the equation (1), the quiescent collector to emitter voltage of the BJT is found from:

$$V_{CEQ} \; = V_{CC} - I_{CQ}R_C - I_{EQ}R_E$$

Example 3 – BJT Amplifier with Emitter Feedback

For analysing the characteristics of the circuit below, use $V_{BE(\mathrm{on})}$ = 0.6 V and β_{DC} = 75. Note the use of an emitter resistor in this circuit.



a. Determine the cut-off voltage $V_{CE(\mathrm{cutoff})}$ and saturation current $I_{C(\mathrm{max})}$ in the load line. [4 marks]

b. Determine the quiescent collector current I_{CQ} and quiescent collector-emitter voltage V_{CEQ} at the operating (Q) point of the BJT and calculate the quiescent base current at this point. [8 marks]

c. Sketch the load line of the amplifier circuit. [4 marks]

Answer

a. Entering values into the equation below, the saturation collector current I_C is:

$$I_{C(\mathrm{max})} = \frac{V_{CC}}{R_C + \left(\frac{\beta_{DC}+1}{\beta_{DC}}\right) R_E}$$

$$= \frac{12}{0.4 + \left(\frac{75+1}{75}\right) 0.6\ \text{k}\Omega} = 11.9\ \text{mA}$$

The cut-off voltage drop across the collector emitter junction is:

$$V_{CE(\text{cutoff})} = V_{CC} = 12\ \text{V}$$

b. Entering the values into the equation below, the quiescent current that flows in the base of the BJT at operating points is:

$$I_{BQ} = \frac{V_{BB} - V_{BE(\text{on})}}{R_B + (\beta_{DC} + 1)R_E}$$

$$= \frac{6\ \text{V} - 0.6\ \text{V}}{25{,}000\ \Omega + (75+1)(600\ \Omega)} = 75.1\ \mu\text{A}$$

Entering values into equation below, the quiescent collector current is:

$$I_{CQ} = \beta_{DC} I_{BQ} = (75)(75.1\ \mu\text{A}) = 5.63\ \text{mA}$$

The quiescent current in the emitter is calculated from:

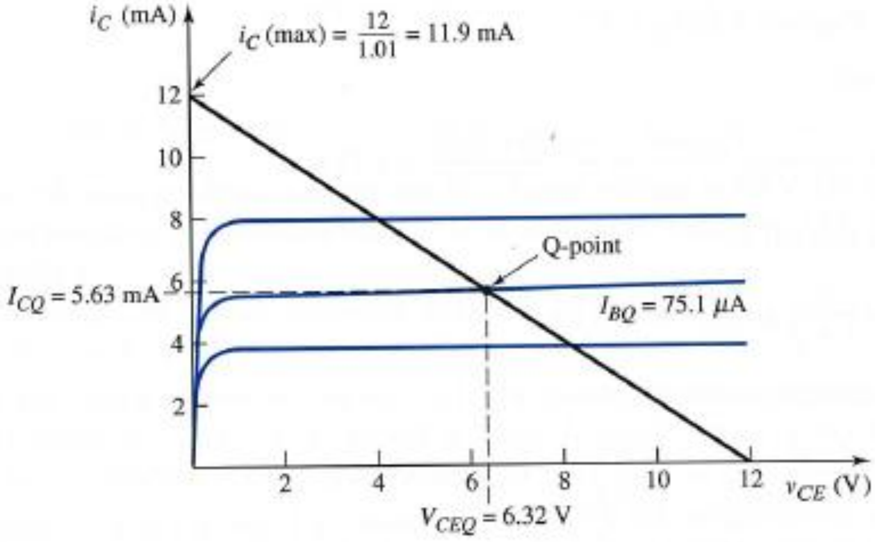
$$I_{EQ} = (\beta_{DC} + 1)I_{BQ} = (75+1)(75.1\ \mu\text{A}) = 5.71\ \text{mA}$$

As a result, the quiescent collector to emitter voltage of the BJT is:

$$V_{CEQ} = V_{CC} - I_{CQ}R_C - I_{EQ}R_E$$

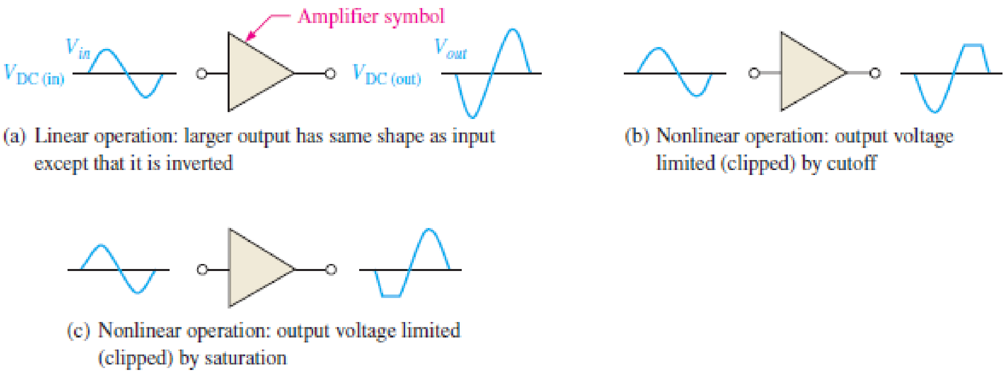
$$= 12\ \text{V} - (5.63\ \text{mA})(0.4\ \text{k}\Omega) - (5.71\ \text{mA})(0.6\ \text{k}\Omega) = 6.32\ \text{V}$$

c. The Q point (6.32 V, 5.63 mA) on the load line is sketched as shown in the figure below. Furthermore, this operating (Q) point is also the intersection of the load line with the line representing a quiescent base current I_{BQ} = 75.1 µA.



5. The Q-point and Transistor Bias

It is then essential that we establish the correct operating point or Q-point for the transistor to operate efficiently as a linear amplifier without distortion.



(a) Linear operation: larger output has same shape as input except that it is inverted

(b) Nonlinear operation: output voltage limited (clipped) by cutoff

(c) Nonlinear operation: output voltage limited (clipped) by saturation

Figure 11: Distortion on the output of BJT amplifier

The DC bias of a transistor circuit is established by the values set for V_{BB} and V_{CC} as well as the resistor values R_B and R_C.

5.1. Q-Point vs. Base Currents (I_B)

Take circuit below and set different values of V_{BB} to achieve different values of I_B:

a. Current I_B = 200 µA. b. Current I_B = 300 µA. c. Current I_B = 400 µA.

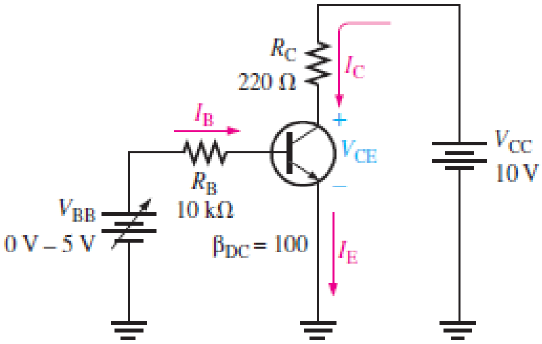


Figure 12: Common emitter BJT amplifier circuit

From the standard calculation we find that I_C = 20 mA for I_B = 200 µA, so that V_{CE} = 5.6 V. This provides us with point Q_1 on curve, i.e. the operating point for the transistor when I_B = 200 µA.

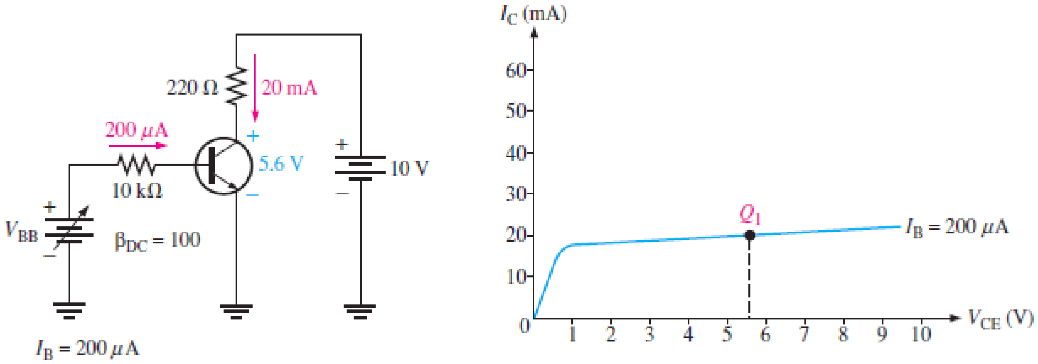


Figure 13: CE BJT amplifier circuit and its Q-point set up at I_b = 200 uA

Similarly, we find a value of V_{CE} = 3.4 V when I_B = 300 µA which provides point Q_2 on the curve.

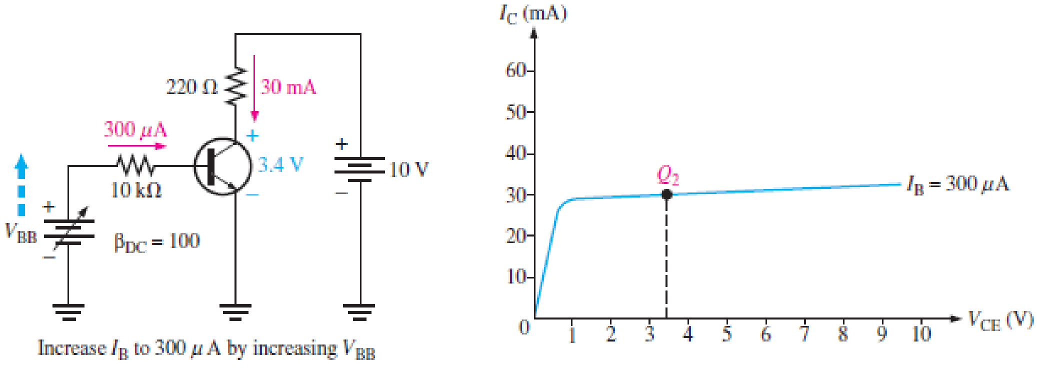


Figure 14: CE BJT amplifier circuit and its q-point set up at I_b = 300 uA

Similarly, we find a value of V_{CE} = 1.2 V when I_B = 400 μA which provides point Q_3 on the curve.

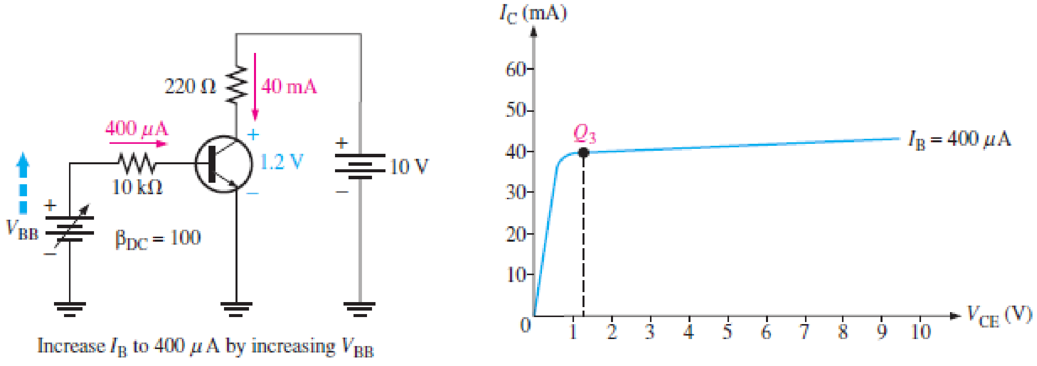


Figure 15: CE BJT amplifier circuit and its q-point set up at I_b = 400 uA

5.2. Q-Points vs. DC Load Line

We can also draw up a DC load line for this circuit as shown by the line below.

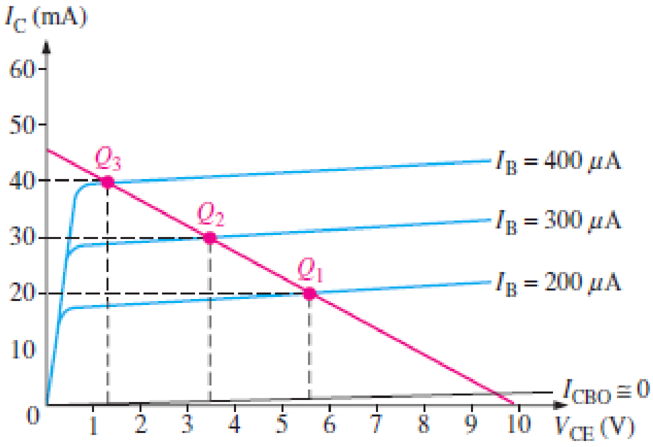


Figure 16: DC load line for the CE BJT amplifier circuit at various I_b values

Set I_B for 300 µA. V_{in} = 0 initially. Now, increase V_{in} so that I_B varies sinusoidally by 100 µA above and below the initial value.

The Q point calculations as below.

$$I_{BQ} = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3.7\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 300\ \mu\text{A}$$

Thus

$$I_{CQ} = \beta_{DC} I_{BQ} = (100)(300\ \mu\text{A}) = 30\text{ mA}$$

And

$$V_{CEQ} = V_{CC} - I_{CQ} R_C = 10\text{ V} - (30\text{ mA})(220\ \Omega) = 3.4\text{ V}$$

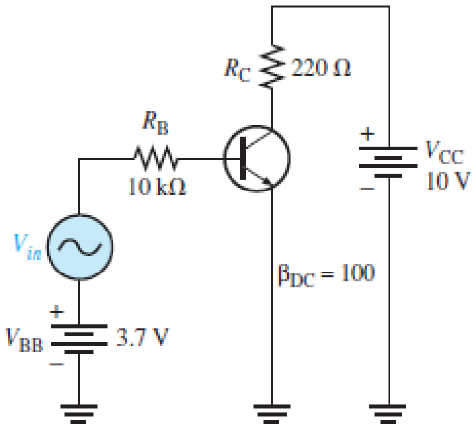


Figure 17: Final configuration of the common emitter BJT amplifier circuit

6. Operation of Various Amplifier Configurations

In this section, we will investigate the operation of various amplifier configurations at normal optimum, saturation, cut-off, and saturation and cut-off conditions.

6.1. Normal Optimum Operation

During normal optimum operation, point Q on the load line gives us the base current Q-point of I_b = 300 μA. We need to find the maximum and minimum peak swings of base current that will result in a proportional change to the collector current, I_c without any distortion to the output signal.

As the load line cuts through the different base current values on the DC characteristics curves, we can find the peak swings of base current that are equally spaced along the load line. These values are marked as points "B" and "A" on the line, giving a minimum and a maximum base current of 200 μA and 400 μA respectively.

These points, "B" and "A" can be anywhere along the load line that we choose if they are equally spaced from Q. This then gives us a theoretical maximum input signal to the base terminal of 200 μA peak-to-peak, (100 μA peak) without producing any distortion to the output signal.

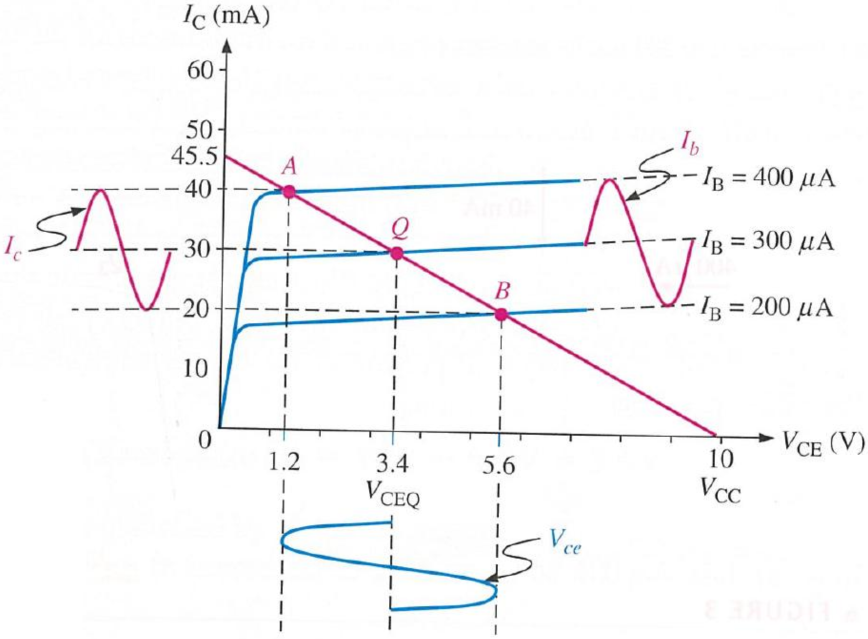


Figure 18: Normal optimum operation of CE BJT amplifier circuit

Any input signal giving a base current greater than this value will drive the transistor to go beyond point “B” and into its “cut-off” region or beyond point “A” and into its saturation region, thereby resulting in distortion to the output signal in the form of “clipping”.

Using points “B” and “A” as an example, the instantaneous values of collector current and corresponding values of collector-emitter voltage can be projected from the load line. The collector-emitter voltage is in anti-phase (–180°) with the collector current.

As the base current I_b changes in a positive direction from 200 µA to 300 µA, the collector-emitter voltage, which is also the output voltage decreases from its steady state value of 3.4 volts to 1.2 volts.

Then, a single stage common emitter amplifier is also an “inverting amplifier” as an increase in base voltage causes a decrease in V_{out} and a decrease in base voltage produces an increase in V_{out}. In other words, the output signal is 180° out-of-phase with the input signal.

6.2. Saturation Condition

When the amplifier in the saturation condition, for a given input signal, clipping could be observed at maximum values of the I_{CQ} and V_{CEQ} when the transistor is saturated, and it could not go further for its signal excursion.

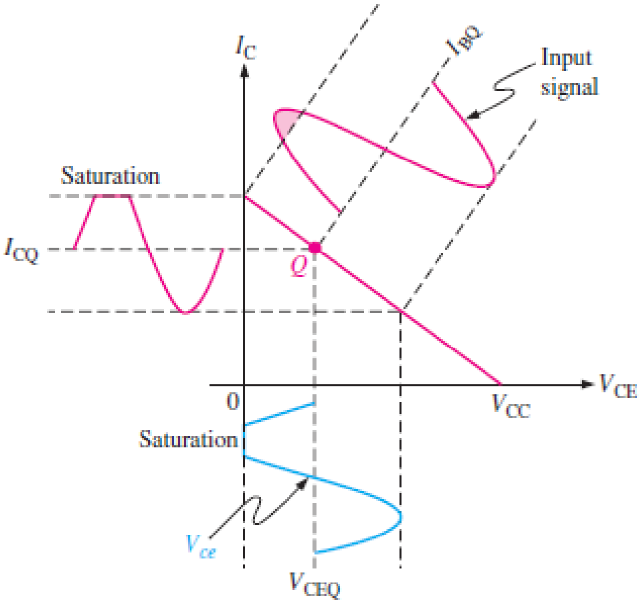


Figure 19: Saturation condition in BJT amplifier circuit

6.3. Cut-off Condition

At cut-off condition, for a given input signal, clipping could be observed at minimum values of the I_{CQ} and V_{CEQ} when the transistor could not go further for its signal excursion as the transistor is already turned off.

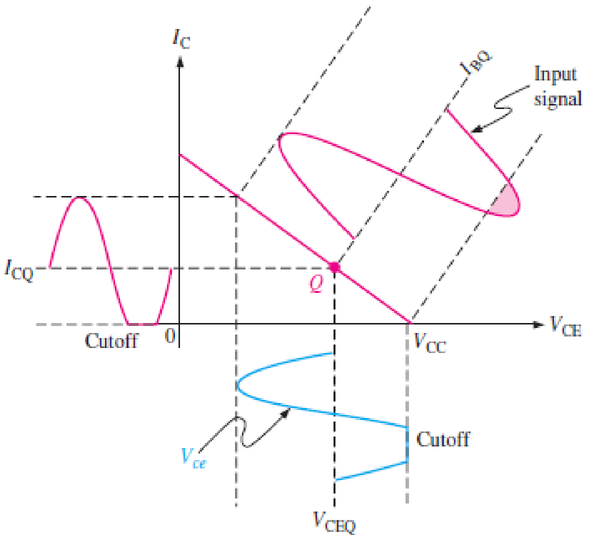


Figure 20: Cut-off condition in the BJT amplifier circuit

6.4. Saturation and Cut-off Conditions

At both saturation and cut-off conditions, for a given input signal, clipping could be observed at maximum and minimum values of the I_{CQ} and V_{CEQ} when the transistor could not go further for its signal excursions as the transistor is either saturated at the maximum values or it is already turned off at minimum values.

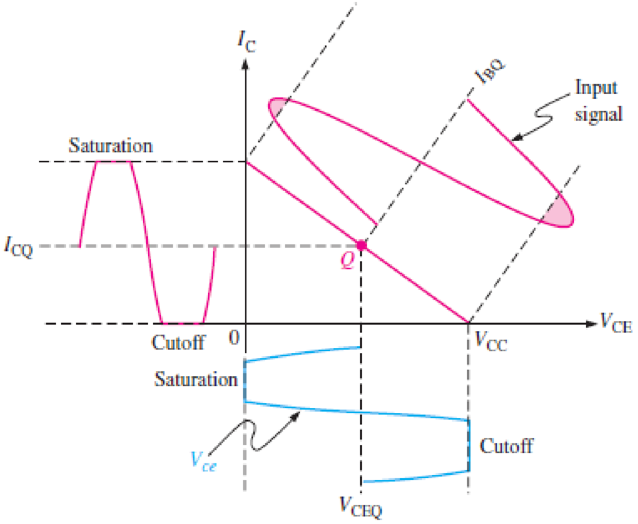


Figure 21: Saturation and cut-off conditions in the BJT amplifier circuit

7. A Graphical Representation on the Transistor Curve

Based on the results from previous section, these set of BJT transistor characteristics we are going to be interested in is as illustrated as a family of I_C - V_{CE} curves.

Each of the curves in this family illustrates the dependence of the collector current (I_C) on the collector emitter voltage (V_{CE}) when the base current (I_B) has a constant value (i.e., V_{BE} is held constant).

The following graphic shows the transistor curve for a typical BJT transistor (β = 100).

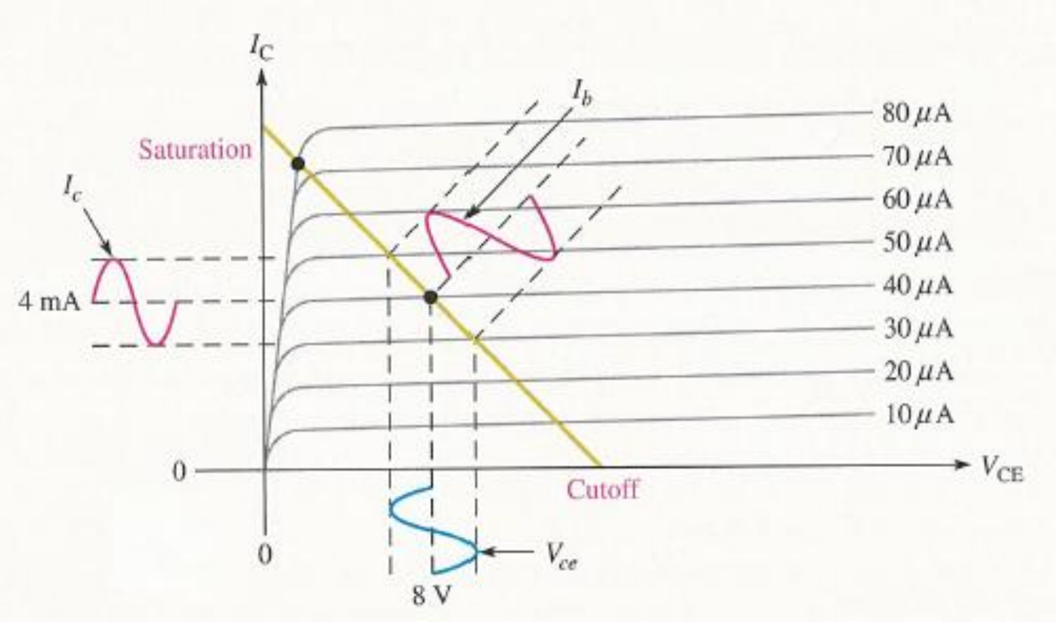


Figure 22: Transistor curve for a typical BJT amplifier circuit

Sinusoidal variation in I_B (μA) range leads to large variation in I_C (mA) range and a variation in V_{CE}. We will look at the amplification of small time-varying (sinusoidal) input voltages. A good example is an audio signal from a microphone that needs to be amplified to drive a speaker.

Figure 23: Audio power amplifier application

The input and output signals of the above given audio power amplifier application are as illustrated below.

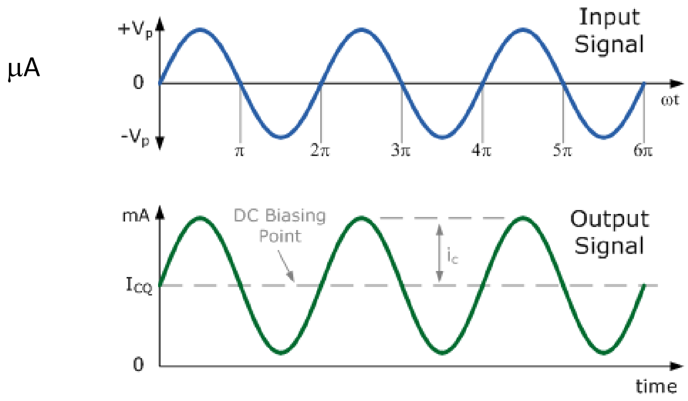


Figure 24: Input & output signals of the audio power amplifier application

7.1. Points to Note for the Type of Amplifiers We Discuss:

These are some of the key points that we cover in this topic:

1. Need to operate in forward active region of output.
2. The base current cannot go to zero or negative. This will go into cut off. Thus, we need to put a bias on the input voltage.
3. Base current cannot go too large. This will go into saturation and the output will not be linear anymore.
4. The amplification is a function of the input frequency i.e. amplifier will have a bandwidth.
5. Critical to get the correct bias point to ensure correct operation.
6. In the course, we will just consider Class A amplifier i.e. the transistor conducts for the full 360° of input cycle. This type is typically used in low power (< 1 W) applications.
7. An increase in collector current means the voltage drop across R_C is increased; this means that V_o will decrease. Thus, an increase in input voltage at the base has produced a decrease in output voltage i.e. an *inverting amplifier.*

7.2. Choice of an Operating Point

As shown in the diagram given below, active operating region for amplification of the BJT transistor circuit can be classified into.

A: Saturation.

B: Exceeding the maximum value of I_C of the transistor.

C: Exceeding the maximum value of V_{BE} of the transistor.

D: Exceeding power dissipation of transistor.

E: Cut-off.

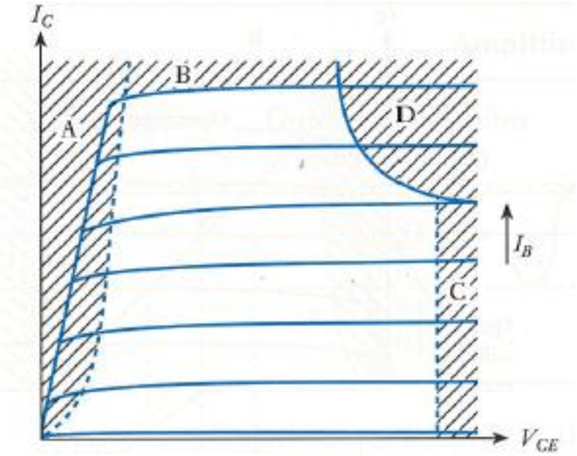


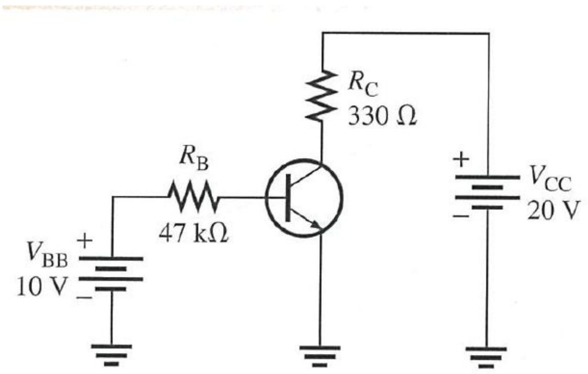
Figure 25: Regions of operation of BJT amplifiers

Notice in the above given figure the area enclosed by the active operating region of the BJT transistor.

Example 4 – BJT Circuit Operating Conditions

Determine the Q-point and draw the DC load line for the amplifier circuit below. Also find the maximum peak value of base current for linear operation. Assume β_{DC} = 200.

[12 marks]



Answer

The Q point of the BJT circuit is calculated as follows.

The extreme points in the load line are:

$$I_{C(\mathrm{sat})} = \frac{V_{CC}}{R_C} = \frac{20\ \mathrm{V}}{330\ \Omega} = 60.6\ \mathrm{mA} \quad (\mathrm{point\ A})$$

And

$$V_{CE(\max)} = V_{CC} = 20\ \mathrm{V} \quad (\mathrm{point\ B})$$

Assuming the BJT is silicon transistor with V_{BE} = 0.7 V, the base current is:

$$I_{BQ} = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\ \mathrm{V} - 0.7\ \mathrm{V}}{47\ \mathrm{k\Omega}} = 0.198\ \mathrm{mA}$$

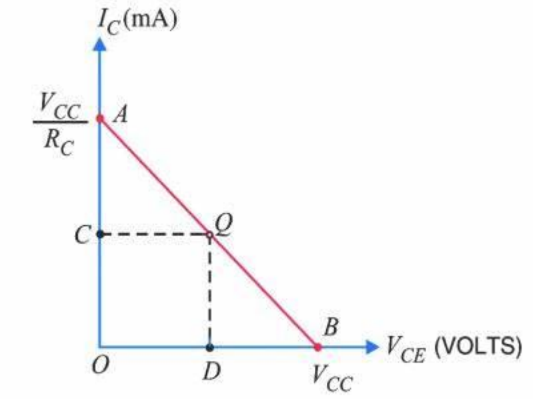
The quiescent collector current is:

$$I_{CQ} = \beta_{DC} I_B = (200)(0.198\ \mathrm{mA}) = 39.57\ \mathrm{mA}$$

The quiescent voltage at the collector emitter junction is:

$$V_{CEQ} = V_{CC} - I_C R_C = 20\ \mathrm{V} - (39.57\ \mathrm{mA})(330\ \Omega) = 6.94\ \mathrm{V}$$

Thus, Q point of the BJT circuit is located at I_{CQ} = 39.57 mA (i.e. point C in the load line graph) and V_{CEQ} = 6.94 V (point D). The DC load line of the BJT circuit is as shown in the figure below.



The maximum peak value of the base current for linear operation of the circuit is:

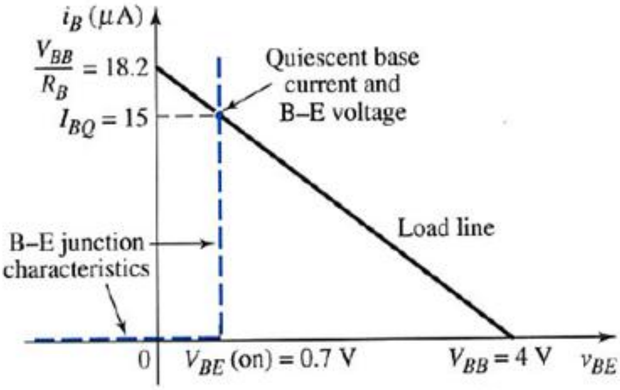
$$I_{C(\text{peak})} = I_{C(\text{sat})} - I_{CQ} = 60.6\ \text{mA} - 39.57\ \text{mA} = 21.03\ \text{mA}$$

Thus

$$I_{B(\text{peak})} = \frac{I_{C(\text{peak})}}{\beta_{DC}} = \frac{21.03\ \text{mA}}{200} = 0.105\ \text{mA}$$

Example 5 – Load Lines of BJT Circuit

For the load line graph of a common-emitter BJT amplifier circuit given below, attempt the following tasks:



a. If the DC gain of the BJT transistor is 150, determine the Q point of the amplifier circuit that ensures maximum voltage swing at the output. [8 marks]

b. When the amplifier is to be powered by V_{CC} = 15 V voltage source, determine the value of collector resistor. [4 marks]

Answer

a. The Q point of the amplifier circuit that ensures maximum voltage swing at the output is calculated as follows.

From the load line graph as given in the figure above, at V_{BE} = 0.7 V, the quiescent base current is 15 µA. Thus, the quiescent current at the collector is:

$$I_{CQ} = \beta_{DC} I_{BQ} = (150)(15\ \mu\text{A}) = 2.25\ \text{mA}$$

For maximum swing, the peak current at the collector should be:

$$I_{C(\text{peak})} = I_{CQ} = 2.25\ \text{mA}$$

Assuming the output is taken at the collector, the voltage at the emitter is:

$$V_E = V_{BB} - V_{BE} = 4\ \text{V} - 0.7\ \text{V} = 3.3\ \text{V}$$

To ensure maximum swing, we need the quiescent voltage at the collector to emitter junction to be at least or more than 3.3 V. Thus

$$V_{CEQ} = V_E = 3.3\ \text{V}$$

As a result, the Q point of the amplifier circuit is located at I_{CQ} = 2.25 mA and V_{CEQ} = 3.3 V.

b. If V_{CC} = 15 V, applying KVL, the voltages at the output of the amplifier are:

$$V_{CC} - I_{CQ} R_C - V_{CEQ} = 0$$

Rearranging and entering the values into the equation above, the value of the collector resistor is:

$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}} = \frac{15\ \text{V} - 3.3\ \text{V}}{2.25\ \text{mA}} = 5.2\ \text{k}\Omega$$