ENG1004 - Electronics & Sensors

Tutorial 2 – BJT Circuits

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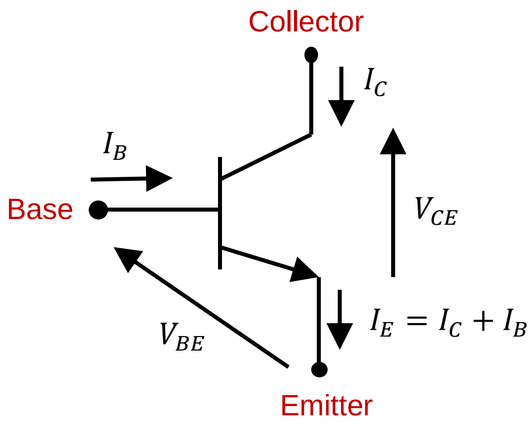
Throughout this tutorial, we assume the use of silicon BJTs with $\beta_F = 100$, $V_{BE,on} = 0.7$ volt, and $V_{CE,sat} = 0.2$ volt.



Three modes of operation

Cut-off

$V_{BE} < V_{BE,on}$
$I_B = 0$
$I_C = 0$
$I_E = 0$

Forward active

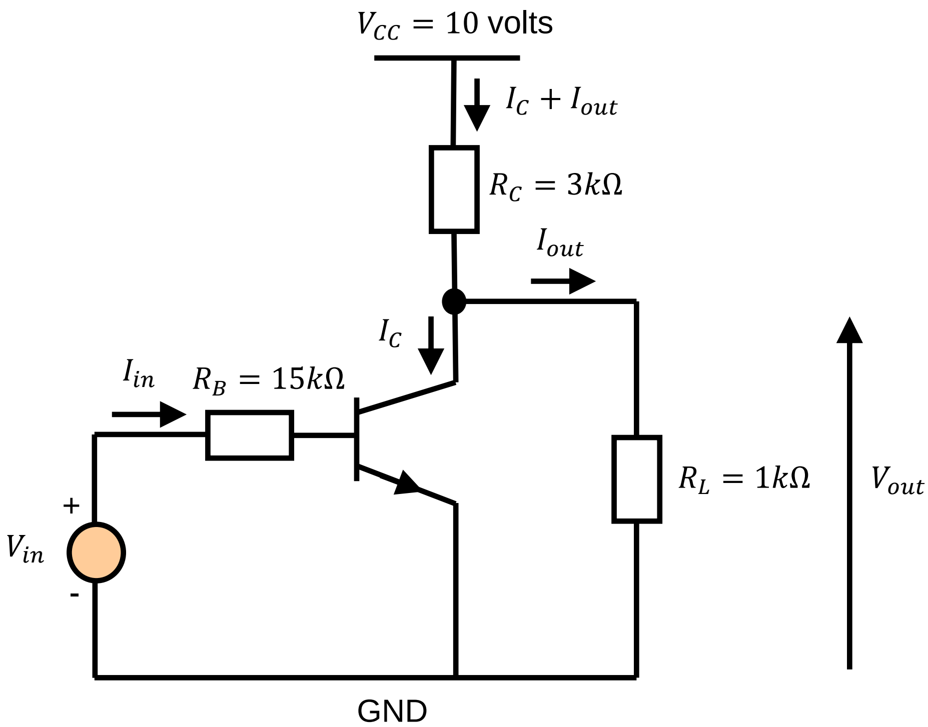
$V_{BE} = V_{BE,on}$
$V_{CE} > V_{CE,sat}$
$I_B > 0$
$I_C > 0$
$I_E > 0$
$I_C = \beta_F \cdot I_B$
$I_E = (\beta_F + 1) \cdot I_B$

Saturation

$V_{BE} = V_{BE,on}$
$V_{CE} = V_{CE,sat}$
$I_B > 0$
$I_C > 0$
$I_E > 0$

Question 1: DC Transfer Characteristics of a Common-Emitter Circuit with a Load Resistance

Consider the BJT circuit depicted below. It is known in electronics as a common-emitter circuit. This circuit is identical to that studied in your lecture notes on BJTs, except that we have added here a load resistance R_L, which is going to complicate the analysis of the common-emitter circuit.



The presence of this load resistance accounts for the fact that in practice any electronic circuit has its output connected to the input of another downstream circuit, the latter being modelled using a load resistance. Also, the fact that there is now a load resistance allows us to introduce the concepts of DC current transfer characteristic, current amplifier, current gain, and so on.

In the common-emitter circuit studied in the lecture notes, no load resistance was used. As a result, no current was able to flow out from that circuit, making it impossible to define an output current.

(a) Determine the four general equations for the common-emitter circuit shown above using Kirchhoff voltage law and Ohm's law.

(b) Assume that the BJT is in the cut-off mode of operation. Using the general equations:
- Determine the expression and compute the value of the output voltage V_{out}.
- Find the value of the input current I_{in}.

- Find the expression and compute the value of the output current I_{out}.
- Determine the condition that V_{in} must satisfy for the BJT to be cut-off.

(c) Assume now that the BJT is in the forward-active mode. Using the general equations:
- Find the expression of V_{out} as a function of V_{in}. Show that V_{out} is a linear function of V_{in}.
- Find the expression of I_{out} as a function of I_{in}. Show that I_{out} is a linear function of I_{in}.
- Find the condition that V_{in} must satisfy for the BJT to be forward-active.
- Find the condition that I_{in} must satisfy for the BJT to be forward-active.

(d) Assume finally that the BJT is in the saturation mode. Using the general equations:
- Determine the expression and compute the value of V_{out}.
- Determine the expression and compute the value of I_{out}.
- Determine the condition that V_{in} must satisfy for the BJT to be saturated.
- Determine the condition that I_{in} must satisfy for the BJT to be saturated.

(e) Using the results obtained in (b), (c), and (d), find the DC voltage transfer characteristic for the common-emitter circuit. In other words, plot the variation of V_{out} as a function of V_{in}, for V_{in} ranging from its minimum possible value, 0 volt, to its maximum possible value, V_{CC}.

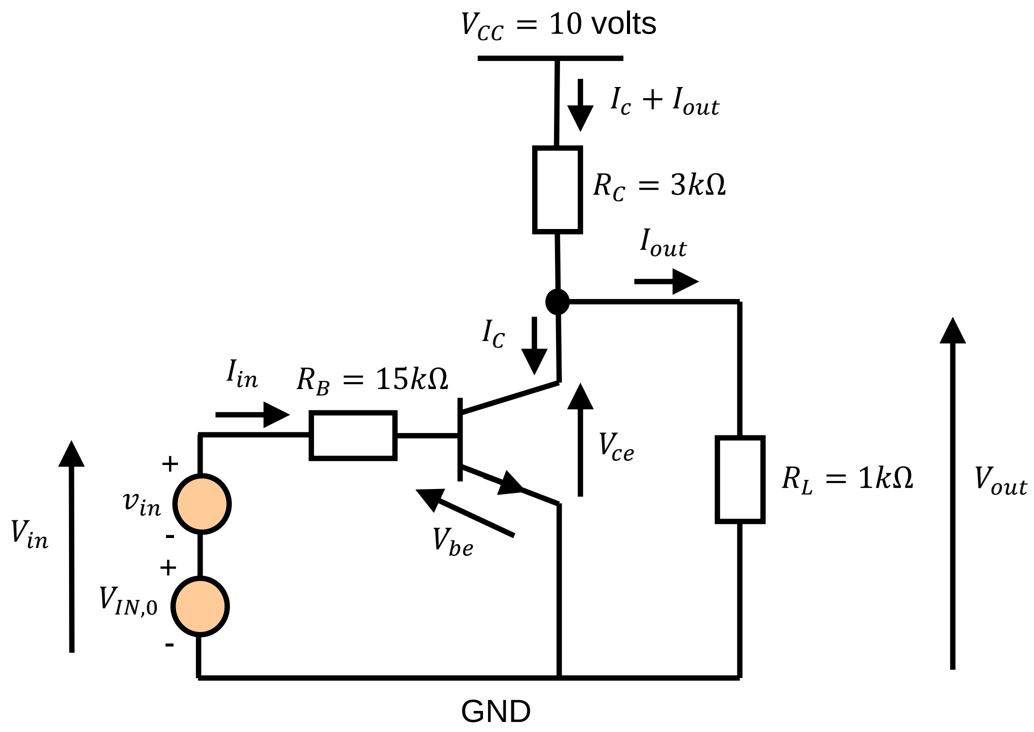
Use this characteristic to evaluate the potential of the circuit as a linear voltage amplifier.

(f) Using the results obtained in (b), (c), and (d), find the DC current transfer characteristic for the common-emitter circuit. In other words, plot the variation of I_{out} as a function of I_{in}, for I_{in} ranging from its minimum possible value, 0 ampere, to its maximum possible value, which is to be computed.

Use this characteristic to evaluate the potential of the circuit as a linear current amplifier.

Question 2: Design of a Linear Common-Emitter Amplifier

We can slightly modify the circuit studied in Question 1 in order to design a linear amplifier. The modified circuit is shown below.

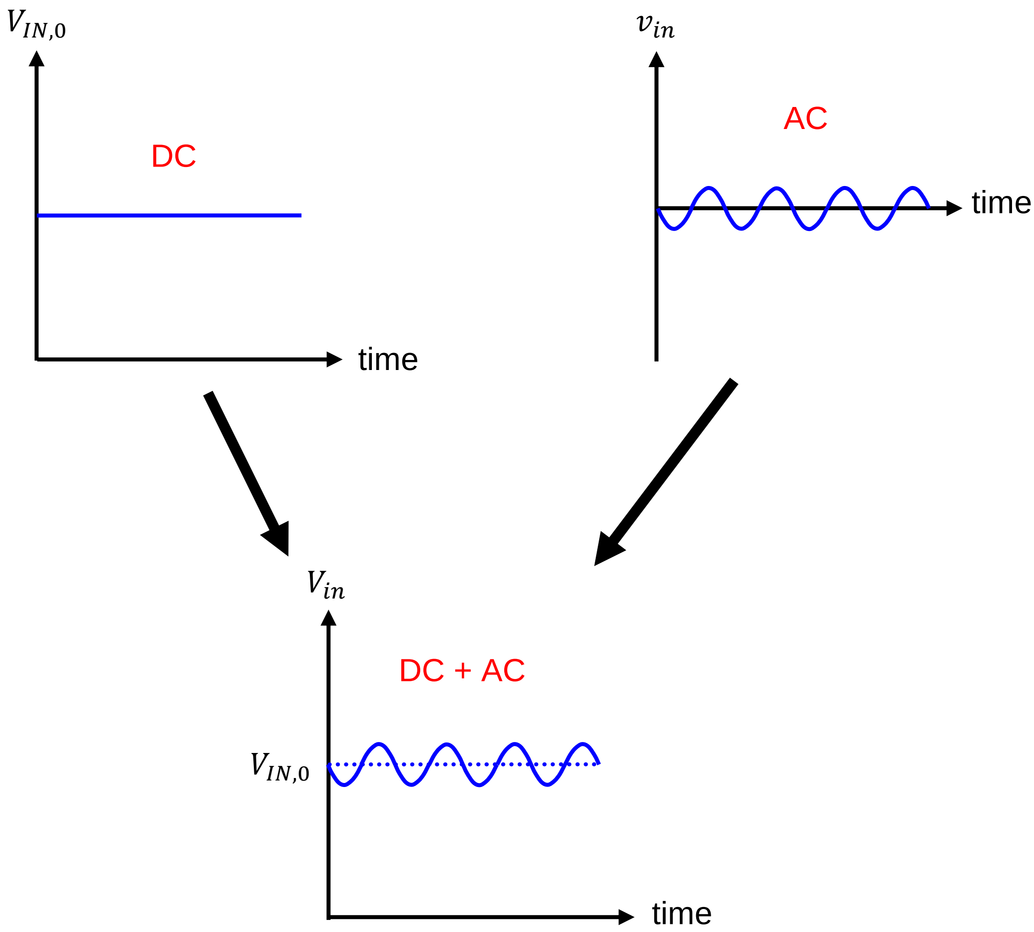


This type of amplifier is referred to as a common-emitter amplifier as both input and output ports have the emitter as a common reference.

The input voltage V_{in} is now composed of two voltage sources $V_{IN,0}$ and v_{in} connected in series. Hence, we can write $V_{in} = V_{IN,0} + v_{in}$.

The DC voltage source $V_{IN,0}$ is used to bias the circuit so that the BJT operates at all times in the forward-active mode. The quantity $V_{IN,0}$ is referred to as bias voltage and its value has to be chosen very carefully by the designer. Remember that a BJT has the ability to amplify a current or voltage only when it operates in the forward-active mode.

The AC voltage source v_{in} generates the AC voltage to be amplified. It is perfectly reasonable to assume that v_{in} is a pure AC voltage signal with zero mean and small-amplitude symmetrical swings around zero volt.



Throughout this question, we are going to assume that the BJT operates in the forward-active mode at all times.

(a) Show that the input current, I_{in}, can be written as the sum of a DC current, denoted as $I_{IN,0}$, and an AC current, called i_{in}, so that we have $I_{in} = I_{IN,0} + i_{in}$. Find the expressions of $I_{IN,0}$ and i_{in}.

(b) Show that the output voltage, V_{out}, can be written as the sum of a DC voltage, denoted as $V_{OUT,0}$, and an AC voltage, called v_{out}, so that we have $V_{out} = V_{OUT,0} + v_{out}$. Find the expressions of $V_{OUT,0}$ and v_{out}.

(c) The voltage gain of the linear common-emitter amplifier is defined as $A_v = \frac{v_{out}}{v_{in}}$. Determine the expression and compute the value of A_v.

(d) Show that the output current, I_{out}, can be written as the sum of a DC current, denoted as $I_{OUT,0}$, and an AC current, called i_{out}, so that we have $I_{out} = I_{OUT,0} + i_{out}$. Find the expressions of $I_{OUT,0}$ and i_{out}.

(e) The current gain of the linear common-emitter amplifier is defined as $A_i = \frac{i_{out}}{i_{in}}$. Determine the expression and compute the value of A_i.

(f) We also need to consider the DC biasing issue. The common-emitter amplifier must be biased in a way that guarantees maximum symmetrical voltage and current swings at both its input and output.

The value of the DC bias voltage $V_{IN,0}$ must therefore be chosen by the circuit designer so that the BJT operates in the middle of the forward-active mode, midway between the start of the cut-off mode and that of the saturation mode, as explained in the lecture notes. This allows for maximum voltage and current swings at both input and output. In other words, this allows both the AC output voltage, given by $v_{out} = A_v \cdot v_{in}$, and the AC output current, given by $i_{out} = A_i \cdot i_{in}$, to have maximum swings in either direction without any distortion.

Let us focus first on the voltage swing issue: we want to maximise the maximum output voltage swing, $\Delta V_{out,max}$, and the maximum input voltage swing, $\Delta V_{in,max}$.

Determine the expression and compute the value of the DC bias voltage, $V_{IN,0}$, that maximises both $\Delta V_{out,max}$ and $\Delta V_{in,max}$.

(g) Let us now turn our attention to the current swing issue. We also want to ensure that the common-emitter amplifier is biased in a way that maximises the maximum output current swing, $\Delta I_{out,max}$, and the maximum input current swing, $\Delta I_{in,max}$.

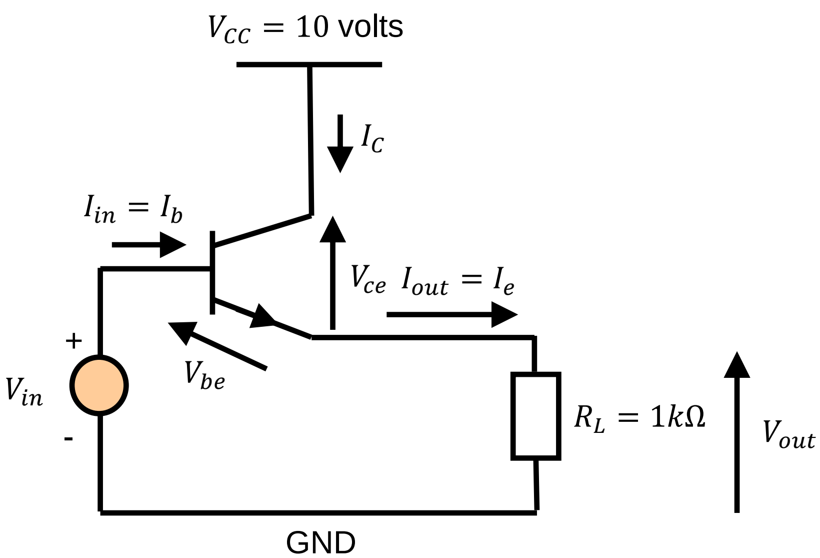
As biasing is achieved in our circuit by using a DC voltage source $V_{IN,0}$ only, the question that comes to mind is the following one: does the optimal bias voltage value determined in (f) also maximise, by default, the maximum current swings $\Delta I_{in,max}$ and $\Delta I_{out,max}$?

You will answer this question by first finding the value of the DC current $I_{IN,0}$ that maximises both $\Delta I_{in,max}$ and $\Delta I_{out,max}$.

Then, you will determine whether or not the optimal value of the DC bias voltage $V_{IN,0}$ computed in (f) leads by default to the optimal value of the DC current $I_{IN,0}$ that has just been obtained.

Question 3: DC Transfer Characteristics of a Common-Collector Circuit with a Load Resistance

Consider the BJT circuit depicted below. This type of configuration is known in electronics as a common-collector circuit. It is also sometimes referred to as an emitter-follower circuit.



The presence of a load resistance R_L accounts for the fact that in practice any electronic circuit has its output connected to the input of another downstream circuit, the latter being modelled using a load resistance.

(a) Determine the three general equations for the common-collector circuit using Kirchhoff voltage law and Ohm's law.

(b) Assume that the BJT is in the cut-off mode of operation. Using the general equations:
- Determine the value of the output voltage V_{out}.
- Find the value of the input current I_{in}.
- Find the value of the output current I_{out}.
- Determine the condition that the input voltage V_{in} must satisfy for the BJT to be cut-off.

(c) Assume now that the BJT is in the forward-active mode. Using the general equations:
- Find the expression of V_{out} as a function of V_{in}. Show that V_{out} is a linear function of V_{in}.
- Find the expression of I_{out} as a function of I_{in}. Show that I_{out} is a linear function of I_{in}.
- Determine the condition that V_{in} must satisfy for the BJT to be forward-active.
- Determine the condition that I_{in} must satisfy for the BJT to be forward-active.

(d) Show that the BJT cannot operate in the saturation mode. To do so, assume that the BJT is saturated and, by using the general equations, show that such assumption leads to results that make no sense.

(e) Using the results obtained in (b) and (c), find the DC voltage transfer characteristic for the common-collector circuit. In other words, plot the variation of V_{out} as a function of V_{in}, for V_{in} ranging from its minimum possible value, 0 volt, to its maximum possible value, V_{CC}.

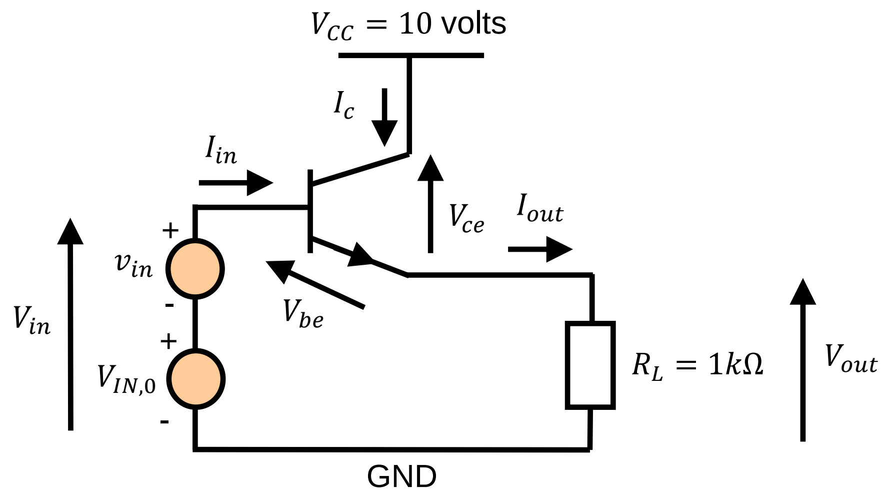
Use this characteristic to evaluate the potential of the circuit as a linear voltage amplifier.

(f) Using the results obtained in (b) and (c), find the DC current transfer characteristic for the common-collector circuit. In other words, plot the variation of I_{out} as a function of I_{in}, for I_{in} ranging from its minimum possible value, 0 ampere, to its maximum possible value, which is to be computed.

Use this characteristic to evaluate the potential of the circuit as a linear current amplifier.

Question 4: Design of a Linear Common-Collector Amplifier

We can slightly modify the circuit studied in Question 3 in order to design a linear amplifier. The modified circuit is shown below.

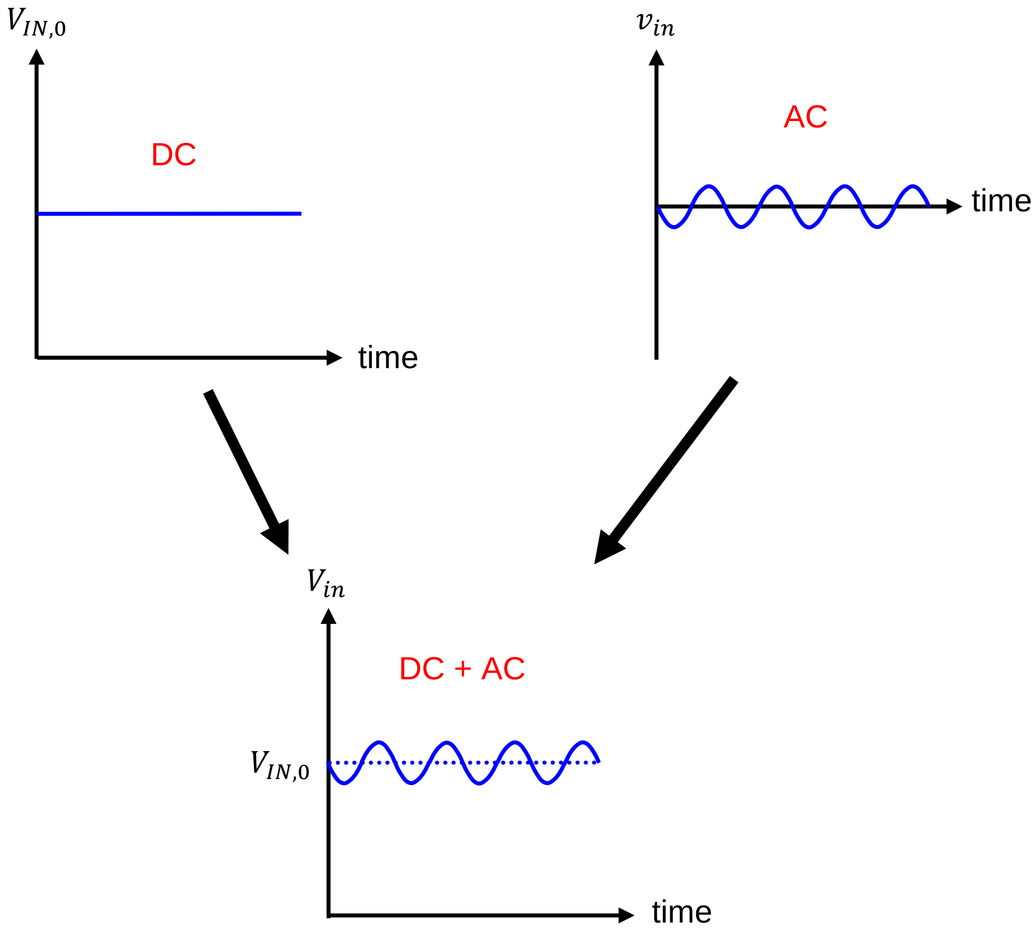


This type of amplifier is referred to as a common-collector amplifier as both input and output ports have the collector as a common reference.

The input voltage V_{in} is now composed of two voltage sources $V_{IN,0}$ and v_{in} connected in series. Hence, we can write $V_{in} = V_{IN,0} + v_{in}$.

The DC voltage source $V_{IN,0}$ is used to bias the circuit so that the BJT operates at all times in the forward-active mode. The quantity $V_{IN,0}$ is referred to as bias voltage and its value has to be chosen very carefully by the designer. Remember that a BJT has the ability to amplify a current or voltage only when it operates in the forward-active mode.

The AC voltage source v_{in} generates the AC voltage to be amplified. It is perfectly reasonable to assume that v_{in} is a pure AC voltage signal with zero mean and small-amplitude symmetrical swings around zero volt.



Throughout this question, we are going to assume that the BJT operates in the forward-active mode at all times.

(a) Show that the input current, I_{in}, can be written as the sum of a DC current, denoted as $I_{IN,0}$, and an AC current, called i_{in}, so that we have $I_{in} = I_{IN,0} + i_{in}$. Find the expressions of $I_{IN,0}$ and i_{in}.

(b) Show that the output voltage, V_{out}, can be written as the sum of a DC voltage, denoted as $V_{OUT,0}$, and an AC voltage, called v_{out}, so that we have $V_{out} = V_{OUT,0} + v_{out}$. Find the expressions of $V_{OUT,0}$ and v_{out}.

(c) The voltage gain of the linear common-collector amplifier is defined as $A_v = \frac{v_{out}}{v_{in}}$. Determine the expression and compute the value of A_v.

(d) Show that the output current, I_{out}, can be written as the sum of a DC current, denoted as $I_{OUT,0}$, and an AC current, called i_{out}, so that we have $I_{out} = I_{OUT,0} + i_{out}$. Find the expressions of $I_{OUT,0}$ and i_{out}.

(e) The current gain of the linear common-collector amplifier is defined as $A_i = \frac{i_{out}}{i_{in}}$. Determine the expression and compute the value of A_i.

(f) We also need to consider the DC biasing issue. The common-collector amplifier must be biased in a way that guarantees maximum symmetrical voltage and current swings at both its input and output.

The value of the DC bias voltage $V_{IN,0}$ should therefore be chosen by the circuit designer so that the BJT operates in the middle of the forward-active mode, midway between the start of the cut-off mode and that of the saturation mode, as explained in the lecture notes.

This allows for maximum voltage and current swings at both input and output. In other words, this allows both the AC output voltage, given by $v_{out} = A_v \cdot v_{in}$, and the AC output current, given by $i_{out} = A_i \cdot i_{in}$, to have maximum swings in either direction without any distortion.

Let us focus first on the voltage swing issue: we want to maximise the maximum output voltage swing, $\Delta V_{out,max}$, and the maximum input voltage swing, $\Delta V_{in,max}$.

Determine the expression and compute the value of the DC bias voltage, $V_{IN,0}$, that maximises both $\Delta V_{out,max}$ and $\Delta V_{in,max}$.

(g) Let us now turn our attention to the current swing issue. We also want to ensure that the common-collector amplifier is biased in a way that maximises the maximum output current swing, $\Delta I_{out,max}$, and the maximum input current swing, $\Delta I_{in,max}$.

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You will answer this question by first finding the value of the DC current $I_{IN,0}$ that maximises both $\Delta I_{in,max}$ and $\Delta I_{out,max}$.

Then, you will determine whether or not the optimal value of the DC bias voltage $V_{IN,0}$ computed in (f) leads by default to the optimal value of the DC current $I_{IN,0}$ that has just been obtained.

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