Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

GE4T (Digital, Analog Circuits and Instrumentation)

Topic – Semiconductor Devices and Amplifiers

Sub Topic – Bipolar Junction Transistors (Last Part)

Introduction:

The basic function of transistor is to do amplification (i.e. to act as an amplifier). The weak signal is given to the base of the transistor and amplified output is obtained in the collector circuit. One important requirement during amplification is that only the magnitude of the signal should increase and there should be no change in signal shape. This increase in magnitude of the signal without any change in shape is known as *faithful amplification*. In order to achieve this, different techniques are provided to ensure that input circuit (i.e. base-emitter junction) of the transistor remains forward biased and output circuit (i.e. collector-base junction) always remains reverse biased during all parts of the signal. This is known as *transistor biasing*.

In this e-report, one specific type of transistor biasing method will be discussed, viz. *Voltage Divider Bias Method*.

Voltage Divider Bias Method:

This is the most widely used method of providing biasing and stabilization to a transistor. In this method, two resistances R_1 and R_2 are connected across the supply voltage V_{CC} (shown in Fig. 1) and provide biasing. The emitter resistance R_E provides stabilization. The word "voltage divider" comes from the voltage divider formed by R_1 and R_2. The voltage drop across R_2 forward biases the base-emitter junction. This causes the base current and hence collector current-flow in the zero signal conditions.

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

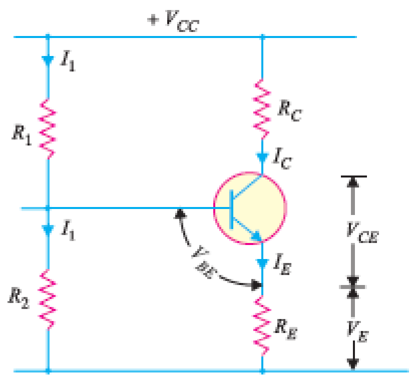

Fig. 1

Circuit Analysis. Let us suppose that the current flowing through resistance R_1 is I_1. As the base current I_B is very small, therefore, it can be assumed with reasonable accuracy that current flowing through R_2 is also I_1 (shown in Fig. 1).

Voltage across resistance R_2 is $V_2 = I_1 R_2 = \frac{V_{CC}}{R_1+R_2} R_2$.

But according to Kirchhoff 's voltage law to the base circuit $V_2 = V_{BE} + V_E = V_{BE} + I_E R_E$. Therefore, $I_E = \frac{V_2 - V_{BE}}{R_E} \approx I_C$.

Though I_C depends upon V_{BE} but in practice $V_2 \gg V_{BE}$ so that I_C is practically independent of V_{BE}. Thus I_C in this circuit is almost independent of transistor parameters and hence good stabilization is ensured.

Now using Kirchhoff 's voltage law to the collector side $V_{CC} = I_C R_C + V_{CE} + I_E R_E \approx I_C R_C + V_{CE} + I_C R_E = I_C(R_C + R_E) + V_{CE}$.

So, $V_{CE} = V_{CC} - I_C(R_C + R_E)$.

Stability Factor. In this circuit, excellent stabilization is provided by R_E. It can be shown mathematically that stability factor of this circuit is given by

$$S = \frac{(\beta+1)(R_\parallel + R_E)}{R_\parallel + R_E + \beta R_E} \text{ where } R_\parallel = R_1 \parallel R_2$$

If $R_\parallel \ll R_E$, then S can be approximated as $\approx \frac{(\beta+1)R_E}{R_E + \beta R_E} = 1$.

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

Hybrid (or *h*) Parameters:

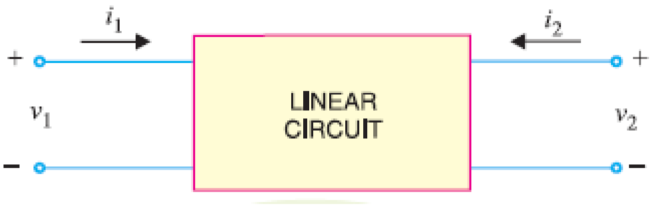

Fig. 2

Every linear circuit having input and output terminals can be analyzed by four parameters (one measured in Ω, one in Ω^{-1} (or mho) and two dimensionless) called hybrid or h parameters. Hybrid means "mixed". Since these parameters have mixed dimensions, the word hybrid comes into play. Let us consider a linear circuit shown in Fig. 2. This circuit has input voltage and current labelled v_1 and i_1. This circuit also has output voltage and current labelled v_2 and i_2. It is crucial to note that both input and output currents (i_1 and i_2) are assumed to flow into the box; input and output voltages (v_1 and v_2) are assumed positive from the upper to the lower terminals.

It can be proved by advanced circuit theory that voltages and currents in Fig. 2 can be related by the following sets of equations:

$$v_1 = h_{11}i_1 + h_{12}v_2$$

$$i_2 = h_{21}i_1 + h_{22}v_2$$

In these equations, the hs are fixed constants for a given circuit and are called h parameters. Once these parameters are known, we can use these equations to find the voltages and currents in the circuit. It is clear that h_{11} has the dimension of Ω and h_{12} is dimensionless. Similarly h_{21} is dimensionless and h_{22} has the dimension of Ω^{-1}.

Determination of *h* Parameters:

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

The major reason for the use of h parameters is the relative ease with which they can be measured. Let us now try to get the physical meaning of these parameters.

For $v_2 = 0$ or a short-circuited output, we get $h_{11} = \frac{v_1}{i_1}$ and $h_{21} = \frac{i_2}{i_1}$.

Now for $i_1 = 0$ or an open-ended input, we get $h_{12} = \frac{v_1}{v_2}$ and $h_{22} = \frac{i_2}{v_2}$.

Therefore h_{11} is called as the *input impedance with the output shorted*, h_{12} is called as the *voltage feedback ratio with input open*, h_{21} is called as the *current gain with the output shorted* and h_{22} is called as the *output admittance with the input open*.

h Parameter Equivalent Circuit:

Fig. 3(i) shows a linear circuit. It is required to draw the h parameter equivalent circuit of Fig. 3(i).

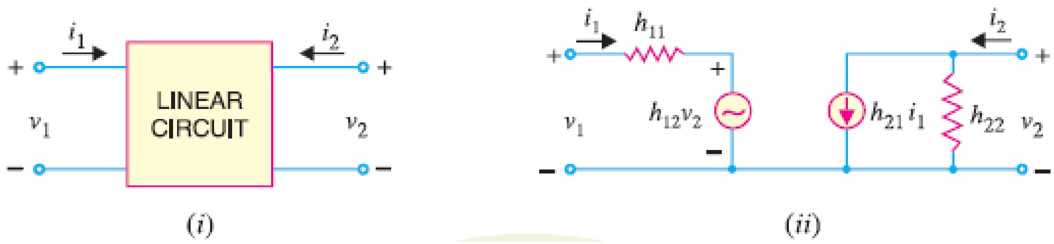

Fig. 3

Fig. 3(ii) shows h parameter equivalent circuit of Fig. 3(i) and is derived from the initial two equations. The *input circuit* appears as an impedance h_{11} in series with a voltage generator $h_{12}v_2$. This circuit is derived from the 1st equation. The *output circuit* involves two components; a current generator $h_{21}i_1$ and shunt admittance h_{22} and is derived from the 2nd equation.

The equivalent circuit of Fig. 3(ii) is extremely useful for two main reasons. Firstly, it isolates the input and output circuits, their interaction being accounted for by the two controlled sources. Thus, the effect of output upon input is represented by the equivalent voltage generator $h_{12}v_2$ and its value depends

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

upon output voltage. Similarly, the effect of input upon output is represented by current generator $h_{21}i_1$ and its value depends upon input current. Secondly, the two parts of the circuit are in a form which makes it simple to take into account source and load circuits.

***h* Parameters of a Transistor:**

It has been seen that every linear circuit is associated with h parameters. When this linear circuit is terminated by load r_L, we can find input impedance, current gain, voltage gain, etc. in terms of h parameters. Fortunately, for small AC signals, the transistor behaves as a linear device because the output AC signal is directly proportional to the input AC signal. Under such circumstances, the AC operation of the transistor can also be described in terms of h parameters. The expressions derived for input impedance, voltage gain etc. shall hold good for transistor amplifier except that here r_L is the AC load seen by the transistor. Fig. 4 shows the transistor amplifier circuit.

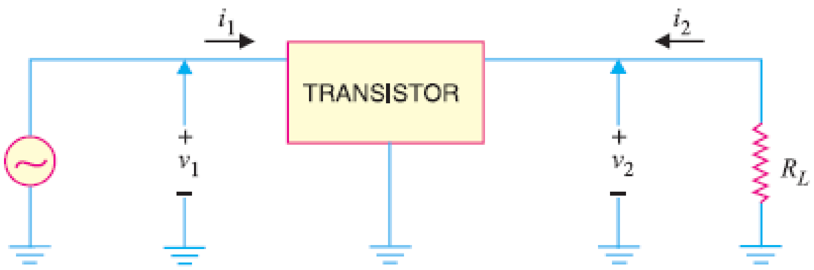

Fig. 4

The following points are worth noting while considering the behaviour of a transistor in terms of h parameters:

(i) For small AC signals, a transistor behaves as a linear circuit. Therefore, its AC operation can be described in terms of h parameters.

(ii) The value of h parameters of a transistor will depend upon the transistor connection (i.e. CB, CE or CC) used.

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

(iii) The expressions for input impedance, voltage gain etc. remain same to transistor amplifier except that r_L is the AC load seen by the transistor i.e. $r_L = R_C \parallel R_L$.

(iv) The values of h parameters depend upon the operating point. If the operating point is changed, parameter values are also changed.

(v) The notations v_1, i_1, v_2 and i_2 are used for general circuit analysis. In a transistor amplifier, we use the notation depending upon the configuration in which transistor is used. Thus for CE arrangement, $v_1 = V_{be}$, $i_1 = I_b$, $v_2 = V_{ce}$, $i_2 = I_c$. Here V_{be}, I_b, V_{ce} and I_c are all the RMS values.

Nomenclature for Transistor *h* Parameters:

The numerical subscript notation for h parameters (viz. h_{11}, h_{12}, h_{21} and h_{22}) is used in general circuit analysis. However, this nomenclature has been modified for a transistor to indicate the nature of parameter and the transistor configuration used. The table below shows the h parameter nomenclature of a transistor.

Serial No.	h parameter	in CB	in CE	in CC
1.	h_{11}	h_{ib}	h_{ie}	h_{ic}
2.	h_{12}	h_{rb}	h_{re}	h_{rc}
3.	h_{21}	h_{fb}	h_{fe}	h_{fc}
4.	h_{22}	h_{ob}	h_{oe}	h_{oc}

Here the first letter indicates the nature of parameter. For example, letters i, r, f and o indicate input impedance, reverse voltage feedback ratio, forward current transfer ratio and output admittance respectively. The second letters b, e and c respectively indicate CB, CE and CC arrangement.

Important Terms of a Linear Circuit in *h* Parameters:

We have already seen that any linear circuit with input and output has a set of h parameters. Now, it is important to develop formulae for various important

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

terms e.g. input impedance, current gain, voltage gain etc. of a linear circuit in terms of h parameters.

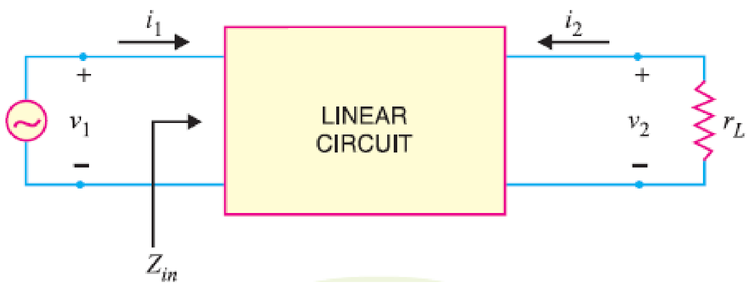

Fig. 5

1. Input Impedance. Let us consider a linear circuit with a load resistance r_L across its terminals as shown in Fig. 5. The input impedance Z_{in} of this circuit is the ratio of input voltage to input current $Z_{in} = \frac{v_1}{i_1}$. Since we already know that $v_1 = h_{11}i_1 + h_{12}v_2$ from h parameters, we can write $Z_{in} = \frac{h_{11}i_1+h_{12}v_2}{i_1} = h_{11} + \frac{h_{12}v_2}{i_1}$. Now from Fig. 5, we can write $i_2 = -\frac{v_2}{r_L}$. The minus sign is used here because the actual load current is opposite to the direction of i_2. But we also know that $i_2 = h_{21}i_1 + h_{22}v_2$. Therefore we can write $-\frac{v_2}{r_L} = h_{21}i_1 + h_{22}v_2$ or $\frac{v_2}{i_1} = -\frac{h_{21}}{h_{22}+\frac{1}{r_L}}$. Using this value of $\frac{v_2}{i_1}$ in the expression of Z_{in}, we write

$$Z_{in} = h_{11} - \frac{h_{12}h_{21}}{h_{22}+\frac{1}{r_L}}$$

This is the expression for input impedance of a linear circuit in terms of h parameters and load connected to the output terminals. This expression can sometime be approximated as $Z_{in} \approx h_{11}$. This is valid when either h_{12} or r_L is very small.

2. Current Gain. Referring to Fig. 5, the current gain A_i of the circuit can be written as $A_i = \frac{i_2}{i_1}$. We already have $i_2 = h_{21}i_1 + h_{22}v_2$ and $i_2 = -\frac{v_2}{r_L}$. Using these two we can write $i_2 = h_{21}i_1 - h_{22}i_2r_L$ or $\frac{i_2}{i_1} = \frac{h_{21}}{1+h_{22}r_L}$. So, we get

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

$$A_i = \frac{h_{21}}{1+h_{22}r_L}$$

This is the expression for current gain. This expression can also be approximated as $A_i \approx h_{21}$, when $h_{22}r_L \ll 1$.

3. Voltage Gain. The voltage gain (A_v) of the circuit is given by $A_v = \frac{v_2}{v_1}$. We already have $v_1 = h_{11}i_1 + h_{12}v_2$ and $Z_{in} = \frac{v_1}{i_1}$. Therefore we write $v_1 = \frac{h_{11}v_1}{Z_{in}} + h_{12}v_2$ or $\frac{v_2}{v_1} = \frac{1-\frac{h_{11}}{Z_{in}}}{h_{12}}$. But $Z_{in} = h_{11} - \frac{h_{12}h_{21}}{h_{22}+\frac{1}{r_L}}$, so we get $\frac{v_2}{v_1} = \frac{1-\frac{h_{11}}{Z_{in}}}{h_{12}} = -\frac{h_{21}}{h_{11}h_{22}+\frac{h_{11}}{r_L}-h_{12}h_{21}}$. Therefore,

$$A_v = -\frac{h_{21}}{h_{11}h_{22}+\frac{h_{11}}{r_L}-h_{12}h_{21}}$$

This is the expression for voltage gain.

4. Output Impedance. In order to find the output impedance, we need to remove the load r_L first. Then the signal voltage v_1 is set to zero and a generator of voltage v_2 is connected at the output terminals. Then h parameter equivalent circuit becomes as shown in Fig. 6. By definition, the output impedance Z_{out} is given by $Z_{out} = \frac{v_2}{i_2}$. Applying Kirchhoff's voltage law to the input circuit, we have $v_1 = 0 = h_{11}i_1 + h_{12}v_2$ or $i_1 = -\frac{h_{12}v_2}{h_{11}}$. We also have in the output circuit $i_2 = h_{21}i_1 + h_{22}v_2 = -\frac{h_{21}h_{12}v_2}{h_{11}} + h_{22}v_2$. Therefore we get

$$Z_{out} = \frac{1}{h_{22}-\frac{h_{12}h_{21}}{h_{11}}}$$

This is the expression for output impedance of a linear circuit in terms of h parameters.

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

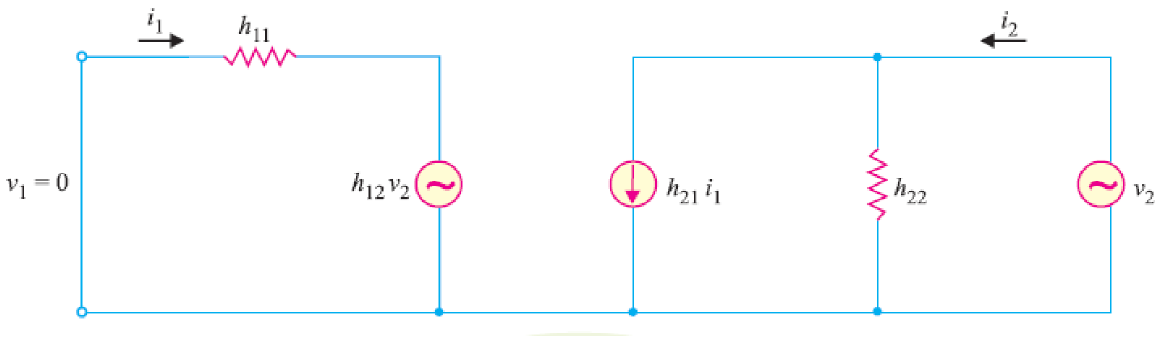

Fig. 6

Analysis of Single Stage Transistor Circuit using *h* Parameters:

The expressions for input impedance, voltage gain etc. in terms of h parameters derived for general circuit analysis apply equally for transistor analysis also. However, it is profitable to rewrite them in standard transistor h parameter nomenclature.

Here in this e-report we will only analyze a single stage CE amplifier circuit.

Single Stage Transistor Amplifier: When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as *single stage transistor amplifier*. A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components. Although a practical amplifier consists of a number of stages, yet such a complex circuit can be conveniently split up into separate single stages. By analysing carefully only a single stage and using this single stage analysis repeatedly, we can effectively analyze the complex circuit. It follows, therefore, that single stage amplifier analysis is of great value in understanding the practical amplifier circuits.

1. Input Impedance. The general expression for input impedance Z_{in} is given as

$$Z_{in} = h_{11} - \frac{h_{12}h_{21}}{h_{22}+\frac{1}{r_L}}$$

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

Using standard h parameter nomenclature for transistor, its value for CE amplifier arrangement will be $Z_{in} = h_{ie} - \frac{h_{re}h_{fe}}{h_{oe}+\frac{1}{r_L}}$. Here r_L is the AC load as seen by the transistor.

2. Current Gain. The general expression for current gain A_i is provided as

$$A_i = \frac{h_{21}}{1+h_{22}r_L}$$

Using standard h parameter nomenclature for transistor, its value for CE amplifier arrangement will be $A_i = \frac{h_{fe}}{1+h_{oe}r_L}$.

3. Voltage Gain. The general expression for current gain A_v is provided as

$$A_v = -\frac{h_{21}}{h_{11}h_{22}+\frac{h_{11}}{r_L}-h_{12}h_{21}}$$

Using standard h parameter nomenclature for transistor, its value for CE amplifier arrangement will be $A_v = -\frac{h_{fe}}{h_{ie}h_{oe}+\frac{h_{ie}}{r_L}-h_{re}h_{fe}}$.

4. Output Impedance. The general expression for output impedance Z_{out} is given as

$$Z_{out} = \frac{1}{h_{22}-\frac{h_{12}h_{21}}{h_{11}}}$$

Using standard h parameter nomenclature for transistor, its value for CE amplifier arrangement will be $Z_{out} = \frac{1}{h_{oe}-\frac{h_{re}h_{fe}}{h_{ie}}}$.

The above expression for Z_{out} is for the transistor. If the transistor is connected in a circuit to form a single stage amplifier, then output impedance of the stage $= Z_{out} \parallel r_L$ where $r_L = R_C \parallel R_L$.

Classifications of Class *A*, Class *B* & Class *C* Amplifiers:

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

Transistor power amplifiers handle large signals. Many of them are driven so hard by the input large signal that collector current is either cut-off or is in the saturation region during a large portion of the input cycle. Therefore, such amplifiers are generally classified according to their mode of operation i.e. the portion of the input cycle during which the collector current is expected to flow. On this basis, they are classified as (i) class A power amplifier, (ii) class B power amplifier and (iii) class C power amplifier.

Class A Power Amplifier. If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as class A power amplifier. Obviously, for this to happen, the power amplifier must be biased in such a way that no part of the signal is cut off.

The operating point is so selected that collector current flows at all times throughout the full cycle of the applied signal. As the output wave shape is exactly similar to the input wave shape, therefore, such amplifiers have least distortion. However, they have the disadvantage of low power output and low collector efficiency.

Class B Power Amplifier. If the collector current flows only during the positive half-cycle of the input signal, it is called a class B power amplifier. In class B operation, the transistor bias is so adjusted that zero signal collector current is zero i.e. no biasing circuit is needed at all. During the positive half-cycle of the signal, the input circuit is forward biased and hence collector current flows. However, during the negative half-cycle of the signal, the input circuit is reverse biased and no collector current flows. Hence a severe distortion occurs in the signal. However, class B amplifiers provide higher power output and collector efficiency. Such amplifiers are mostly used for power amplification in push-pull arrangement. In such an arrangement, two transistors are used in class B operation. One transistor amplifies the positive half-cycle of the signal while the other amplifies the negative half-cycle.

Class C Power Amplifier. If the collector current flows for less than half-cycle of the input signal, it is called class C power amplifier. In class C amplifier, the base is given some negative bias so that collector current does not flow just

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

when the positive half-cycle of the signal starts. Such amplifiers are never used for power amplification. However, they are used as tuned amplifiers i.e. to amplify a narrow band of frequencies near the resonant frequency.

Reference:

Principles of Electronics, V.K. Mehta & Rohit Mehta, S. Chand & Company

(All the figures have been collected from the above mentioned reference)