CONTENTS

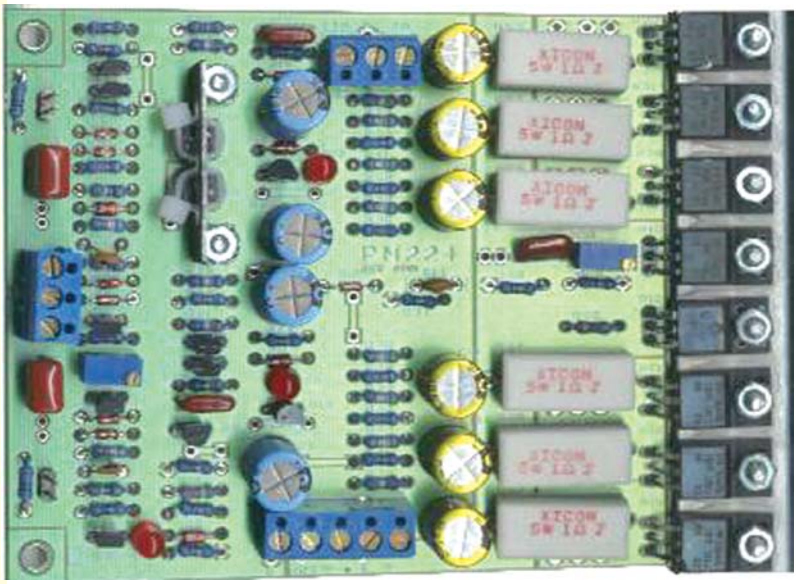
CHAPTER **60**

SINGLE-STAGE TRANSISTOR AMPLIFIERS

Learning Objectives

- Classification of Amplifiers
- Common Base (CB) Amplifier
- Common Emitter (CE) Amplifier
- Common Collector (CC) Amplifier
- Comparison of Amplifier Configurations
- Class-A Amplifier
- Power Rectangle
- Power Efficiency
- Class-B Amplifier
- Maximum Values
- Class-B Push-pull Amplifier
- Crossover Distortion
- Class-B Amplifier
- Class-C Amplifier
- Tuned Amplifier
- Distortion in Amplifiers
- Noise
- The Decibel System
- Value of 1 dB
- Cause of Amplifier Gain Variations
- Miller Effect
- Cut-off Frequencies of Cascaded Amplifiers
- The f_T of a Transistor
- Relation between f_α, f_β and f_T
- Gain-bandwidth Product

CONTENTS



Single stage amplifier analysis is of great value in understanding the practical amplifier circuits

60.1. Classification of Amplifiers

Linear amplifiers are classified according to their mode of operation *i.e.* the way they operate according to a predetermined set of values. Various amplifier descriptions are based on the following factors :

1. **As based on its input**
   (*a*) small-signal amplifier (*b*) large-signal amplifier
2. **As based on its output**
   (*a*) voltage amplifier (*b*) power amplifier
3. **As based on its frequency response**
   (*a*) audio-frequency (AF) amplifier (*b*) intermediate-frequency (IF) amplifier
   (*c*) radio-frequency (RF) amplifier
4. **As based on its biasing conditions**
   (*a*) class-A (*b*) class-AB (*c*) class-B (*d*) class-C
5. **As based on transistor configuration**
   (*a*) common-base (CB) amplifier (*b*) common-emitter (CE) amplifier
   (*c*) common-collector (CC) amplifier

The description ***small-signal, class-A, CE, voltage amplifier*** means that input signal is small, biasing condition is class-A, transistor configuration is common-emitter and its output concerns voltage amplification.

We will first take up the basic working of a single-stage amplifier *i.e.* an amplifier having one amplifying element connected in *CB*, *CE* and *CC* configuration.

60.2. Common Base (CB) Amplifier

Both Fig. 60.1 and 60.2 show the circuit of a single-stage *CB* amplifier using *NPN* transistor. As seen, input ac signal is injected into the emitter-base circuit and output is taken from the collector-base circuit. The *E/B* junction is forward-biased by V_{EE} whereas *C/B* junction is reverse-biased by V_{CC}. The *Q*-point or dc working conditions are determined by dc batteries along with resistors R_E and R_C. In other words, values of I_E, I_B and V_{CB} are decided by V_{CC}, V_{EE}, R_E and R_C. The voltage V_{CB} is given by the equation $V_{CB} = V_{CC} - I_C R_C$.

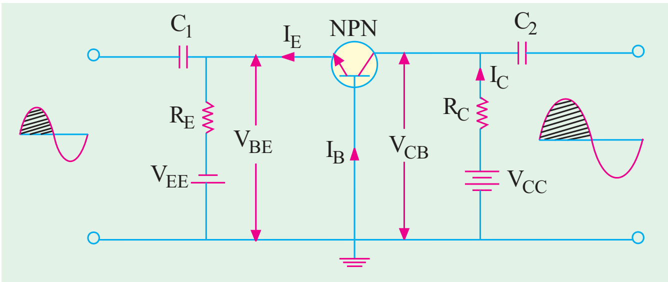


Fig. 60.1

When no signal is applied to the input circuit, the output just ***sits at the Q-point so that there is no output signal.*** Let us now see what happens when we apply an ac signal to the *E/B* junction via a coupling capacitor C_1 (which is assumed to offer no reactance to the signal).

Circuit Operation

When positive half-cycle of the signal is applied, then

1. .forward bias is **decreased** because V_{BE} is already negative with respect to the ground as per biasing rule of Art. 60.3.
2. consequently, I_B is ***decreased.***
3. I_E and hence I_C are ***decreased*** (because they are both nearly β times the base current).
4. the drop $I_C R_C$ is ***decreased.***
5. hence, V_{CB} is ***increased*** as seen by the equation given above.

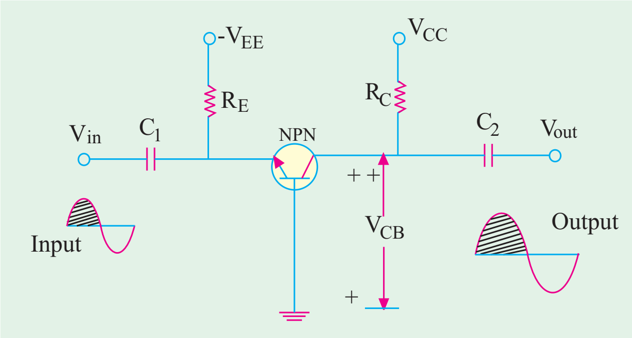


Fig. 60.2

It means that a positive output half-cycle is produced.

Since a ***positive-going*** input signal produces a ***positive-going*** output signal, there is no phase reversal between the two.

Voltage amplification in this circuit is possible by reason of relative input and output circuitry rather than current gain (α) which is always less than unity. The input circuit has low resistance whereas output circuit has very large resistance. Although changes in input and output currents are the same, the ac drop across R_L is very large. Hence, changes in V_{CB} (which is the output voltage) are much larger than changes in input ac signal. Hence, the voltage amplification.

60.3. Various Gains of a CB Amplifier

1. Input Resistance

The ac input resistance of the transistor is given by the emitter junction resistance

$$r_e = \frac{25\,\text{mV}}{I_E} \quad \text{or} \quad \frac{50\,\text{mV}}{I_E}$$

As seen from the ac equivalent circuit (Fig. 10.3)

$$\boxed{r_{in} = r_e \,||\, R_E}$$

2. Output Resistance

$r_0 = R_C$ — Fig. 60.2

If a load resistance R_L is connected across output terminals, then

$\boxed{r_0 = R_C \,||\, R_L}$ — Fig. 60.3

It is called the output resistance of the stage and is written as $r_{0(stage)}$ or r_0'

3. Current Gain $\boxed{A_i = \alpha}$

4. Voltage Gain $\boxed{A_v = \dfrac{r_0}{r_{in}} = \dfrac{r_0}{r_e}}$

5. Power Gain $\boxed{A_p = A_v . A_i}$

The decibel gain is given by $G_p = 10 \log_{10} A_p$ dB

60.4. Characteristics of a CB Amplifier

Common-base amplifier has

1. very low input resistance (30 – 150 Ω),
2. very high output resistance (upto 500 K),
3. a current gain α < 1,
4. large voltage gain of about 1500,
5. power gain of upto 30 dB,
6. no phase reversal between input and output voltages.

Uses

One of the important uses of a *CB* amplifier is in matching a low-impedance circuit to a high-impedance circuit.

It also has high stability of collector current with temperature changes.

Example 60.1. *For the single-stage CB amplifier shown in Fig. 60.3 (a), find*
(a) stage input resistance, *(b) stage output resistance,*
(c) current gain, *(d) voltage gain of the stage,*
(e) stage power gain in dB,
Assume α = 1. Neglect V_{BE} and use r_e = 25 mV/I_E

(Basic Electronics, Bombay Univ. 1991)

Solution. The ac equivalent circuit is shown in Fig. 60.3 (*b*).

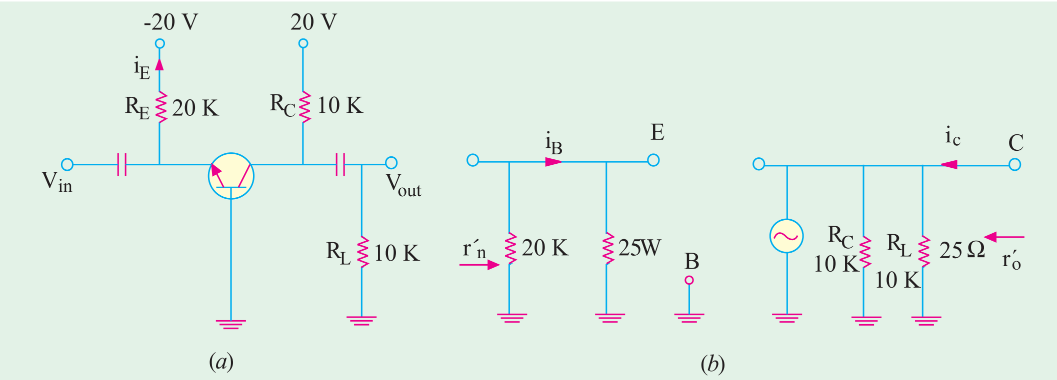


Fig. 60.3

I_E = 20/20 = 1mA $\qquad r_e = 25/I_E = 25\ \Omega$

(a) stage $r_{in} = r_e \| R_E = 25\ \Omega \| 20K \cong$ **25 Ω**

(b) stage $r_0 = R_C \| R_L \qquad \therefore \qquad r_0' = 10K \| 10K =$ **5K**

(c) $\qquad A_i = \alpha = 1 \qquad$ **(d)** $\qquad A_v = \dfrac{r_0'}{r_e} = \dfrac{5000}{25} =$ **200**

(e) $\qquad A_p = A_v \cdot A_i = 200 \times 1 =$ **200**

$G_p = 10 \log_{10} A_p$ dB $= 10 \log_{10} 200 =$ **23 dB**

60.5. Common Emitter (CE) Amplifier

Fig. 60.4 and 60.5 show the circuit of a single-stage *CE* amplifier using an *NPN* transistor. Here, base is the driven element. The input signal is injected into the base-emitter circuit whereas output signal is taken out from the collector-emitter circuit. The *E/B* junction is forward-biased by V_{BB} and *C/B* junction is reversed-biased by V_{CC} (in fact, same battery V_{CC} can provide dc power for both base and collector as in Fig. 60.5). The *Q*-point or working condition is determined by V_{CC} together with R_B and R_C. The dc equation is (Fig. 60.5).

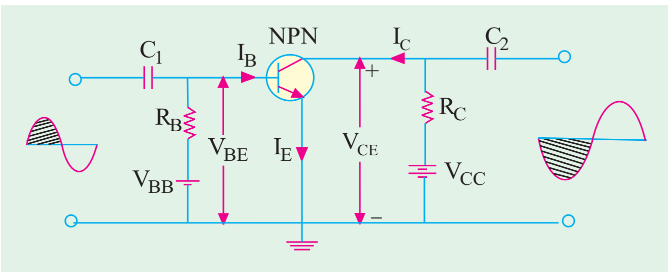


Fig. 60.4

$I_B \cong V_{BB}/R_B$ —neglecting V_{BE}

$I_C = \beta I_B$ and $V_{CE} = V_{CC} - I_C R_C$

Now, let us see what happens when an ac signal is applied at the input terminals of the circuit.

Circuit Operations

When positive half-cycle of the signal is applied (Fig. 60.4)

1. V_{BE} is **increased** because it is already positive w.r.t. the ground as per biasing rule of Art 6.3.
2. it leads to increase in forward bias of base-emitter junction
3. I_B is **increased** somewhat
4. I_C is increased by α times the **increased** in I_B.
5. drop $I_C R_C$ is **increased** considerably and cons- equently.
6. V_{CE} is decreased as seen from the equation given above.

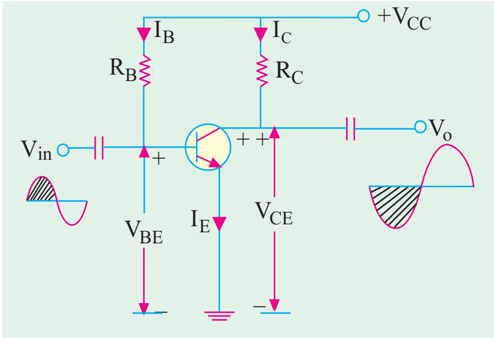


Fig. 60.5

Hence, negative half-cycle of the output is obtained. It means that a positive-going input signal becomes a negative going output signal as shown in Fig. 60.4 and 60.5.

60.6. Various Gains of a CE Amplifier

The ac equivalent of the given circuit (Fig. 60.5) is similar to the one shown in Fig. 60.6 (*b*).

1. Input Resistance

When viewed from base, ac resistance of the emitter junction is β_{re}. As seen, from Fig. 60.6 (*b*), circuit input resistance is

$$r_{in}' = R_B \,||\, \beta r_e \qquad \text{—remember } \beta\text{-rule}$$
$$\cong \beta r_e \qquad \text{—when } R_B >> \beta r_e$$

It is called input resistance of the stage *i.e.* $r_{in(stage)}$.

2. Output Resistance : $r_0 = R_C$ —Fig. 60.5

However, if a load resistor R_L is connected across the output terminals (Fig. 60.6), then

$$r_0 = R_C \,||\, R_L = r_L \qquad \text{— Fig. 60.6 (b)}$$

It is called output resistance of the stage and is written as $r_{o(stage)}$ or r_o'.

3. Current Gain : $A_i = \beta$

4. Voltage Gain : $A_v = \beta.\dfrac{r_0'}{r_{in}'} = \beta.\dfrac{r_0}{\beta r_e} \cong \dfrac{r_0'}{r_e}$ —if $R_B >> \beta r_e$

It is the stage voltage gain,

5. Power Gain : $A_p = A_v . A_i = \beta . \dfrac{r_0'}{r_e}$; $G_p = 10 \log_{10} A_p$ dB

60.7. Characteristics of a CE Amplifier

A *CE* transistor amplifier has the following characteristics :

1. it has moderately low input resistance (1 K to 2 K),
2. its output resistance is moderately large (50 K or so),
3. its current gain (β) is high (50–300),
4. it has very high voltage gain of the order of 1500 or so,
5. it produces very high power gain of the order of 10,000 times or 40 dB,
6. it produces ***phase reversal*** of input signal *i.e.* input and output signals are 180° out of phase with each other.

Uses

Most of the transistor amplifiers are of CE type because of large gains in voltage, current and power. Moreover, their input and output impedance characteristics are suitable for many applications.

Example. 60.2. *For the single-stage CE amplifier circuit shown in Fig. 60.6 (a), calculate* **(a)** r_{in} **(b)** r_0 **(c)** A_i **(d)** A_v *and* **(e)** G_p
Take transistor $\beta = 50$. *Neglect* V_{BE} *and take* $r_e = 25\ mV/I_E$

Solution. $I_B = \dfrac{20}{1M} = 20\,\mu A$; $\quad I_C = \beta I_B = 50 \times 20 = 1$ mA

$r_e = 25/1 = 25\ \Omega$, $\quad \beta r_e = 50 \times 25 = 1250\ \Omega$

The ac equivalent circuit is shown in Fig. 60.6 (*b*).

(*a*) $r_{in}' = 1M \parallel 1250\ \Omega \cong$ **1250 Ω**

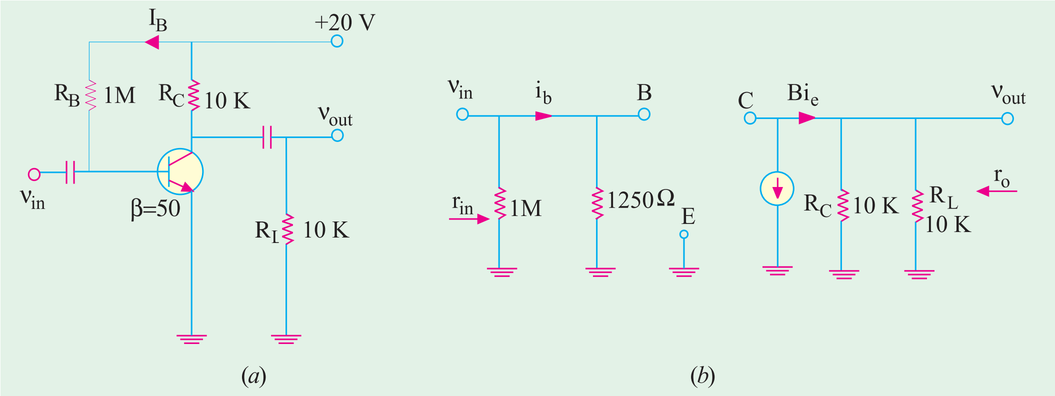


Fig. 60.6

Obviously, it is the input resistance of the stage and not that of the transistor alone.

(*b*) $r_0' = R_C \parallel R_L = 10K \parallel 10K = 5K$ $\qquad$ **(*c*)** $A_i = 50$

(*d*) $A_v = \dfrac{5K}{25\Omega} = 200$ $\qquad$ **(*e*)** $G_p = 10\log_{10}200 =$ **23** dB

60.8. Common Collector (CC) Amplifier

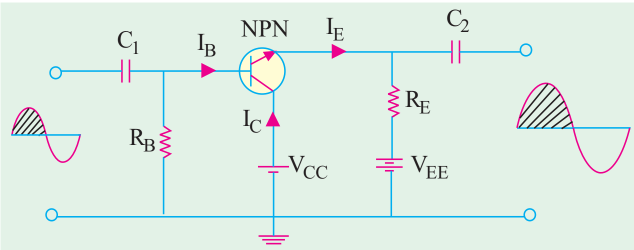


Fig. 60.7

Fig. 60.7 and 60.8 show the circuit of a single-stage *CC* amplifier using an *NPN* transistor. The input signal is injected into the base-collector circuit and output signal is taken out from the emitter-collector circuit. The *E*/*B* junction is forward-biased by V_{EE} and *C*/*B* junction is reverse-biased by V_{CC}. The quiescent values of I_B and I_E are set by V_{CC} and V_{EE} together with R_B and R_E. As seen from Fig. 60.8.

$$I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/\beta} \cong \frac{V_{EE}}{R_E + R_B/\beta}$$

Let us now see what happens when an ac signal is applied across the input circuit.

Circuit Operation

When positive half-cycle of the signal is applied, then

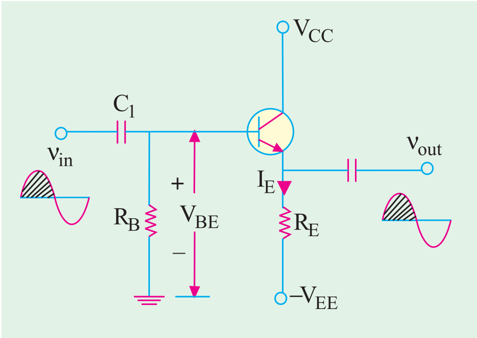


Fig. 60.8

1. forward bias is **increased** since V_{BE} is positive w.r.t. collector i.e. ground,
2. base current is **increased**,
3. emitter current is **increased**,
4. drop across R_E is **increased**,
5. hence, output voltage (*i.e.* drop across R_E is **increased**.

Consequently, we get positive half-cycle of the output.

It means that a ***positive-going*** input signal results in a ***positive going*** output signal and, consequently, the input and output signals are in phase with each other as shown in Fig. 60.8.

60.9. Various Gains of a CC Amplifier

The ac equivalent circuit of the *CC* amplifier (Fig. 60.8) is given in Fig. 60.9.

1. $r'_{in} = R_B \,||\, \beta\,(r_e + r_0)$
2. $r'_0 = R_E \,||\, R_L$
3. $A_i = \beta$
4. $A_v = \dfrac{r_0'}{r_0' + r_e}$

Since usually $r_0' >> r_e'$, $A_v \cong \dfrac{r_0'}{r_0'} = 1$

$A_p = A_v . A_i$,

$G_p = 10 \log 10 A_p$ dB

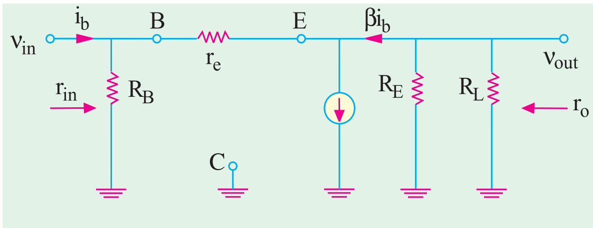


Fig. 60.9

60.10. Characteristics of a CC Amplifier

A *CC* amplifier has the following characteristics :

1. high input impedance (20-500 K),
2. low output impedance (50-1000 Ω),
3. high current gain of (1 + β) *i.e.* 50 – 500,
4. voltage gain of less than 1,
5. power gain of 10 to 20 dB,
6. no phase reversal of the input signal.

60.11. Uses

The CC amplifiers are used for the following purposes :

1. for impedance matching *i.e.* for connecting a circuit having high output impedance to one having low input impedance;
2. for circuit isolation;
3. as a two-way amplifier since it can pass a signal in either direction;
4. for switching circuits.

Example 60.3. *For the CC amplifier circuit of Fig. 60.10 (a), compute*
(i) r_o' ***(ii)*** r_{in}' ***(iii)*** A_v *and* ***(iv)*** A_p
Take transistor $\beta = 100$*. Neglect* V_{BE} *and use* $r_e = 25\ mV/I_E$ **(Electronics-I, M.S. Univ. 1991)**

Solution. $I_E = \dfrac{20}{20} = 1\text{mA}$; $r_c = \dfrac{25}{1} = 25\Omega$

The ac equivalent circuit is shown in Fig. 60.10 (*b*).

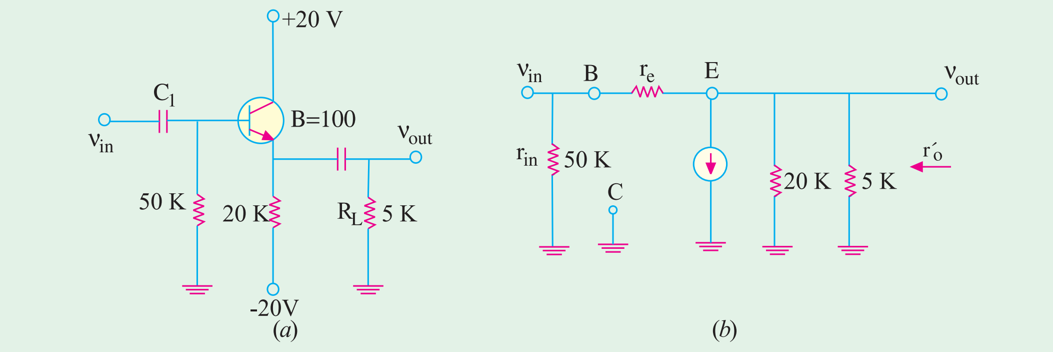


Fig. 60.10

(*i*) $r_o' = R_E \,||\, R_L = 20K \,||\, 5K =$ **4K**

(*ii*) $r_{in}' = R_B \,||\, \beta\,(r_e + r_0) \cong R_B \,||\, \beta r_0' = \dfrac{50 \times 400}{450} =$ **44.4 K**

(*iii*) $A_v = \dfrac{4k}{4k + 25\,\Omega}$ (*iv*) $A_p = A_v . A_i = 1 \times 100 = 100$

60.12. Comparison of Amplifier Configurations

The basic building blocks of transistor amplifiers are single-stage common-base, common-emitter and common-collecter circuits. The choice of configuration and type of transistor for a given application will depend largely upon the desired input and output impedances, voltage, current and power gains and frequency response. For convenience, these values are tabulated in Table No. 10.1. Here the input and output parameters are resistances and apply only to ***low-frequency conditions.***

Table No. 60.1

	Type of Circuit		
Characteristic	***Common base***	***Common emitter***	***Common collector***
Current gain	nearly unity (α)	high (β)	highest ($1 + \beta$)
Voltage gain	high	very high	nearly unity
Power gain	moderate	highest	lowest
Input impedance	lowest	moderate	highest
Output impedance	highest	moderate	lowest
Phase reversal	No	Yes	No

In each case, the amplifying action depends on low-power input circuits controlling the high-power output circuits.

In the common-base circuit, although the input and output currents are nearly equal, the low-impedance emitter circuit absorbs for less power as compared to that which is available at the high-impedance collector.

The low base current flowing into the common-emitter circuit (where the impedance is a few kilohms) gives rise to much higher collector current flowing out of the high-impedance output circuit.

The common-collector circuit with approximately equal input and output resistances requires a low input current to control much larger output current.

60.13. Amplifier Classification Based on Biasing Conditions

This classification is based on the amount of transistor bias and amplitude of the input signal. It takes into account the portion of the cycle for which the transistor conducts. The three main classifications are :

(*a*) Class-A Amplifier

In this case, the transistor is so biased that output current flows for the full-cycle of the input signal (360°) as shown in Fig. 60.11 (*a*). In other words, the transistor remains *FR*-biased throughout the input cycle. Hence, its conduction angle is 360°.

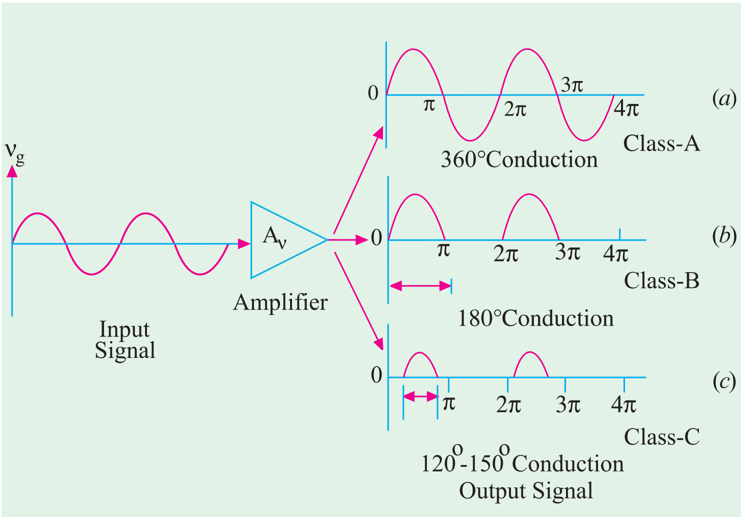


Fig. 60.11

(*b*) Class-B Amplifier

In this case, the transistor bias and the amplitude of input signal are such that output current flows for only half-cycle (180°) of the input signal. It means that transistor stays *FR*-biased for half the input cycle. The transistor conduction angle equals 180°.

(*c*) Class-C Amplifier

In this case, transistor bias and signal amplitude are such that output current flows for appreciably less than half-cycle of the input signal *i.e.* upto 120 ° or 150° angle of conduction as shown in 60.11 (*c*). In other words, transistor remains FR-biased for less than half the cycle.

(*d*) Class-AB Amplifier

The characteristics of such an amplifier lie in-between those of class-A and class-B. Here, biasing conditions are such that output current flows for appreciably more than half but less than the entire cycle *i.e.* current flows for more than 180° but less than 360°.

60.14. Graphic Representation

Since common-emitter is the most versatile and widely-used configuration, we will use CE output characteristic curves to differentiate between main classes of amplifiers.

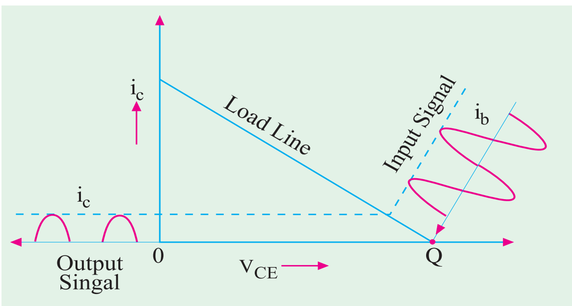


Fig. 60.12

Fig. 60.12 shows the biasing condition for class-A operation. It is seen that *Q*-point is located at the centre of the load line so that output (collector) current flows for the complete cycle of the input signal (conduction angle of 360°). Because of centred Q-point, the positive and negative swings of the input signal are confined to linear portions of the load line. In this linear region, equal changes in input base current produce equal changes in output (collector) current and voltage. Hence, output is an exact replica of the input. If the amplitude of the input signal is so large as to drive the *Q*-point closer to either cut-off or saturation region (where base current lines are not equally spaced), the output

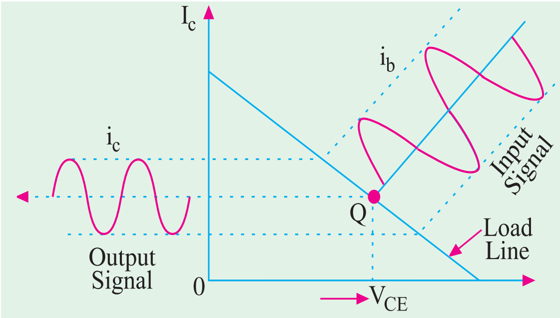


Fig. 60.13

will not be an exact replica of the input *i.e.* output signal will be distorted (Art. 60.30).

Fig. 60.13 shows biasing conditions for class-B operation. In this case, *Q*-point is located at cut-off point or very close to it. It is seen that the output current only flows for positive half-cycles of the input signal. For negative half-cycles, there is no output (collector) current. Obviously, output current flows only for 180° during the positive half-cycles of the input signal.

Fig. 60.14 shows biasing conditions for class-C operation. Here, the transistor is biased well into cut-off. In this case, (collector) current flows only for a part (upto 150°) of the positive half-cycle of the input signal when transistor comes out of the cut-off. During negative half-cycles of the input, the transistor remains deep in cut-off.

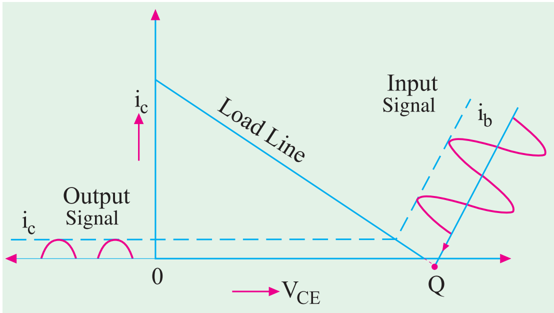


Fig. 60.14

60.15. Class-A Amplifier

It is one which has centred Q-point so that the transistor operates only over the linear region of its load line.

Another way of defining is that it is an amplifier in which the output current flows during the entire cycle of the input signal *i.e.* it has a conduction angle of 360°. In other words, the transistor remains FR-biased throughout the input cycle.

Characteristics

1. Since the transistor operates over the linear portion of the load line, the output waveform is exactly similar to the input waveform. Hence, class-A amplifiers are characterised by a high fidelity of the output. They are used where linearity or freedom from distortion is the prime requisite.
2. Since its operation is restricted only over a small central region of the load line, this amplifier is meant only for amplifying input signals of small amplitude. Large signals, will shift the Q-point into non-linear regions near saturation or cut-off and produce distortion (Art. 60.30).
3. Due to the limitation of the input signal amplitude, ac power output per active device (i.e. transistor) is small.
4. The overall efficiency of the amplifier circuit is

$$= \frac{\text{ac power delivered the load}}{\text{total power delivered by dc supply}} = \frac{\text{average ac power output}}{\text{average dc power input}}$$

5. The collector efficiency of a transistor is defined as

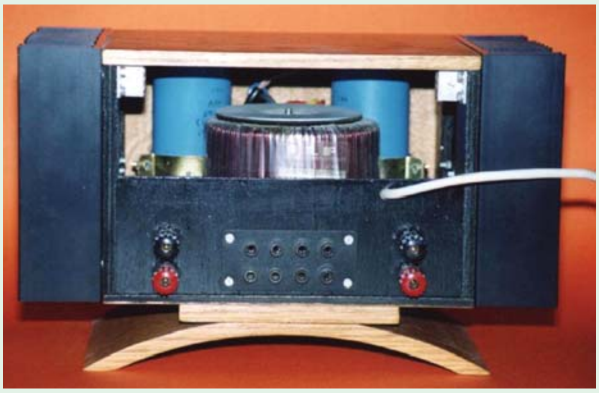
$$= \frac{\text{average ac power output}}{\text{average dc power input to transistor}}$$

The maximum possible collector efficiency of a class – A amplifier with resistive load is 50%

6. In case an output transformer is used, the maximum possible overall efficiency and maximum possible collector efficiency for a class-A amplifier are both 50%.

60.16. Power Distribution in a Class-A Amplifier

Fig. 60.15 (*a*) shows a *CE* connected transistor which forms the active element of a single-stage class-A amplifier. Fig. 60.15 (*b*) shows its output characteristic with a centred *Q*-point. When ac input signal is applied, *Q*-point shifts up and down from its central position. The output current will also increase or decrease from its quiescent (or no-signal) value I_{CQ}. Similarly, collector-emitter voltage V_{CE} will increase or decrease from its quiescent value V_{CEQ}. So long as signal variations are confined to linear region of the load line, average value of collector current is I_{CQ} because positive and negative input signal swings will produce equal changes in I_{CQ}.



Class-A amplifier

Hence, total average dc power drawn by the circuit from collector battery V_{CC} is

$$P_{in(dc)} = V_{CC} \cdot I_{CQ}$$

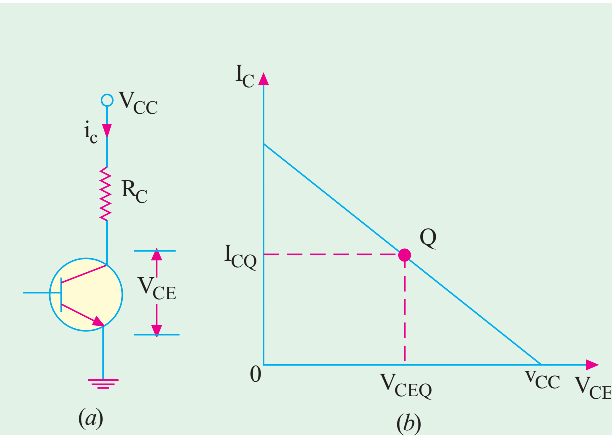


Fig. 60.15

Now, this power goes to supply the following :

(*i*) heat dissipated by the load resistor *RC* connected to the collector

$P_{RC(dc)} = R_C$

(*ii*) the balance $P_{tr(dc)}$ is given to the transistor.

It is further subdivided into :

(*a*) ac power developed across the load resistor which constitutes the ac power output

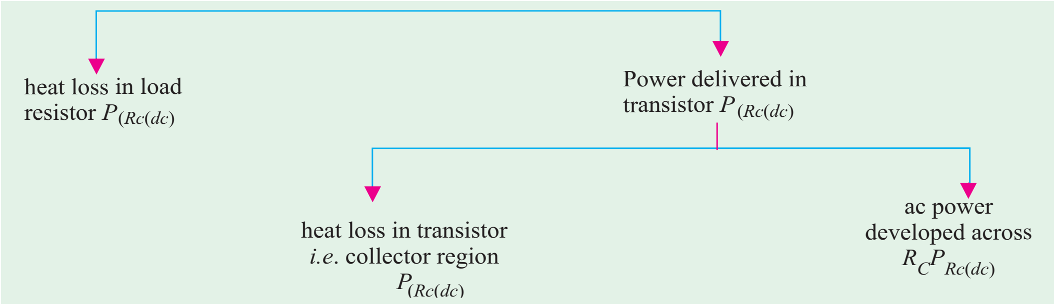
$$P_{o(ac)} = I^2 R_C = \frac{V^2}{R_C} = \frac{V_m^{\,2}}{2R_C}$$

where *I* is the rms value of the ac output current through the load, *V* is rms value of ac voltage and V_m is its maximum value.

(*b*) power dissipated (in the form of heat) by the transistor itself *i.e.* its collector region. It may be called $P_{c(dc)}$.

Since, under zero-signal condition, there is no ac output power, all the power given to the transistor is wasted as heat. Hence, **a transistor dissipates maximum power under zero-signal condition**.

The power flow diagram of the transistor is as follows :



60.17. Power Rectangle

The output or collector characteristic of a *CE*-connected transistor is shown in Fig. 60.16 with centred *Q*-point for class-A operation. When input signal is applied, the *Q*-point shifts to positions Q_1 and Q_2 alternately. The output current varies around its quiescent value from maximum value of $I_{C(max)}$ to minimum value $I_{C(min)}$. Similarly, collector-emitter voltage varies from maximum value of $V_{CE(max)}$ to $V_{CE(min)}$ around its quiescent value of V_{CEQ}.

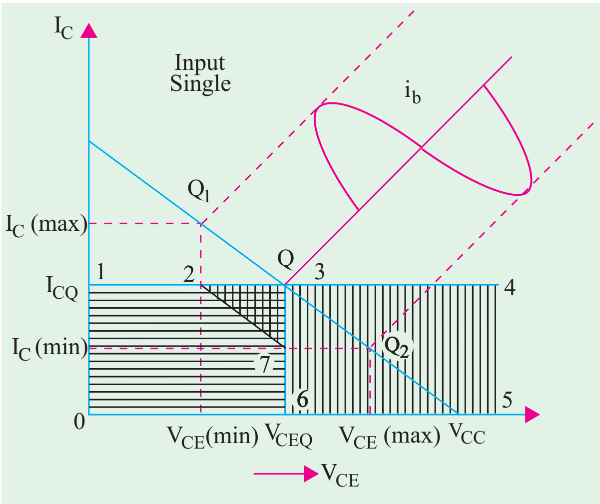


Fig. 60.16

Let us construct the various rectangles as shown in Fig. 60.16.

1. rectangle 0-1-4-5
   $= V_{CC} \times I_{CQ}$
   = total average power supplied to the circuit by V_{CC} battery
   $= P_{in(dc)}$

Now, $V_{CC} - V_{CEQ}$
   = voltage drop across load resistor R_C

2. rectangle 3-4-5-6 = $(V_{CC} — V_{CEQ})\, I_{CQ}$
   = power lost as heat in load resistor $R_C = I_{CQ}^2 R_C$

Now, V_{CEQ} is the voltage drop across the transistor itself *i.e.* potential difference between its collector and emitter as shown in Fig. 60.15 (*b*).

3. rectangle 0-1-3-6 = $V_{CEQ}.I_{CQ}$ = power delivered to transistor = $P_{tr(dc)}$
4. triangle 2-3-7 = ac power across $R_C = P_{o(ac)} = \text{I}^2 R_C$

   It can also be proved that

$$P_{o(ac)} = \frac{V_{CE(\max)} - V_{CE(\min)}}{2\sqrt{2}} \times \frac{I_{C(\max)} - I_{C(\min)}}{2\sqrt{2}}$$

$$= \frac{[V_{CE(\max)} - V_{CE(\min)}] \times [I_{c(\max)} - I_{c(\max)}]}{8}$$

5. area 0-1-2-7-6 = power dissipated by the collector region of the transistor
   $= P_{c(dc)}$.

Obviously, when there is no input signal, there is no output signal. Hence, $P_{o(ac)} = 0$, which means that area of triangle 2-3-7 is zero. In that case, the transistor collector will have to dissipate maximum power equal to the area of the rectangle 0-1-3-6. It is called ***worst-case*** condition of the transistor and equals quiescent power.

60.18. Power Efficiency

Fig. 60.17. shows the power rectangles and triangles of a class-A amplifier in a very simple way.

$P_{in(dc)}$ = areas $A + B + C$
$P_{o(ac)}$ = area B
$P_{c(dc)}$ = area C
$P_{Rc(dc)}$ = area A

Amplifier efficiency or circuit efficiency or overall efficiency.

$$\eta_{overall} = \frac{B}{A+B+C} = \frac{P_{o(ac)}}{P_{in(dc)}}$$

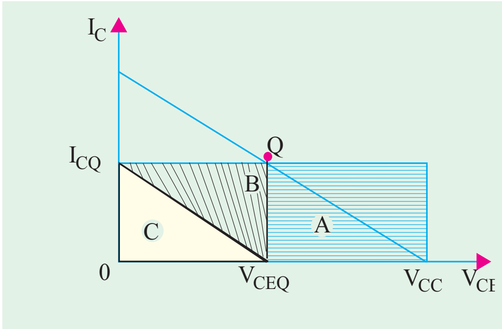


Fig. 60.17

The collector efficiency is given by

$$\eta_{overcall} = \frac{B}{B+C} = \frac{P_{o(ac)}}{P_{tr(dc)}}$$

Incidentally, it can be proved that $\eta_{overall} = 25\left[\frac{V_{CE(max)} - V_{CE(min)}}{V_{CC}}\right]$

Now, maximum value of $V_{CE} = V_{CC}$ and minimum value is = 0

$$\therefore \text{ maximum } \eta_{overall} = 25\left[\frac{V_{CC} - 0}{V_{CC}}\right]\% = 25\%$$

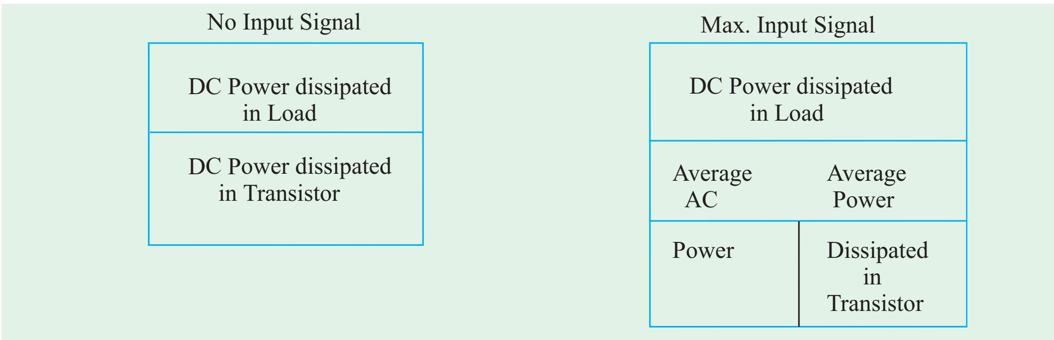


Fig. 60.18

Summary

In a direct-coupled class-A amplifier

1. maximum ac power equals half the power transistor can dissipate (or one-fourth of the total dc input power);
2. maximum ac power the transistor can dissipate is half the dc input power supplied by the battery;
3. the dc input power equals 4 times the ac output in load or twice the maximum power dissipated by the transistor.

The above facts have been illustrated with the help of power square shown in Fig. 60.18.

60.19. Maximum AC Power in Load

Fig. 60.19 (*a*) shows part of a base-driven *CE* amplifier with a collector load of R_C. Fig. 60.19 (*b*) shows its ac load line with centered *Q*-point. For the time being, we will neglect limitations of cut-off and saturation and assume (at least theoretically) that voltage and current swings down to zero are possible. Obviously, under such conditions, we will get the maximum possible ac output power.

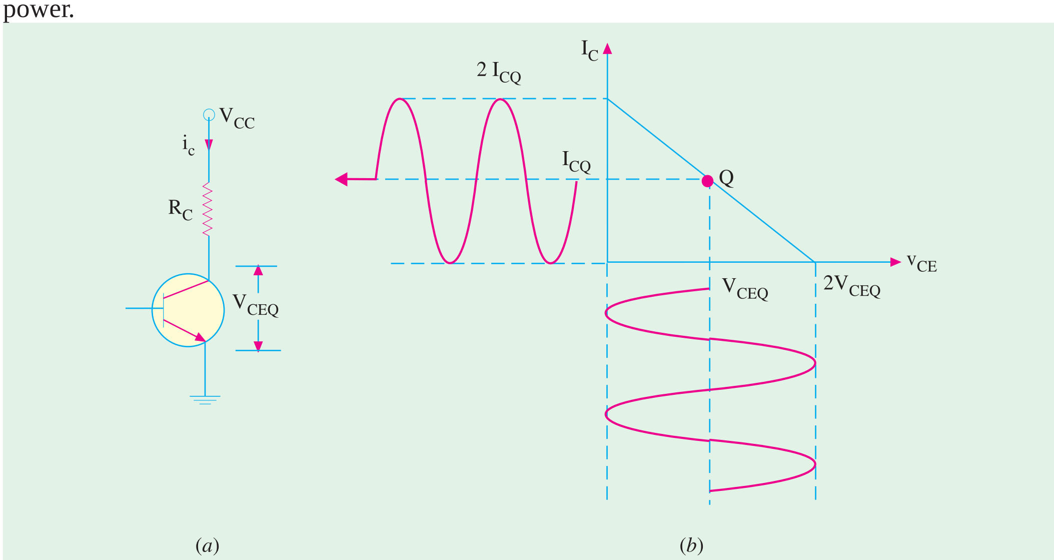


Fig. 60.19

As seen, collector current is a sine wave having peak-to-peak value of 2 I_{CQ} or a maximum value of I_{CQ} or an rms value of $I_{CQ}/\sqrt{2}$. Since it passes through R_C, it delivers an ac power of

$$P_{o(ac)} = (I_{CQ}/\sqrt{2})^2 R_C = 0.5 I_{CQ}^{\ 2} R_C$$

Similarly, ac collector-emitter voltage is a sine wave of peak-to-peak value 2 V_{CEQ} or peak value V_{CEQ} or rms value $V_{CEQ}/\sqrt{2}$. Since this sine wave is applied across R_C, the ac power can also be expressed as

$$P_{o(ac)} = \left(\frac{V_{CEQ}}{\sqrt{2}}\right)^2 / R_C = \frac{0.5\, V_{CEQ}{}^2}{R_C}$$

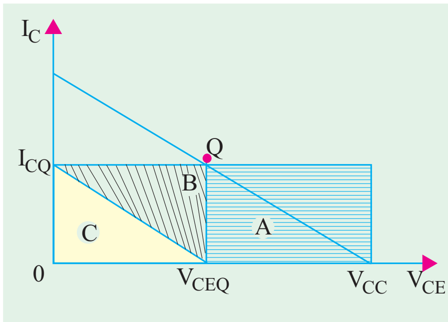


Fig. 60.20

Note. If there had been an unbypassed resistor R_E in the emitter, then ac load R_{ac} or $r_L = R_C + R_E$. Then, we would have used this value rather than R_C alone.

As seen from power rectangle diagram of Fig. 60.20, under maximum ac power condition

area *B* = area *C*

Also, area *A* = area *B* + area *C* = 2B

$$\therefore \quad \text{max imum}\ \eta_{overall} = \frac{B}{A+B+C}$$

$$= \frac{B}{2B+2B} = \frac{B}{4B} = 0.25 \quad \text{or} \quad 25\%$$

Example 60.4. *The 2N 1491 power transistor is used in a CE amplifier meant for class-A operation. If its zero-signal power dissipation is 10 W and ac output power is 3.5 W, find*

(a) *collector efficiency and* ***(b)*** *power rating of the transistor*

Solution. *(i)* $\eta_{coll} = \dfrac{P_{o(ac)}}{P_{tr(dc)}} = \dfrac{3.5}{10} = 0.35 =$ **35%**

(ii) Since zero-signal condition represents worst case condition for the transistor, it means that all the 10 W power is dissipated by it. Hence, transistor power rating is **10 W.**

Example 60.5. *For the class-A, CE amplifier circuit of Fig. 60.21, V_{CEQ} = 10 V and I_{CQ} = 500 mA. If collector i.e. output current varies by ± 250 mA when an input signal is applied at the base, compute*

(i) *total dc power taken by the circuit,* *(ii)* *dc power dissipated by the collector load,*
(iii) *ac power developed across the load,* *(iv)* *power delivered to the transistor,*
(v) *dc power wasted in transistor collector,* *(vi)* *overall efficiency.*
(vii) *collector efficiency.*

Solution. *(i)* $P_{in(dc)} = V_{CC} \cdot I_{CQ} = 20 \times 500 = 10^4 \text{ mW} =$ **10 W**

(ii) $P_{Rc(dc)} = I_{CQ}^2 R_C = 0.5^2 \times 20 = 5$ **W**

(iii) $P_{o(ac)} = I^2 R_C$

Now, maximum value of output ac current is 250 mA = 0.25A.

Hence, rms value $I = 0.25/\sqrt{2}$ A.

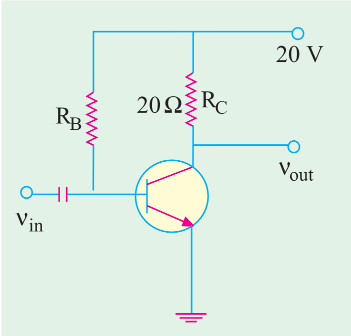


Fig. 60.21

$\therefore \quad P_{o(ac)} = (0.25/\sqrt{2})^2 \times 20 =$ **0.625 W**

(iv) $P_{tr(dc)} = 10 - 5 =$ **5 W**

(v) $P_{c(dc)} = 5 - 0.625 =$ **4.375 W**

(vi) $\eta_{overall} = \dfrac{0.625}{5} \times 100 =$ **6.25%**

(vii) $\eta_{coll} = \dfrac{0.625}{5} \times 100 =$ **12.5%**

It is seen that due to resistive load in the collector, efficiency of the circuit is very low.

Example 60.6. *For a class-A amplifier, V_{CE}(max) = 25V, V_{CE}(min) = 5V, V_{CC} = 30V. Find its overall efficiency.*

Solution. As seen from Art. 10.18

$$\% \, \eta_{overall} = 25\left[\frac{V_{CE(max)} - V_{CE(min)}}{V_{CC}}\right] = 25\left(\frac{25-5}{30}\right) = \mathbf{16.7}$$

60.20. Transformer-Coupled Class-A Amplifier

The main reason for the poor efficiency of a ***direct-coupled*** class-A amplifier is the large amount of dc power that the resistive load in collector must dissipate. This problem can be solved by using a suitable transformer for coupling the load (say, a speaker) to the amplifier stage as shown in Fig. 60.22. Since the load is not ***directly*** connected to the collector terminal, the dc collector current does not pass through it. In an ideal transformer, primary winding resistance is zero. Hence, dc power loss in the load is zero. In practice, however, there is a small dc resistance of the primary winding which does absorb some power though much less than a direct-coupled load.

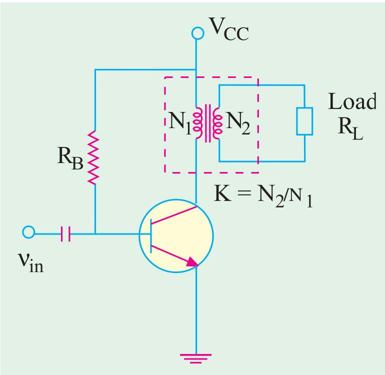


Fig. 60.22

In short, what the transformer does is to substitute ***ac load*** in place of ***ohmic*** or dc load.

The secondary load R_L when referred to primary becomes

$$R_L' = R_L / K^2 = a^2 R_L$$

where K = voltage transformation ratio$=N_2/N_1=V_2/V_1$

a = turns ratio $N_1/N_2 = 1/K$

Since a is usually made much more than unity or K is much less than unity, R_L can be made to look much bigger than what it actually is

In an ideal transformer, there is no primary drop, hence $V_{CC} = V_{CEQ}$. Now, all the power supplied by V_{CC} is delivered to the transistor. Hence, the overall and collector efficiencies become equal.

$$\eta_{overall} = \frac{P_{o(ac)}}{V_{CC}\, I_{CQ}} = \frac{P_{o(ac)}}{V_{CEQ} . I_{CQ}}$$

Power Diagram

The power distribution for a transformer-coupled class-A amplifier is shown in Fig. 60.23. Since load loss is zero, the triangle A of Fig. 60.17 is non-existent. Moreover, the load line of Fig. 60.17 becomes a.c. load line in Fig. 60.23. Consequently, $V_{CEQ} = V_{CC}$. Area of triangle B equals that of triangle C. Also, sum of A and B represents power delivered to the transistor.

$$\therefore \quad \eta_{overall} = \frac{B}{B+C} = \frac{B}{2B} = 0.5 \text{ or } 50\%$$

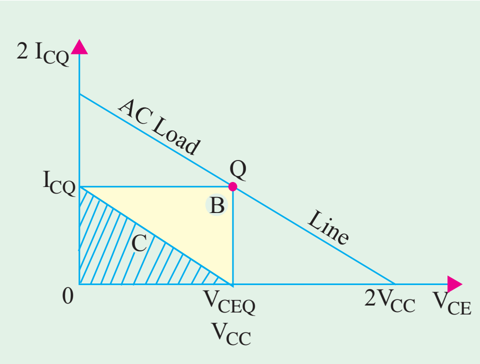


Fig. 60.23

It can be proved that maximum possible overall efficiency and the maximum possible collector efficiency of a class-A amplifier using an output transformer are both 50%.

In general, overall efficiency of a transformer-coupled class-A amplifier is given by

$$\%\eta = 50\left[\frac{V_{CE(max)} - V_{CE(min)}}{2V_{CC}}\right]^2 = 50\left[\frac{V_{CE(max)} - V_{CE(min)}}{V_{CE(max)} + V_{CE(min)}}\right]^2$$

Obviously, larger the value of $V_{CE(max)}$ and smaller that of $V_{CE(min)}$ closer the efficiency to the theoretical limit of 50%.

Proof

The conditions for the development of maximum ac power are shown in Fig. 60.24. It must be kept in mind that here

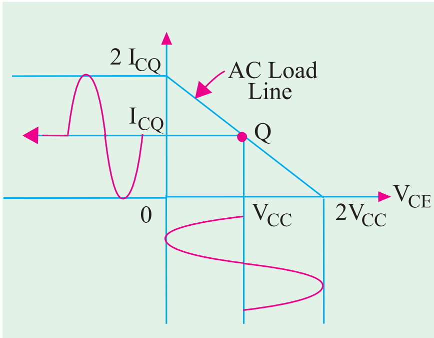


Fig. 60.24

$$V_{CEQ} = V_{CC}$$

Now, average power delivered by the battery

$$P_{in(dc)} = V_{CC} \cdot I_{CQ}$$

Whole of the power is given to the transistor.

rms output voltage $= \dfrac{V_{CC}}{\sqrt{2}}$

rms output current $= \dfrac{I_{CQ}}{\sqrt{2}}$

$\therefore$ maximum $P_{o(ac)} = \dfrac{V_{CC}}{\sqrt{2}} \times \dfrac{I_{CQ}}{\sqrt{2}} = \tfrac{1}{2} V_{CC} . I_{CQ}$

= half the input ac power

Hence, maximum value of overall efficiency

$$\eta_{overall} = \frac{P_{o(ac)}}{P_{in(dc)}} = \frac{V_{CC} \cdot I_{CC}/2}{V_{CC} \cdot I_{CQ}} = \frac{1}{2} \text{ or } 0.5 \text{ or } 50\%$$

$$\eta_{coll} = \frac{P_{o(ac)}}{P_{tr(dc)}}$$

Example 60.7. *The optimum load resistance for a certain transistor is 200 Ω. What is the turns ratio (N_1/N_2) of a transformer required to couple an 8-Ω loud-speaker to the transistor ?*

Solution. $R_L' = a^2 R_L$ ∴ $200 = a^2 \times 8$ or $a = \mathbf{5}$

Hence, it should be a 5 : 1 *step-down* transformer.

Example 60.8. *In a transformer-coupled class-A amplifier $V_{CE(max)} = 27$ V and $V_{CE(min)} = 3$V. Compute its overall efficiency.*

Solution. $\eta_{overall} = 50\left(\frac{27-3}{27+3}\right)^2 = \mathbf{32\%}$

Example 60.9. *For the transformer-coupled optimally-biased class-A amplifier shown in Fig. 10.25, find*

(a) transformer turns ratio *(b) collector current* *(c) transistor power rating*

Solution. As shown in Fig. 60.25, if V_2 is the rms secondary voltage, then

$$P_{load} \text{ or } P_{o(ac)} = \frac{V_2^2}{R_L} = \frac{(V_{2m}/\sqrt{2})^2}{R_L} = \frac{V_{2m}^2}{R_L}$$

where V_{2m} is the maximum value of secondary voltage.

∴ $V_{2m} = \sqrt{2\,RP_{load}} = \sqrt{2 \times 4 \times 4.5} = 6\text{ V}$

Now, peak, value of primary voltage is

$V_{1m} = a \,.\, V_{2m} = 6\,a$

This also represents the peak value of collector voltage. For optimally-biased circuit, peak value of collector-emitter voltage equals V_{CC} = 30V.

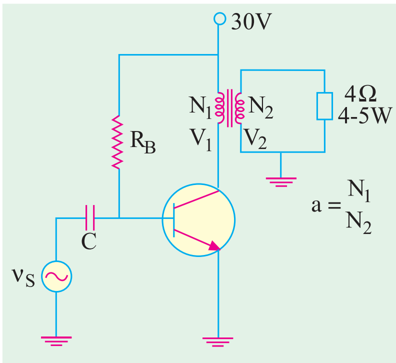


Fig. 60.25

∴ $6a = 30$ or $a = 5$ ∴ $N_1/N_2 = \mathbf{5}$

(a) Hence, it is a step-down transformer with a turns ratio of **5 : 1**

(b) The overall efficiency is 50%. Hence, for a load power of 4.5 W, total dc input power supply must be 4.5/0.5 = 9 W

∴ $V_{CC}I_C = P_{in(dc)} = 9$W or $30\,I_C = 9000$ mW ∴ $I_C = \mathbf{300\ mA}$

(c) Worst case condition for the transistor is when there is no input signal. In that case, transistor has to dissipate the entire input. Therefore, transistor power rating = **9W.**

Example 60.10. *For the optimally-biased transformer -coupled class-A amplifier, maximum collector current change is 100 mA. Find the power transferred to a 4-W speaker load if it is **(a)** directly-coupled **(b)** transformer-coupled to the transistor. Find also the turn ratio of the transformer required.* **(Applied Electronics, Kerala Univ.)**

Solution. (a) Direct-coupled Load [Fig. 60.26 (a)]

It should be remembered that for an optimally-biased class-A amplifier, peak change in collector-emitter voltage equals V_{CC} = 10 V.

RMS value of ac output current I = $(100/\sqrt{2})$ mA

Average power delivered to the speaker

$$= I^2 R_L = \left(\frac{100}{\sqrt{2}} \times 10^{-3}\right)^2 \times 4 = 0.02\text{W} = \textbf{20 mW}$$

(*b*) Transformer-coupled Load

Now, $\Delta V_{CE} = V_{CC} = 10$ V : $\Delta I_{CQ} = 100$ mA

If $R_L{}'$ is the secondary load reflected into the primary, then

$$R_L{}' = \frac{\Delta V_{CE}}{\Delta I_{CQ}} = \frac{10\text{ V}}{100\text{ mA}} = 100\,\Omega$$

Now, $a^2 R_L = R_L{}'$

$\therefore \quad a_2 \times 4 = 100,$

$a = 5$

Hence, it is a step-down transformer with a turns ratio of 5 : 1

Peak value of secondary voltage = 10 × 1/5 = 2 V

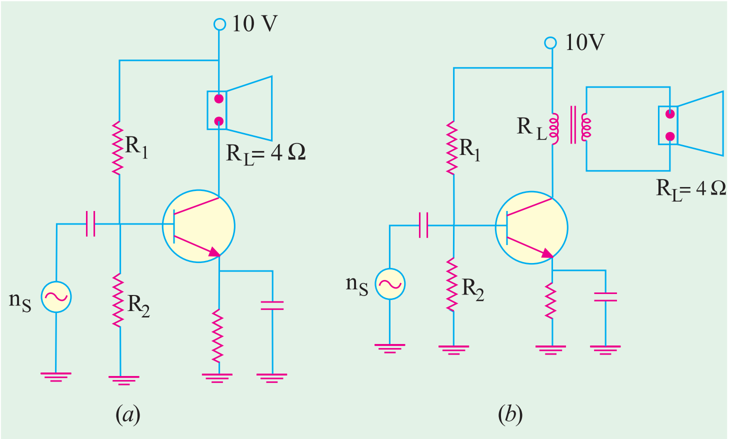


Fig. 60.26

Peak value of secondary current = 2 / 4 = 0.5 A

RMS value = $0.5/\sqrt{2}$ A

$$\text{Average power transferred to the speaker} = \left(\frac{0.5}{\sqrt{2}}\right)^2 \times 4 = 0.5\text{ W} = \textbf{500 mW}$$

Obviously, power transferred has increased 500/20 = 25 times *i.e.* $a^2 = (N_1/N_2)^2$ times where *a* is transformer primary-to-secondary turn ratio *i.e.* $a = N_1/N_2$.

Example 60.11. *A class-A amplifier shown in Fig. 60.27 operates from V_{CC} = 20 V, draws a no-signal current of 5A and feeds a load of 40 Ω through a step-up transformer of N_2/N_1 = 3.16. Find*

(a) *whether the amplifier is properly matched for maximum power transfer,*

(b) *maximum ac signal power output,* ***(c)*** *maximum dc power input,*

(d) *conversion efficiency at maximum signal input.*

(Electronic Circuits, Gauhati Univ. 1990)

Solution. (*a*) Here, $a = N_1/N_2 = 1/3.16$

$$R_L{}' = a^2 R_L = (1/3.16)^2 \times 40 = \textbf{4 Ω}$$

Also, $$R_L{}' = \frac{V_{CC}}{I_{CQ}} = \frac{20}{5} = \textbf{4Ω}$$

Since, the two resistance values are the same, the amplifier is properly-matched.

(*b*) As seen from Art. 60.20, Maximum value of

$$P_{o(ac)} = \frac{1}{2} V_{CC}\, I_{CQ}$$

$$= \frac{1}{2} \times 20 \times 5 = \textbf{50 W}$$

(*c*) The dc power input

$= V_{CC} I_{CQ} = 20 \times 5 =$ **100 W**

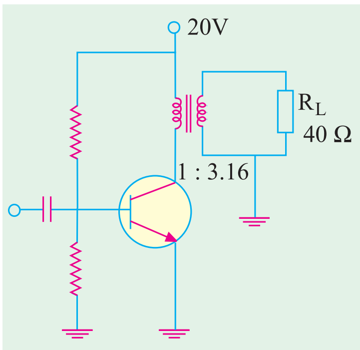


Fig. 60.27

(*d*) $\eta = \frac{50}{100} \times 100 =$ **50%**

60.21. Class-B Amplifier

Biasing condition for class-B operation has been shown both on current transfer characteristic and output characteristic for *CE* configuration in Fig. 60.28.

As seen, the transistor has been biased to cut-off. It remains FR-biased for only half-cycle of the input signal. Hence, its conduction angle is only 180°. It is obvious that with zero signal, its collector current is zero.

Characteristics

1. Since negative half-cycles are totally absent from the output, the signal distortion is high as compared to class-A amplifiers.
2. Since input voltage is large (upto V_{CC}), voltage amplification is reduced.
3. Zero-signal input represents worst condition for class-A amplifiers but best condition for class-B amplifiers.
4. In class-B amplifiers, transistor dissipates more power with increase in signal strength but opposite is the case in class-A amplifiers.
5. Average current in class-B operation is less than in class-A, hence power dissipated is less. Consequently, maximum circuit (or overall) efficiency of a class-B amplifier is 78.5% when peak signal makes $V_{CE(min)} = 0$. In general

$$\eta_{overall} = 78.5\left[1 - \frac{V_{CE(\text{min})}}{V_{CC}}\right]\%$$

6. The half-sinewave type of collector current contains very pronounced ***even harmonics*** (particularly the second one). These impulses can be rendered useful either by employing push-pull circuit (Art. 60.24) or by using tuned amplifiers (Art. 60.29).

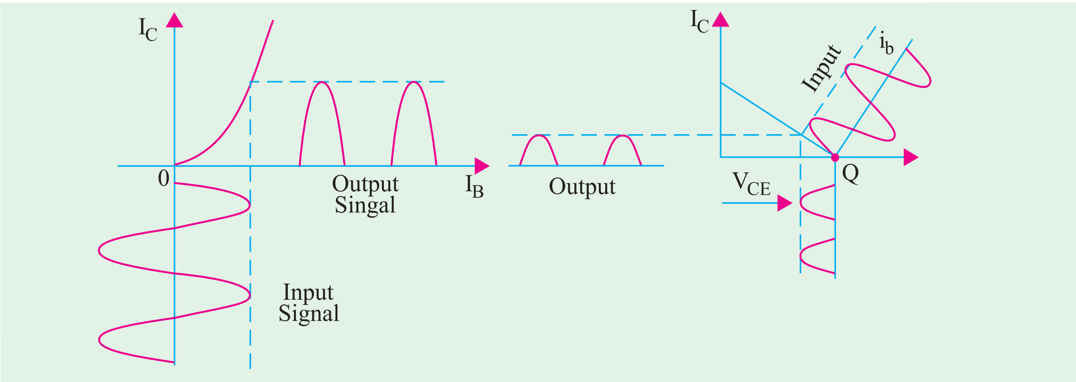


Fig. 60.28

60.22. Power Relations for Class-B Operation

(*i*) Input DC Power : $P_{in(dc)} = V_{CC}\, I_{dc}$

where I_{dc} is the average or dc current drawn from the supply.

If $I_{C(max)}$ is the maximum or peak value of collector or output current, then

$$I_{dc} = \frac{I_{C(\text{max})}}{\pi} \qquad \therefore \qquad P_{in(dc)} = V_{CC}\frac{I_{C(\text{max})}}{\pi}$$

(*ii*) DC Power Loss in Load : $P_{Rc(dc)} = I_{dc}^{\,2}\, R_C$ where $I_{dc} = I_{C(max)}/\pi$

(iii) **AC Power Output in Load** : $P_{o(ac)} = I^2 R_C = \frac{V^2}{R_C} = \frac{V_m^{\ 2}}{2R_C}$

where I = rms value of output ac current
V = rms value of output ac voltage
V_m = maximum value of output ac voltage

(iv) **DC Power Loss in Collector Region or Transistor**

$$P_{c(d)} = P_{in(dc)} - P_{Rc(dc)} - P_{o(ac)}\,; \quad \eta_{overall} = \frac{P_{o(ac)}}{P_{in(dc)}}$$

60.23. Maximum Values

The operation for maximum signal input is shown in Fig. 60.29.

Here,

$$I_{dc} = \frac{I_{C(\max)}}{\pi} \qquad \therefore \quad P_{in(dc)} = V_{CC}.I_{dc} = \frac{V_{CC}.I_{C(\max)}}{\pi}$$

RMS value of output or collector current

$$= \frac{I_{C(max)}}{\sqrt{2}}$$

RMS value of output voltage = $\frac{V_{CC}}{\sqrt{2}}$

Hence,ac output power during half-cycle

$$= \frac{1}{2} \times \frac{V_{CC}}{\sqrt{2}} \frac{I_{C(\max)}}{\sqrt{2}}$$

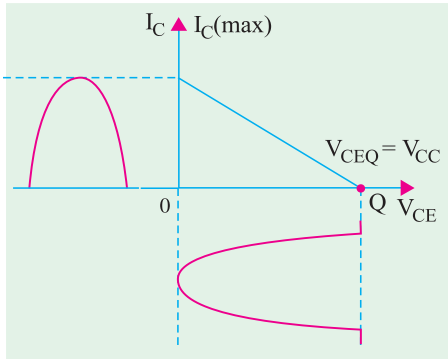


Fig. 60.29

The factor $\frac{1}{2}$ comes in because power is produced during one half-cycle only.

$$P_{o(ac)} = \frac{1}{4}.V_{CC}.I_{C(max)}$$

$$\therefore \quad \eta_{overall} = \frac{P_{o(ac)}}{P_{in(dc)}} = \frac{\pi}{4} = 0.785 \text{ or } \mathbf{78.5\%}$$

Example 60.12. *In a class-B amplifier, $V_{CE(min)}$ = 2V and V_{CC} = 15 V. Find its overall efficiency*

Solution. As seen from Art 60.21, % η = 78.5 $\left(1 - \frac{2}{15}\right)$ = **68%**

60.24. Class-B Push-Pull Amplifier

It employs two identical transistors operating as a ***single-stage of amplification.*** As shown in Fig. 60.30, the base of the two *CE*-connected transistors have been connected to the opposite ends of the secondary of the input transformer T_1 and collectors to the opposite ends of the primary of the output transformer T_2. For getting a balanced circuit, the two emitters have been returned to the centre tap of T_1 secondary and V_{CC} connected to the centre tap on the primary of T_2. Since zero bias is required for cut-off, the two bases have been earthed. A push-pull amplifier is sometimes referred to as ***balanced amplifier.***

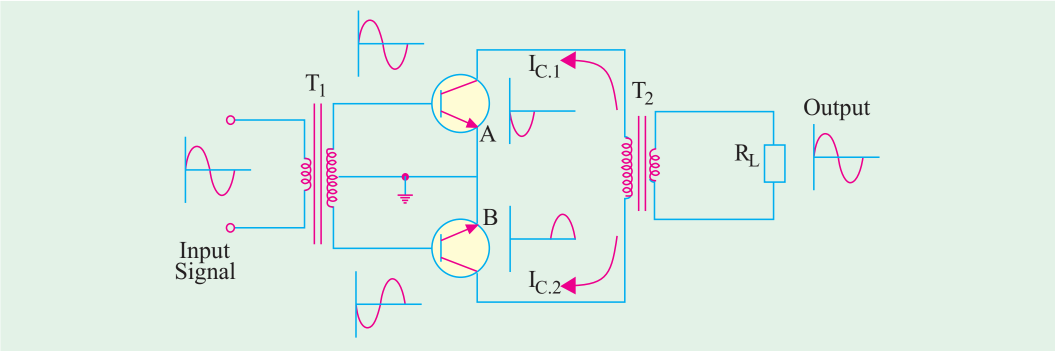


Fig. 60.30

Principle of Operation

It is seen from Fig. 60.30 that transistor *A* and *B* are driven by two input signals which are 180° out of phase with each other. These two signals are produced by T_1.

Transistor *A* takes positive half-cycles of the signal whereas *B* handles negative half-cycles. When the two outputs are combined, an almost undistorted output waveform is produced as seen from Fig. 60.31.

In Fig. 60.31, the transfer characteristic of transistor *B* has been plotted upside down with respect to that of *A* in order to get the combined output.

Detailed operation is as under :

During the positive half-cycle of the signal, *A* is turned ON because its base is driven positive. It draws collector current $I_{C\text{-}1}$ in the upward direction from V_{CC}. Meanwhile, transistor B remains OFF because its base has negative voltage. Hence, $I_{C\text{-}2} = 0$. Obviously, one positive half-cycle of the output signal appears across secondary load R_L of T_2.

During negative half-cycle of the input signal, *B* conducts whereas *A* remains OFF. Hence, $I_{C\text{-}2}$ is taken by B but $I_{C\text{-}1} = 0$. Now, negative output half-cycle is produced across R_L because $I_{C\text{-}2}$ is pulled down through secondary of T_2. It is obvious that in the absence of input signal, neither *A* nor *B* draws any collector current. Hence, there is no drain on V_{CC} battery.

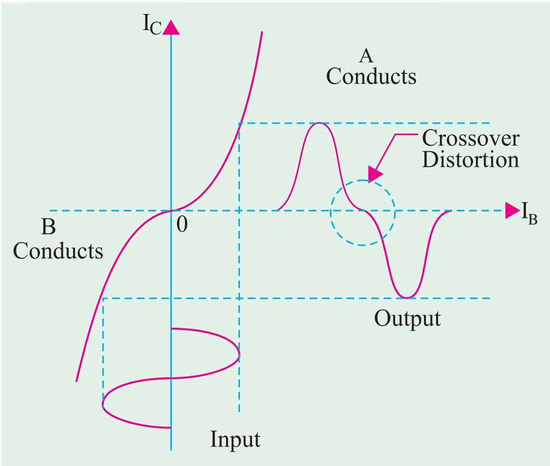


Fig. 60.31

Advantages

1. It has high efficiency, theoretical limit being 78.5%. It is primarily due to the fact that there is ***no power drawn by the circuit under zero-signal condition.***
2. Since in push-pull arrangement, 180° phase difference exists between even-order harmonics produced by each transistor, they cancel out thereby giving an almost distortion-free output. This automatic cancellation of all even-order harmonics from the output current makes class-B push-pull amplifiers highly desirable for ***communication sound equipment.***
3. This double-ended class-B amplifier provides practically four times the power supplied by a single-ended amplifier provided signal load resistance remains the same.

4. The dc components of the two collector currents through the two halves of the primary of T_2 flow in ***opposite directions*** so that net dc magnetisation of the transformer core is almost nil. Hence, distortions due to the effect of dc magnetic saturation of the trans former core are eliminated. Moreover, smaller size core can be used due to very small net core flux.

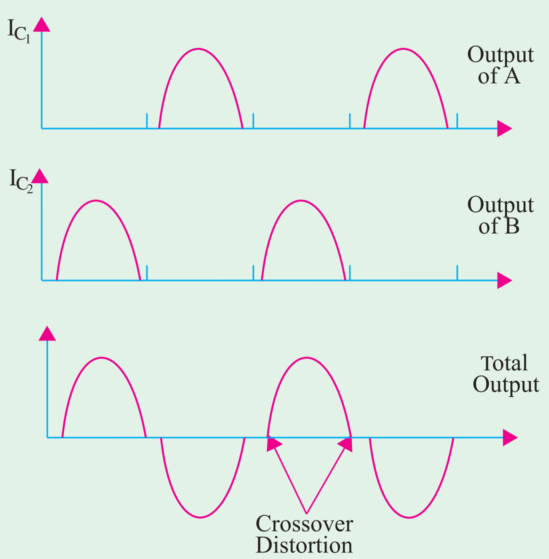


Fig. 60.32

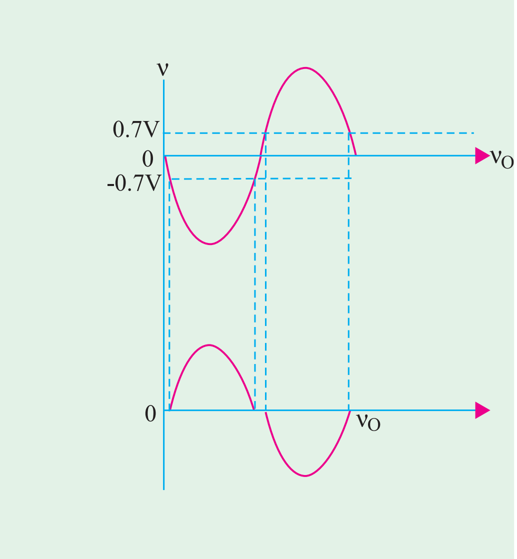


Fig. 60.33

Uses

Class-B push-pull amplifiers are extensively used for audio work in portable record players, as stereo amplifiers and in high-fidelity radio receivers.

60.25. Crossover Distortion

In class-B push-pull operation, there is severe distortion at very low signal level because

(*a*) bases of the transistors do not turn ON at 0 V but at 0.3 V for Ge and 0.7 V for Si

(*b*) there is non-linearity in the low-signal area.

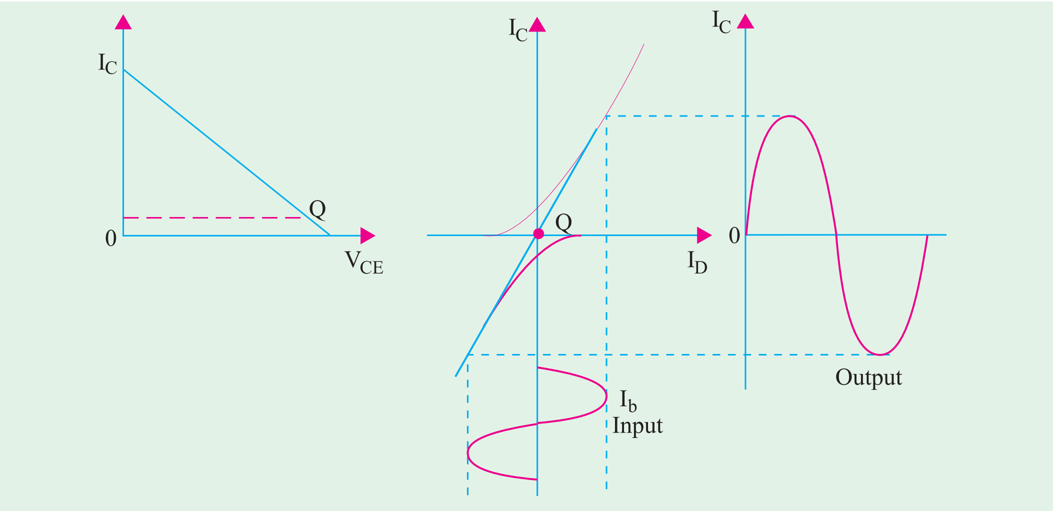


Fig. 60.34

In simple words, crossover distortion occurs as a result of one transistor cutting off before the other begins conducting. The effect is illustrated in Fig. 60.32. For silicon transistors, there is 2 × 0.7 = 1.4 V ***dead zone*** on the input signal within which neither transistor is turned ON and output is zero (Fig. 60.33).

The distortion so introduced is called ***crossover distortion*** because it occurs during the time operation ***crosses over from one transistor to the other in the push-pull amplifier.*** The same was shown earlier in Fig. 60.31 by using transfer characteristics of the two transistors.

Crossover distortion can be eliminated by applying slight forward bias to each emitter diode. It, in effect, means locating the *Q*-point of each transistor slightly above cut-off as shown in Fig. 60.34 so that each one operates for more than one half-cycle. Strictly speaking, it results in class-AB operation because each transistor may operate for about 200° (instead of 180°). However, for all practical purposes, it is still regarded as class-B push-pull operation.

60.26. Power Efficiency of Push-Pull Amplifiers

Consider the circuit shown in Fig. 60.35.

Since the two transistors are identical, $I_{C.1} = I_{C.2} = I_C$

$\therefore \quad I_C = I_m/\pi$

Total dc supply current I_{dc} for the two transistors is

$$I_{dc} = 2I_C = 2\frac{I_m}{\pi}$$

$$\therefore \quad P_{in(dc)} = V_{CC} \times I_{dc}$$

$$= \frac{2I_m}{\pi} V_{CC}$$

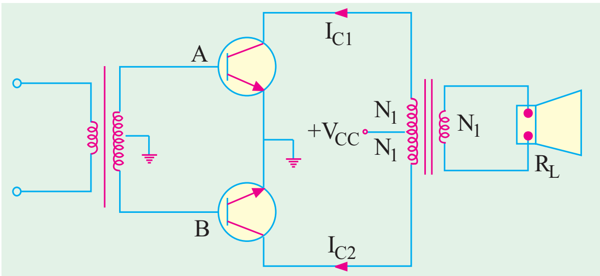


Fig. 60.35

For the sake of simplicity, we will assume transformer turns ratio as $(N_1 + N_1) : N_1$ so that for each transistor, turns ratio is $N_1 : N_1$ *i.e.* 1 because each uses half the secondary of the output transformer.

If V_m is the peak voltage at either collector, then peak load voltage is also V_m. The peak current in the load is I_m. Then, ac power delivered to the load is

$$P_{o(dc)} = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}} = \frac{V_m I_m}{2}$$

The total collector dissipation for the two transistors is

$$2.P_{c(dc)} = P_{in(dc)} - P_{o(dc)} = \frac{2I_m V_{CC}}{\pi} - \frac{V_m I_m}{2} = 2I_m\left(\frac{V_{CC}}{\pi} - \frac{V_m}{4}\right)$$

$$\eta_{overall} = \frac{P_{o(ac)}}{P_{in(dc)}} \times 100 = \frac{V_m I_m / 2}{2I_m / \pi} \times 100 = \frac{\pi}{4} \cdot \frac{V_m}{V_{CC}} \times 100$$

Under ideal condition of maximum power in the load, $V_m = V_{CC}$

$$\therefore \quad \text{maximum } \eta_{overall} = \frac{\pi}{4} \times 100 = 78.5\%$$

Same is the value of collector efficiency.

60.27. Complementary Symmetry Push-Pull Class-B Amplifier

The push-pull amplifier discussed in Art. 60.24 suffers from two disadvantages :

(*i*) it requires a bulky and expensive output transformer (*ii*) it requires two out-of- phase input signals which necessitates an input centre-tapped transformer or phase inverter. It makes the driver circuitry quite complicated.

The complementary symmetry amplifier eliminates these two disadvantages while retaining the advantages of push-pull configuration.

As we know, a standard class-B push-pull amplifier requires two power transistors of the ***same type*** with closely-matched parameters. But the chief requirement of a complementary amplifier is a pair of closely-matched but ***oppositely-doped*** power transistors. The term 'complementary' arises from the fact that one transistor is *PNP* type and the other is of *NPN* type. They have ***symmetry i.e.*** both are made with the same material and technology and have the same maximum rating.

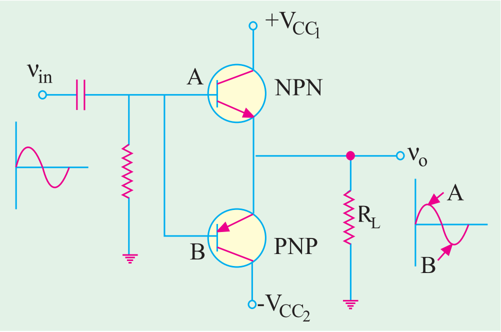


Fig. 60.36

An elementary complementary symmetry class-B push-pull amplifier is diagrammed in Fig. 60.36. The two transistors are complementary to each other and operate as emitter-follower amplifiers. The input is capacitively-coupled whereas output is direct-coupled.

With no input signal, neither transistor conducts and, therefore, current through R_L is zero.

When input signal is positive-going, transistor *A* is biased into conduction whereas *B* is driven into cut-off. When the signal is negative-going. *A* is turned OFF while *B* conducts. Obviously, this circuit is a push-pull amplifier because ***turning one transistor ON turns the other OFF.***

The circuit possesses the essential characteristics of an emitter follower *i.e.* unity voltage gain, no phase inversion and input impedance much higher than output impedance.

The circuit shown in Fig. 60.36 requires two dc supply batteries. Only one dc battery would be enough if ***'totem-pole'*** circuit configuration is used.

Due to the elimination of transformer both the high and low-frequency responses of the circuit are extended apart from reduced cost and weight.

60.28. Class-C Amplifier

In such amplifiers, the active device *i.e*. the transistor is biased much beyond cut-off. Hence,

1. output current flows only during a part of the possible half-cycle of the input signal,

2. there is no output current flow during any part of the negative half-cycle of the input signal,

3. output signal has hardly any resemblance with the input signal. It consists of short pulses only,

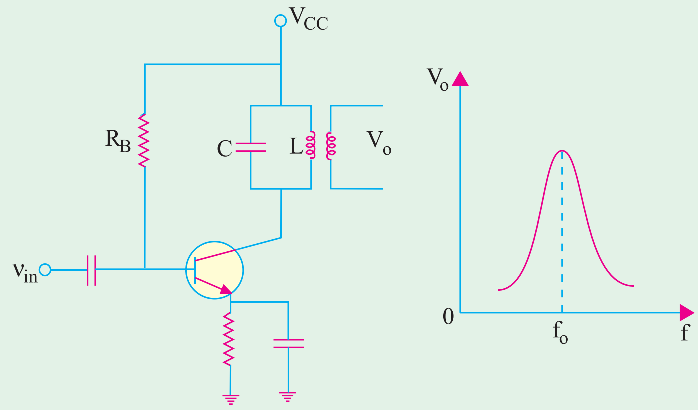
4. class-C amplifiers have high circuit efficiency of about 85 to 90%.

Because of his distortion, class-C amplifiers are not used for audio-frequency work. They are used for high-power output at radio frequencies (*i.e.* RF amplifiers) where harmonic distortion can be removed by simple circuits. In reality, they are used as high-frequency power switchers in radio transmitters rather than as amplifiers.

60.29. Tuned Amplifier

The gain of a transistor amplifier depends directly on the value of its load impedance. Such a high impedance can be obtained by using a high-*Q* tuned or resonant *LC* circuit as load (Fig. 60.37). The frequency response curve of the amplifier assumes the same shape as the resonance curve of the tuned circuit. Obviously, only a narrow band of frequencies around the resonant frequency f_o would be amplified well whereas other frequencies would be discriminated against.

Non-linear distortion is eliminated because of high selectivity of the load impedance. Hence, output is nearly sinusodial. With the removal of distortion, high amplifier efficiency can be achieved by operating the transistor in its nonlinear region.




Tuned amplifier

Fig. 60.37

60.30. Distortion in Amplifiers

Amplifiers are supposed to produce an output which does not differ from the input in any respect except amplitude *i.e.* the output is expected to be larger than the input. In actual practice, it is impossible to construct such an ideal amplifier whose output is an exact duplication or replica of the input. The output is always found to differ from the input either in its waveform or frequency content. This difference between the output and input of an amplifier is called distortion.

The amplifier distortions may be divided into two broad categories depending on the region of the characteristic used by the transistor and the associated circuit and device reactances.

(*a*) non-linear distortion

This occurs when transistor operates in the non-linear region of its characteristic.

(*i*) when we visualize the signal in time domain, it is called amplitude distortion or waveform distortion;

(*ii*) when we think of the signal in the frequency domain, it is called harmonic distortion.; This distortion occurs when input signal is of one frequency, say, a pure sine wave.

(*iii*) Intermodulation (IM) distortion—when input signal has more than one frequency (like speech).

Non-linear distortion occurs in the case of large-signal inputs when the active device is driven into the non-linear regions of its characteristic.

(*b*) linear distortion

It occurs even when the active device is ***working on linear part of its characteristic with small-signal inputs***. It is primarily due to frequency-dependent reactances associated with the circuit or active device itself and occurs when input signal is composite *i.e.* has signals of different frequencies (say, fundamental and its harmonics). However, output contains no frequencies other than those at the input. It may be further subdivided into :

(*i*) ***frequency distortion***—due to unequal amplification of different frequencies present in the input signal;

(*ii*) ***phase or delay distortion***—due to unequal phase shift of various signal components.

60.31. Non-Linear Distortion

Fig. 60.38 gives time-domain view of this distortion when it is called ***amplitude distortion***. As seen, the positive half-cycle of the input signal has been amplified more than its negative half-cycle. Consequently, waveshape of the output signal differs from that of the input signal. As shown below, it is due to the appearance of new frequencies (called harmonics) at the output which are not present in the input.

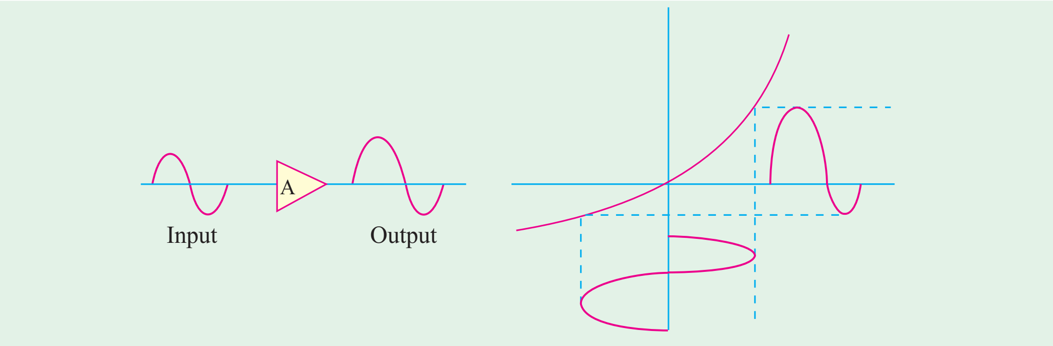


Fig. 60.38

The frequency-domain view of non-linear distortion is shown in Fig. 60.39. The input is a single-frequency (f_1) signal but output signal contains dc component and different harmonics *i.e.* frequencies which are harmonically related to each other. These harmonics are an integral multiple of the input signal frequency. Consequently, the output is distorted—the magnitude of distortion depending on the strength and number of these harmonics.

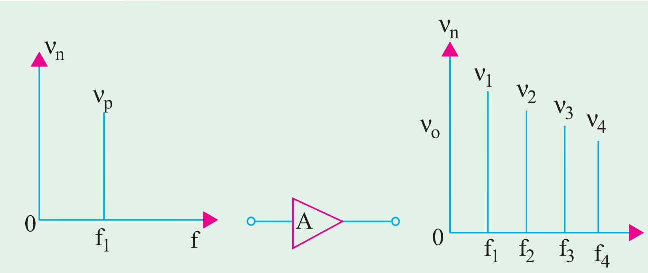


Fig. 60.39

In audio amplifiers used for amplification of speech or music, lesser the harmonic distortion, the better. For speech, harmonic distortion should not exceed 10% otherwise intelligibility will suffer. High-fidelity amplifiers have harmonic and *IM* distortion of less than 1 per cent.

60.32. Intermodulation Distortion

It occurs when input signal (like speech) consists of ***more than one frequency***. It is also a type of non-linear distortion which generates frequency components not harmonically related to the signal frequencies. Suppose, an input signal contains two frequencies f_1 and f_2. The output signal will contain their harmonics *i.e.* f_1, $2f_1$, $3f_1$ etc. and f_2, $2f_2$, $3f_2$ etc. In adddition, there would be components $(f_1 + f_2)$ and $(f_1 - f_2)$ and also the sum and difference of the harmonics. These sum and difference frequencies are called intermodulation (*IM*) frequencies and are quite undesirable in amplifiers because they subtract from original intelligence. Since *IM* frequencies are not harmonically related to the signal, they are easily detected by human ear as noise. Hence, great care is taken to minimize them particularly in hi-fi audio amplifiers.

60.33. Frequency Distortion

It occurs even when the device is working with small-signal inputs over linear region of its characteristic. It is basically due to change in the amplifier gain with frequency *i.e.* the different input signal frequencies are amplified by different amounts.

Suppose the input signal has two frequencies of 50 Hz and 100 Hz. If they are equally amplified, their resultant output wave is as shown in Fig. 60.40.

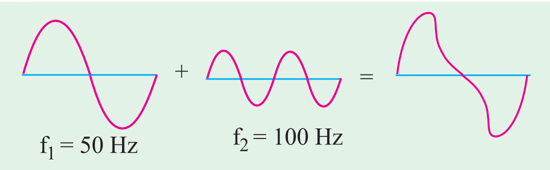


Fig. 60.40

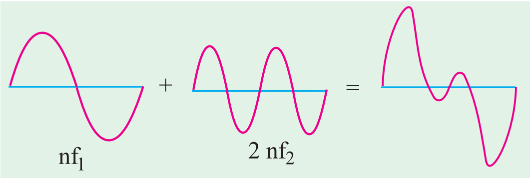


Fig. 60.41

Suppose that the amplifier amplifies the first frequency n times and the second one 2n times. Then their frequency-distorted output would be as shown in Fig. 60.41.

This distortion is due to the various frequency-dependent reactances (both capacitive and inductive) associated either with the circuit or the active device itself. In the case of audio signals the frequency distortion leads to a change in the quality of sound. Hence, in the design of untuned or wide-band amplifiers, special steps are taken to reduce variation of gain with signal frequency.

60.34. Phase or Delay Distortion

Phase distortion is said to take place when phase angles between the component waves of the output are not the same as the corresponding angles of the input. These changes in phase angles are also due to frequency-dependent capacitive and inductive reactances associated with the circuit and the active device of the amplifier.

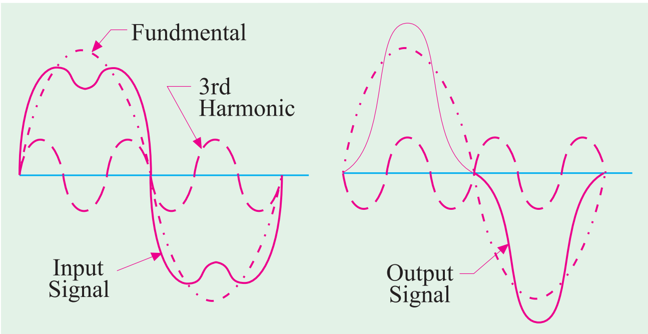


Fig. 60.42

As seen from Fig. 60.42, there has been a phase shift in the third harmonic. Hence, the resultant wave so obtained is entirely different from the input wave.

This type of distortion which is due to the non-uniform phase shift of different frequency components, is difficult to eliminate. It should be noted that if all the frequency components in a signal are shifted in phase by an integral multiple of 180°, the resultant output waveform is not changed, although the polarity of the wave may be altered but changes in polarity do not constitute distortion.

Fortunately, the human ear is unable to distinguish phase difference (though eye can) and is thus not sensitive to this distortion. Consequently, phase distortion is of no practical significance in audio amplifiers. But in amplifiers used in television sets (video amplifiers) and other systems where ear is not the final receiver, elimination of phase distortion is important.

60.35. Noise

In general , it may be defined as any kind of unwanted signal not derived from or related to the input signal. Just as distortion is the limiting factor in the amplification of large signals, noise is the limiting factor in the case of small signals.

The signal-to-noise (S/N) ratio should be high for good signal intelligibility. Since all amplifiers contribute some noise of their own to the signal being processed, their output S/N is bound to be less than their input S/N. High quality amplifiers are designed to have an output S/N as close to input S/N as possible. The amplifier performance is measured in terms of noise factor given by

Noise factor, $F = \dfrac{\text{input } S/N}{\text{output } S/N} = \dfrac{S_i/N_i}{S_0/N_0}$; obviously, ***F* is greater than unity.**

When expressed in decibels, the noise factor is called noise figure (*NF*).

$\therefore \qquad NF = 10 \log_{10} F \; dB$

If an amplifier could be built which generated no noise of its own, then

(i) $S_i/N_i = S_o/N_o$ ***(ii)*** $F = 1$ ***(iii)*** $NF = 0$ dB

If *G* is the power gain of the amplifier, then output and input signal powers are related by

$$G = \frac{S_0}{S_i} \quad i.e. \quad S_o = G.S_i$$

The output noise $N_o = GN_i + N_A$

where N_i = input noise power

N_A = noise power generated by amplifier itself

Example 60.13. *The signal input to a small-signal amplifier consists of 50 µW of signal power and 0.5 µW of noise power. The amplifier generates an internal noise power of 50 µW and has a gain of 20 dB. For this amplifier, compute*

(a) *input S/N,* ***(b)*** *output S/N,* ***(c)*** *noise factor,* ***(d)*** *noise figure.*

(Electronics & Commun. Engg. Pune Univ. 1991)

Solution. (*a*) $\frac{S_i}{N_i} = \frac{50}{0.5} = \mathbf{100}$

(*b*) Now, $10 \log_{10} G = 20$ dB or $10\log_{10} G = 2$ or $G = 10^2 = 100$

$S_o = GS_i = 100 \times 50 = 5000$ µW

$N_o = GN_i + N_A = 100 \times 0.5 + 50 = 100$ µW $\quad \therefore \quad \frac{S_0}{N_0} = \frac{5000}{100} = \mathbf{50}$

(*c*) $F = \frac{S_i / N_i}{S_0 / N_0} = \frac{100}{50} = \mathbf{2}$

(*d*) $N_F = 10\log_{10} 2$ dB $= 10 \times 0.3 = \mathbf{3\ dB}$

60.36. The Decibel System

The decibel system of measurement is widely used in audio, radio, TV and instrument industries for comparing two voltage or power levels. It is based on the established fact that an individual's response to ***seeing or hearing is nonlinear.*** It has been found that the changes in power and audio levels are related logarithmically. For example, when power is increased from 4 W to 16 W, the audio level does not increase 16/4 = 4 times but by a factor of 2 ($\because 4^2 = 16$). Similarly, for a power change from 4 W to 64 W, the audio level changes by a factor of 3 and not by 64/4 = 16. In logarithmic form, the relationship can be written as

increase in audio level = $\log_{10} 64 = 3$.

While comparing two powers, it is common practice to choose the log base of 10. Suppose, we want to compare any two powers P_1 and P_2. The simple method is to take their ratio P_2/P_1 and to state how many times P_2 is bigger or smaller than P_1 which is used as reference power. In the decibel system, we take the log of this ratio.

$\therefore$ power level = $10\log_{10} R_2/P_1$ bel

Since bel is too large, we use decibel (dB) instead. Remembering that 1 bel = 10 decibel, the power level becomes

$= 10 \log_{10} P_2/P_1$

Similarly, if P_i is the input power of an amplifier and P_o its power output, then power gain of the amplifier in decibels is

$= 10 \log_{10} P_0/P_i$ dB

Also, if the output power of an amplifier changes from P_1 to P_2, the power level change is

$= 10 \log_{10} P_2/P_1$

It is obvious that dB is the unit of power change (*i.e.* increase or decrease) and not of power itself.

Another point worth remembering is that 20 dB is not twice as much power as 10 dB.

Example 60.14. *An amplifier has an input signal of 16 V peak-to-peak and an input impedance of 320 K. It gives an output voltage of 8 V peak-to-peak across a load resistor of 4 W. Calculate the dB power gain of the amplifier.* **(Electronics-I, Gujarat Univ.)**

Solution. $$P_i = \frac{V_i^2}{R_i} = \frac{(16/2\sqrt{2})^2}{320\,\text{K}} = 100\,\mu\text{W}$$

where V_i = rms value of input voltage = $\frac{V_{i\times p-p}}{2\sqrt{2}}$

If V_o is the rms value of the output voltage, then

$$P_o = \frac{V_o^2}{R_o} = \frac{(8/2\sqrt{2})^2}{4} = 2\,\text{W}$$

$\therefore$ power amplification, $\frac{P_0}{P_i} = \frac{2\,\text{W}}{100\,\mu\,\text{W}} = 20,000$

decibel power gain = 10 $\log_{10}$ 20,000 = 10 × 4.4 = **43 dB**

60.37. Other Expressions for Power Gain

Suppose P_o and P_i are the respective output and input powers of an amplifier, R_o and R_i are its output and input resistances and V_0 and V_i the rms values of output and input voltages, then

$$P_o = \frac{V_o^2}{R_o} \qquad \text{and} \qquad P_i = \frac{V_i^2}{R_i}$$

Power amplification, $A_p = P_o/P_i$. But power gain is given by

$$G_p = 10\log_{10} P_o/P_i = 10\log_{10}\frac{V_0^2/R_o}{V_i^2/R_i} = 10\log_{10}(V_o/V_i)^2.R_i/R_o$$

$$= \left[\log_{10}(V_o/V_i)^2 + \log_{10} R_i/R_o\right] = 10\log_{10}(V_0/V_i)^2 + 10\log_{10} R_0/R_i$$

$$= 20\log_{10} V_o/V_i + 10\log_{10} R_i/R_o$$

Also $\quad P_o = I_o^2 R_0 \quad$ and $\quad P_i = I_i^2\, R_i$

$\therefore$ power gain, $G_p = 10\log_{10} P_o/P_i = 10\log_{10} I_o^2 R_o/I_i^2 R_i = 10\left[\log_{10}(I_o/I_i)^2 R_o/R_i\right]$

$$= 10[2\log_{10} I_o/I_i + \log_{10} R_o/R_i] = 20\log_{10} I_o/I_i + 10\log_{10} R_o/R_i\ \text{dB}$$

Of course, if $R_o = R_i$, then $\log_{10} R_o/R_i = \log_{10} 1 = 0$

Hence, in that case, power gain, G_p = 20$\log_{10} I_o/I_i$ dB

60.38. Voltage and Current Levels

Though decibel was initially defined as the unit of power level, it can also be used with voltage and current levels.

Suppose, an amplifier has an input voltage of V_i and gives an output voltage of V_0. Then, its voltage amplification is $A_n = V_o/V_i$ but its decibel voltage gain is

$$G_v = 20\log_{10} A_v\text{dB} = 20\log10\ V_0/V_i$$

It should be carefully noted that multiplying factor of 20 has been used and not of 10 as is done for finding power level. In fact, it implies that R_o has been taken equal to R_i in the power gain equation derived in Art 60.37.

Similarly, current amplification is $A_i = I_o/I_i$. However, current gain of the amplifier is

$$G_i = 20\log_{10} I_o/I_i\ \text{dB}$$

Example 60.15. *The input and output voltages of a network are 16 V and 8V respectively. If input impedances are equal, find the voltage gain.*

Solution. $G_v = 20 = \log_{10} V_o/V_i = 20 \log_{10}{}^{8/16}$
$= 20 [\log_{10} 8 - \log_{10} 16] = 20 (0.90 - 1.2) = 20 \times (-0.3) = -$ **6 dB.**

Alternative Method

When the voltage ratio is less than 1, *its log is negative* which is often difficult to handle. In such cases, it is best to invert the fraction and then make the result negative. The above problem could be solved thus :

$G_v = -20 \log_{10}{}^{16/8} = -20 \times 0.3 -$ **6 dB**

Example 60.16. *A microphone delivers 30 mV to the 300 Ω input of an amplifier. The ac power delivered to an 8-Ω speaker is 18 W. What is the power gain of the amplifier ?*

Solution. We may use any one of the equations given above.

$G_p = 20 \log_{10} V_0/V_i + 10 \log_{10} R_i/R_0$

Now, $P_o = \dfrac{V_o^2}{R_o}$ or $18 = \dfrac{V_o^2}{8}$ $\therefore$ $V_o = \sqrt{8 \times 18} = 12\,\text{V}$

$\therefore$ $G_p = 20 \log_{10} 12\text{V}/30\text{mV} + 10 \log_{10} 300/8 = 20 \log_{10} 400 + 10 \log_{10} 37.5$
$= 20 \times 2.6 + 10 \times 1.57 =$ **67.7 dB.**

Example 60.17. *The output power of an amplifier is 100 mW when the signal frequency is 5 kHz. When the frequency is increased to 25 kHz, the output power falls to 50 mW. Calculate the dB change in power.* **(Electronics, Gujarat Univ. 1991)**

Solution. The decibel change in power level

$= 10 \log_{10} 50/100 = 10 \log_{10}{}^{1/2} = -10 \log_{10} 2 = -10 \times 0.3 = -$ **3 dB.**

Example 60.18. *The output voltage of an amplifier is 10 V at 5 kHz and 7.07 V at 25 kHz. What is the decibel change in output power level ?*

Solution. Since changes in voltage are across the same output resistance, the decibel change in power is

$= 20\log_{10} V_2/V_1 = 20 \log_{10} 7.07/10 \text{ dB} = -20 \log_{10} 10/7.07 = -20 \log_{10} 1.414 \text{ dB}$
$= -20 \times 0.15 = -3 \text{ dB}$

It is seen from Ex. 60.17 and Ex. 60.18 that output decibel power falls by a 3 dB when

(i) absolute value of power falls to half its original value

or

(ii) output voltage falls to 0.707 or $1/\sqrt{2}$ *of its original value.*

Example 60.19. *A certain radio receiver delivers an output power of 3.6 W.*
(i) what would be the decibel gain if power output is increased to 7.2 W ?
(ii) what power output would be required to produce a power gain of 10 dB?

Solution. *(i)* $G_p = 10 \log_{10} P_2/P_1 = 10 \log_{10} 7.2/3.6 =$ **3 dB**

(ii) Here, $G_p = 10$, $P_1 = 3.6$ W, $P_2 = ?$

$\therefore$ $10 = 10 \log_{10} P_2/3.6$ $\therefore$ $\log_{10} P_2/3.6 = 1$ or $\dfrac{P_2}{3.6} = 10^1 = 10$

$\therefore$ $P_2 = 3.6 \times 10 =$ **36 W**

60.39. Characteristics of the Decibel System

1. a decibel is a measure of **ratio** and not of **an amount**. It tells us how many times one quantity is greater or lesser with respect to another or the reference quantity. It does not measure the actual (or absolute) voltage or power but only their **changes;**

2. decibel is non-linear *i.e.* 20 dB is not twice as much power or voltage as 10 dB;
3. this log-based system allows a tremendous range of power ratios to be encompassed by using only two-digit numbers. For example
   1 dB = 1.26 : 1 power ratio and 50 dB = 100,000 : 1 power ratio;
4. total dB of a cascaded amplifier can be found by simply adding the stage dBs.

60.40. Value of 1 dB

It can be proved that 1 dB represents the log of two powers which ***have a ratio of 1.26.***

$$1 \text{ dB} = 10 \log_{10} P_2/P_1$$

$$\therefore \quad \log_{10} P_2/P_1 = \frac{1}{10} = 0.1 \quad \textit{or} \quad \frac{P_2}{P_1} = 10^{0.1} = 1.26$$

Hence, +1 dB represents an increase in power of 26%.

60.41. Zero Decibel Reference Level

By now, it should be clear that decibel does not measure any physical quantity like voltage or power etc., but merely ratio of two physical quantities. For determining the power levels of various powers like P_1, P_2, P_3 etc. it is essential to fix some reference power with which their ratios can be taken. If we fix P_0 as the reference power, then different power levels would be

$$10 \log_{10} P_1/P_o \qquad \text{and} \qquad 10 \log_{10} P_2/P_o \text{ etc.}$$

Obviously, ***P_o cannot be 0 watt i.e.*** 0 watt cannot be taken as 0 dB because, in that case, power level of P_1 would be

$$= 10 \log_{10} P_1/0 = \infty$$

In fact, any power compared with zero power is infinity. Hence, decibels would not be defined if zero watt is taken as zero reference level.

Following three zero reference levels are in common use :

1. Zero dB refers to 6 mW dissipated in a 500 Ω resistive load.
   The reference voltage value corresponding to 0 dB is
   $P = V^2/R$ or $6 \times 10^{-3} = V^2/500$ or $V = 1.73$ V
2. Zero dB refers to 1 mW dissipated in 600 Ω.
   Here, $1 \times 10^{-3} = V^2/600$; $V = 0.774$ V
3. Zero dB refers to a 1-mW dissipation.
   It is written as dBm indicating that it uses 1 mW as a reference.
   This reference does not depend on any particular load impedance value.
   Calculations are performed by using the relation.

$$G_p = 10 \log_{10} P_2/0.001 \text{ dB}_{in}$$

60.42. Variations in Amplifier Gain with Frequency

If the input voltage of an amplifier is kept constant but its frequency is varied, it is found that the amplifier gain

(*i*) remains practically constant over a sizable range of mid-frequencies,
(*ii*) decreases at low as well as high frequencies.

A typical frequency- versus-gain curve is shown in Fig. 60.43. While analyzing this curve, three value of frequency are important

(*i*) mid-frequency range, (*ii*) lower cut-off frequency, f_1,
(*iii*) upper cut-off frequency, f_2.

The lower and upper cut-off frequencies are defined as those frequencies.

(*a*) where voltage gain of the amplifier decreases to 0.707 times the mid-frequency gain *i.e.* to

$$\frac{1}{\sqrt{2}} A_{v(mid)} = 0.707\, A_{v(mid)}$$ or

(*b*) in terms of power, where power amplification of the amplifier decreases to half its value at mid-frequencies

i.e. $A_{p.1}$

or $A_{p.2} = \frac{1}{2} A_{p(mid)}$

(*c*) in terms of decibels, where power gain **falls by 3 dB**.

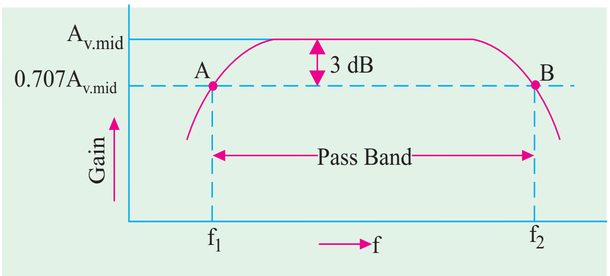


Fig. 60.43

That is why the two cut-off frequencies are referred to as

(*i*) –3 dB frequencies or

(*ii*) down 3 dB frequencies or

(*iii*) 3 dB loss frequencies.

The points A and B in Fig. 60.43 are called 3-dB points or (sometime) as ***minus 3 dB points.*** The cut-off frequencies are also called roll-off frequencies because at these frequencies the amplifier gain starts rolling down from its midband value or maximum value.

The frequency span between these two cut-off frequencies is called the passband or bandwidth (BW) of the amplifier.

$\therefore \quad \Delta f = f_2 - f_1$ = band width (BW) = passband

All frequencies lying between f_1 and f_2 are amplified almost equally.

For maximum bandwidth, the stray capacitances in the amplifier must be kept to the minimum.

60.43. Causes of Amplifier Gain Variations

The primary cause of gain variation in amplifiers is the presence of capacitances, some of which are connected in series along the signal path and some in parallel.

The different types of external capacitances present in an amplifier circuit are :

1. coupling and bypass capacitors–usually of large capacitance value,
2. internal or inter-element capacitances of the transistor [Fig. 60.44 (a)] and stray wiring capacitance [Fig. 60.44 (*b*)].

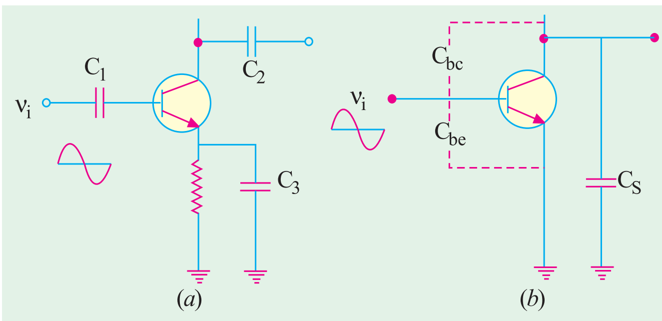


Fig. 60.44

The coupling and bypass capacitors [C_1, C_2 and C_3 in Fig. 60.44 (*a*)] are series-connected whereas interelement capacitances and stray capacitances are parallel-connected [Fig. 60.44 (*b*)] to the signal path. At mid-frequencies, C_1, C_2 and C_3 act almost as 'shorts' but C_{bc} and C_{be} act as 'open'. Hence, their effect on mid-frequencies is negligible.

However, at low frequencies, series-connected capacitors *i.e.* coupling and by-pass capacitors offer relatively large reactance thereby dropping off a large part of the input signal. Hence, amplifier gain starts decreasing as frequency is lowered.

The internal transistor capacitances and stray capacitances are **(*i*)** small and **(*ii*)** parallel-connected to the signal path. At low frequencies, they offer very high reactance and so act as effective 'open'. But with increase in frequency, their reactance keeps decreasing till at very high frequencies, they almost short or shunt the ac signal to ground both at the input and output ends. This explains why amplifier gain starts decreasing at high frequencies.

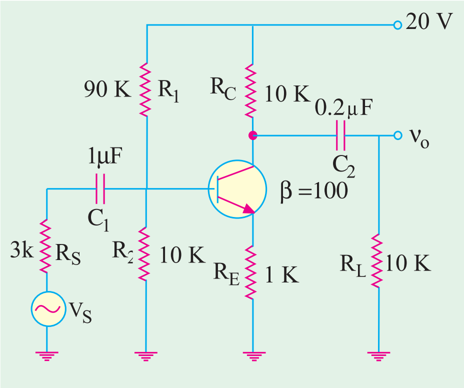


Fig. 60.45

In summary

(*i*) series-connected coupling and bypass capacitors cause decrease in amplifier gain at low frequencies,

(*ii*) parallel-connected internal transistor capacitances and stray wiring capacitances cause decrease in amplifier gain at high frequencies.

Example 60.20. *For the RC- coupled circuit of Fig. 60.45, calculate the lower cut-off frequency* ***(i)*** *at C_1* ***(ii)*** *at C_2 and* ***(iii)*** *for the amplifier.*

Solution. The low-frequency cut-off for each coupling capacitor is given by

$$f_1 = \frac{1}{2\pi C R_{eq.}}$$

where R_{eq} is the resistance 'seen' by the capacitor on its right and left.

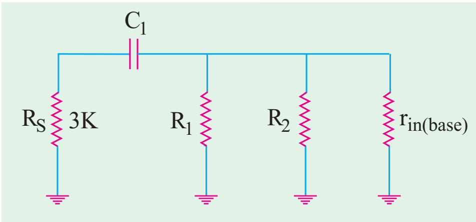


Fig. 60.46

(*i*) f_1 at C_1

For finding the resistance 'seen' by C_1, the dc and ac sources are shorted out because they have negligible resistance. The circuit becomes as shown in Fig. 60.46.

$$R_{eq} = R_S + R_1 \,||\, R_2 \,||\, r_{in(base)}$$

Now, $r_{in(base)} = \beta(r_e + R_E) \cong \beta R_E$
$= 100$ K

$$\therefore \quad R_{er} = 3K + 90K \,||\, 10K \,||\, 100K$$
$$= 3 + 8.26$$
$$= 11.26 \text{ K}$$

$$\therefore \quad f_1 = \frac{1}{2\pi\times 11.26\times 10^3 \times 1\times 10^{-6}} = \mathbf{40\ Hz}$$

(*ii*) f_1 at C_2

Let us first find the resistance 'seen' by C_2. On one side, it sees R_L = 10 K load resistor to the ground and on the other side, it sees R_C to ground in parallel with the resistance seen looking into transistor collector.

Since *C/B* junction is reverse-biased, its resistance is very high. If we consider it as 'open', the equivalent circuit becomes as shown in Fig. 60.47.

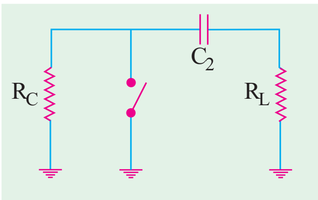


Fig. 60.47

$$\therefore \quad R_{eq} = R_L + R_C = 10 + 10 = 20 \text{ K}$$

$$\therefore \quad f_1 = \frac{1}{2\pi\times 20\times 10^3 \times 0.2\times 10^{-6}} = \mathbf{Hz}$$

(*iii*) Since cut-off frequency for C_2 occurs at 40 Hz while cut-off for C_1 occurs way down at 14 Hz, C_2 determines the lower cut-off frequency for the amplifier i.*e*. **14 Hz.**

60.44. Miller Effect

According to this effect, when viewed from input base terminal of the *CE*-connected transistor, the capacitance C_{bc} appears as $(1 + A_v)\, C_{bc}$ *i.e.* it is amplified by a factor of $(1 + A_v)$. In fact, Miller effect takes into account the feedback from the collector to base and *vice-versa* due to C_{bc}.

Proof

When V_i is applied to the transistor's base in Fig. 60.44 (*b*), the change in collector voltage is

$$\Delta V_C = -A_v . V_i$$

The negative sign is due to phase shift inherent in a *CE* amplifier. As seen, V_C is reduced by $(A_v . V_i)$ when base voltage is increased by V_i. Hence, total reduction in collector base voltage is

$$\Delta V_{CB} = V_i + A_v . V_i = V_i (1 + A_v)$$

This also represents the change of voltage across C_{bc} because it is connected across collector and base. Using $Q = CV$, the charge supplied to the input of the circuit is

$$Q = C_{bc} \times \Delta V_{CB} = C_{bc} \times (1 + A_v)\, V_i = (1 + A_v)\, C_{bc} \times V_i$$

Hence, C_{bc} appears as $(1 + A_v)\, C_{bc}$ when looked from the input side of the circuit.

Incidentally, the total input capacitance to the transistor is

$$C_{in} = C_{be} \,||\, (1 + A_v) C_{bc} = C_{be} + (1 + A_v)\, C_{bc}$$

At high frequencies, C_{in} reduces the input impedance of the circuit and affects the frequency response (Ex. 60.22).

Example 60.21. *A CE-connected amplifier has C_{bc} = 4 pF, C_{be} = 10 pF and r_e = 50Ω. If circuit load resistor is 10 K, calculate the value of C_{in}.*

Solution. $A_v \cong \dfrac{R_E}{r_e} = \dfrac{100\,K}{50\,\Omega} = 200$ $\quad\therefore\quad$ C_{in} = 10 + (1 + 200)4 = **814 pF**

Example 60.22. *Calculate the upper cut-off frequency of the CE amplifier shown in Fig. 60.48. Given the input wiring capacitance C_{wi} = 40 pF, C_{bc} = 8 pF, C_b = 10 pF and β = 100.*

(Electronic Engg-I, Osmania Univ.)

Solution. $f_2 = \dfrac{1}{2\pi R_{eq} C_{in}}$

The voltage amplification of the amplifier is

$$A_v \cong \frac{R_C \,||\, R_L}{R_L} = \frac{20\,K \,||\, 20\,K}{400\,\Omega} = 25$$

The total capacitance from base to ground is

$$C_{in} = C_{wi} + C_{be} + (1 + A_v)\, C_{bc}$$
$$= 40 + 10 + (1 + 25) \times 8 = 258 \text{ pF}$$

Now, let us determine the resistance 'seen' by C_{in}. If we look to the right, a resistance of $\beta(r_e + R_E) \cong \beta R_E$ is seen while to the left $R_1 \,||\, R_2 \,||\, R_S$ is seen–all in parallel.

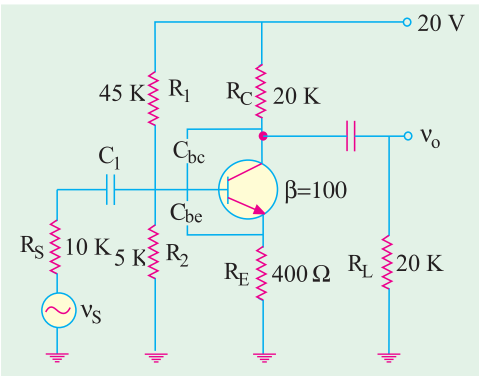


Fig. 60.48

$$\therefore \quad R_{eq} = R_1 \,||\, R_2 \,||\, R_S \,||\, \beta R_E$$
$$= 45\text{ K} \,||\, 5\text{K} \,||\, 10\text{K} \,||\, 40\text{ K} = 2.88\text{ K}$$

$$\therefore \quad f_2 = \frac{1}{2\pi \times 2.88 \times 10^3 \times 258 \times 10^{-12}} = \textbf{214 kHz}$$

60.45. Cut-Off Frequencies of Cascaded Amplifiers

Cascading of stages gives higher amplification but narrow bandwidth because the product of the two remains almost constant. The approximate values of composite lower and upper cut-off frequencies of the cascaded amplifier having n identical stages are

$$f_{1.n} = 1.1\sqrt{n} \times f_1 \qquad \text{per stage} = \frac{f_1 \text{ per stage}}{\sqrt{(2^{1/n} - 1)}}$$

$$f_{2.n} = \frac{f_2 \text{ per stage}}{1.1\sqrt{n}} = \sqrt{(2^{1/n} - 1)} \times f_2 \text{ per stage}$$

The reduced bandwidth of the cascaded amplifier is = $f_{2n} - f_{1.n}$

60.46. Transistor Cut-off Frequencies

Even if no external stray capacitances were present in an amplifier, there would still be an upper limit on its frequency response due to

(*i*) internal or interelement capacitances of the transistor and

(*ii*) transit time of charge carriers across the transistor junctions and through the semiconductor material.

This limitation is expressed in terms of

(*i*) alpha cut-off frequency (f_α) and (*ii*) beta cut-off frequency (f_β)

The two are defined below.

60.47. Alpha Cut-off Frequency

It is found that at high frequencies, the value of transistor α begins to fall. This decrease in α is related to the transit time effect of the charge carriers as they move from the emitter to collector.

The alpha cut-off frequency f_α is that high frequency at which the α of a *CB*-connected transistor becomes 0.707 of its low-frequency value (usually 1 kHz).

For example, if value of α at 1 kHz is 0.98, then its value at f_α would be

= 0.707 × 0.98 = 0.693

It means that at f_α, the collector current I_C would be only 0.693 of the emitter current rather than 0.98 I_E.

It is found that f_α is

(a) inversely proportional to the square of the base width,

(b) directly proportional to the minority carrier mobility.

In this regard, NPN transistors are superior to *PNP* type because electrons have greater mobility than holes. For decreasing the base transit time, base should be as thin as possible.

It may be noted that alpha cut-off frequency of any given transistor is always greater than its beta cut-off frequency f_β. In fact, $f_\alpha \cong \beta f_\beta$.

60.48. Beta Cut-off Frequency

It is that high frequency at which the β of a *CE*-connected transistor drops to 0.707 of its low-frequency (1 kHz) value.

60.49. The f_T of a Transistor

It is another high-frequency characteristic of a transistor.

It is that high frequency of a *CE*-connected transistor where its β drops to unity *i.e.* β = 1. This frequency is much larger than f_β but less than f_α. For example, for a typical transistor, their values may be f_β = 6 MHz, f_T = 300 MHz and f_α = 345 MHz.

60.50. Relation Between f_α, f_b and f_T

(*i*) For simple junction transistors $f_\alpha = 1.2\, f_T$ and (*ii*) $f_\beta = \dfrac{f_T}{\beta}$, where β refers to its low-frequency value.

60.51. Gain-Bandwidth Product

At its name indicates, it is the product of the gain and bandwidth of an amplifier. It is very useful in comparing the performance capability of various circuits.

For any amplifier, gain-bandwidth product (GBP) is constant and is equal to f_T.

If, for example, β = 1, at a frequency of 6 MHz, then f_T = **6 MHz.**

$\therefore$ gain-bandwidth product = **6 MHz.**

Hence, for a given f_T in an amplifier, increased gain may be obtained only at the expense of its bandwidth.

Example 60.23. *A transistor has f_α = 8 MHz and β = 80. When connected as an amplifier, it has stray capacitance of 100 pF at the output terminal. Calculate its upper 3 dB frequency when R_L is **(a)** 10 K and **(b)** 100 K.*

Solution. It should be remembered that stray capacitance would reduce the amplifier gain by 3-dB when

capacitive reactance = output resistance

i.e. $$\frac{1}{2\pi f_S C_S} = R_L \quad \text{or} \quad f_s = \frac{1}{2\pi C_S R_L}$$

First, let us find the value of f_β for comparison with f_s.

$$f_\beta = \frac{f_1}{80} = \frac{8\,\text{MHz}}{80} = 100\,\text{kHZ}$$

(*a*) R_L = 10 K

$$f_2 = \frac{1}{2\pi C_s R_L} = \frac{1}{2\pi \times 100 \times 10^{-12} \times 10 \times 10^3} = 159\,\text{kHz}$$

Obviously, before this frequency is reached, cut-off would have been achieved at f_β = 100 kHz. Hence, $f_2 = f_\beta$ = **100 kHz.**

(*b*) R_L =100 K

In this case, $$f_s = \frac{10}{100} \times 159 = 15.9\,\text{kHz}$$

In this case, cut-off would be achieved much earlier at 15.9 kHz before f_β is reached

$\therefore$ f_2 = **15.9 kHz.**

Tutorial Problems No. 60.1

1. An amplifier raises the power level of its 5-µW input signal by 30 dB. What is the output power ? **[5 mW]**

2. An attenuation network provides an output of 5 µW with an input of 5 mW. Calculate the decibel loss of the network. **[–30 dB]**

3. What is the decibel difference between a 100 kW and 500 kW radio transmitters? **[6.98 dB]**

4. The noise level of a certain tape recording is 30 dB below the signal level. If the signal power is 5 mW, calculate the noise power. **[5 mW]**

5. An amplifier rated at 72-W output is connected to an 8 Ω speaker
(*a*) what input power is required for full power output if power gain is 30 dB,
(*b*) what is the input voltage for rated output if amplifier voltage gain is 40 dB.
[(*a*) 72 µW (b) 240 mV]

6. The characteristics of a certain audio amplifier are such that it gives a voltage amplification of 10 at 100 Hz, 30 at 3 kHz and 60 at 10 kHz. Taking the amplification at 3 kHz as the reference level, calculate the loss or gain in decibels at the other two frequencies. **[–9.54 dB, 6.02 dB]**

7. An amplifier with full power rating of 100 W drives a speaker load of 16 Ω . The hum-level rating of the amplifier is 80 dB below its full-power rating. Calculate (*i*) hum-level in the load,

(*ii*) voltage produced by the hum across the load. **[(i) 1 µW (ii) 4 mW]**

8. Derive the voltage, current and power gain relationships and then find the voltage gain of the single-stage amplifier shown in Fig. 60.49. An *NPN* transistor that has h_{ie} = 500 Ω, h_{re} negligible, h_{fe} = 150, and h_{oe} = 50 µ*S* is used. Neglect all coupling and stray capacitances.

Comment on the various methods available for biasing the base and discuss their merits. **[– 545]**

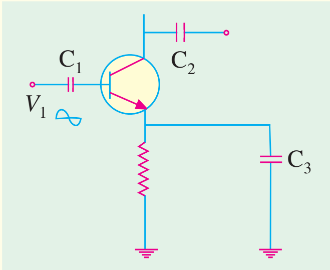


Fig. 60.49

OBJECTIVE TESTS – 60

1. A CB amplifier has very low input resistance because
(*a*) low emitter ac resistance r_e' shunts all other resistances
(*b*) it handles small input signals
(*c*) emitter bulk resistance is small
(*d*) its base is at ac ground.

2. CE amplifier is characterised by
(*a*) low voltage gain
(*b*) moderate power gain
(*c*) signal phase reversal
(*d*) very high output impedance.

3. A CC amplifier has the highest
(*a*) voltage gain (*b*) current gain
(*c*) power gain (*d*) output impedance.

4. In a CC amplifier, voltage gain
(*a*) cannot exceed unity
(*b*) depends on output impedance
(*c*) is dependent on input signal
(*d*) is always constant.

5. In a class-A amplifier, conduction extends over 360° because Q-point is
(*a*) located on load line
(*b*) located near saturation point
(*c*) centred on load line
(*d*) located at or near cut-off point.

6. The circuit efficiency of a class-A ampli- fier can be increased by using
(*a*) low dc power input
(*b*) direct-coupled load
(*c*) low-rating transistor
(*d*) transformer-coupled load.

7. In a class-A amplifier, worst-case condi- tion occurs with
(*a*) zero signal input
(*b*) maximum signal input
(*c*) high load resistance
(*d*) transformer coupling.

8. The output of a class-B amplifier
(*a*) is distortion-free
(*b*) consists of positive half-cycle only
(*c*) is like the output of a full-wave rectifier
(*d*) comprises short-duration current pulses.

9. The maximum overall efficiency of a transformer-coupled class-A amplifier is – per cent.
(*a*) 78.5 (*b*) 25 (*c*) 50 (*d*) 85

10. A transistor audio amplifier is found to have an overall efficiency of 70 per cent. Most probably, it is a .... amplifier.
(*a*) class-B push-pull
(*b*) single-stage class-C
(*c*) transformer-coupled class-A
(*d*) direct-coupled class-A

11. The main purpose of using transformer coupling in a class-A amplifier is to make it more
(*a*) distortion-free (*b*) bulky
(*c*) costly (*d*) efficient.

12. A class-B push-pull amplifier has the main ad-vantage of being free from
(*a*) any circuit imbalances
(*b*) unwanted noise
(*c*) even-order harmonic distortion
(*d*) dc magnetic saturation effects.

13. Crossover distortion occurs in .... am-plifiers.
(*a*) push-pull (*b*) class-A
(*c*) class-B (*d*) class AB

14. The maximum overall efficiency of a class-B push-pull amplifier cannot exceed – per cent.
(*a*) 100 (*b*) 78.5 (*c*) 50 (*d*) 85

15. The circuit of a class B push-pull amplifier is shown in Fig. 60.50 . If the peak output voltage, V_0 is 16 V, the power drawn from the dc source would be
(*a*) 10 W (*b*) 16 W (*c*) 20 W (*d*) 32 W

16. The dissipation at the collector is zero in the qui-escent state and increases with excitation in the case of a
(*a*) class A series-fed amplifier
(*b*) class A transistor coupled amplifier
(*c*) class AB amplifier
(*d*) class B amplifier

17. Class AB operation is often used in power (large signal) amplifiers in order to,

(*a*) get maximum efficiency
(*b*) remove even harmonics
(*c*) overcome cross-over distortion
(*d*) reduce collector dissipation

18. The main use of a class-C amplifier is
(*a*) as an RF amplifier
(*b*) as stereo amplifier
(*c*) in communication sound equipment
(*d*) as distortion generator.

19. If a class C power amplifier has an input signal with frequency of 200 kHz and the width of collector current pulses of 0.1μS, then the duty cycle of the amplifier will be
(*a*) 1% (*b*) 2% (*c*) 10% (*d*) 20%

20. The primary cause of linear distortion in amplifiers is
(*a*) change of gain with frequency
(*b*) unequal phase shift in component frequencies
(*c*) reactances associated with the circuit and active amplifying element
(*d*) inherent limitations of the active de vice.

21. An amplifier is said to suffer from distortion when its output is
(*a*) low
(*b*) different from its input
(*c*) noisy
(*d*) larger than its input.

22. While discussing amplifier performance, noise is defined as any kind of unwanted signal in the output which is
(*a*) unrelated to the input signal
(*b*) derived from the input signal
(*c*) not generated by the amplifier
(*d*) due to associated circuitry.

23. An ideal amplifier has
(*a*) noise figure of less than 1 dB
(*b*) noise factor of unity
(*c*) output S/N more than input S/N
(*d*) noise figure of more than 0 dB.

24. The decibel is a measure of
(*a*) power (*b*) voltage
(*c*) current (*d*) power level.

25. When power output of an amplifier doubles, the increase in its power level is .... decibels.
(*a*) 2 (*b*) 20 (*c*) 3 (*d*) 10

26. When output power level of a radio recei- ver increases by 3 dB, its absolute power changes by a factor of
(*a*) 2 (*b*) 10 (*c*) 1/2 (*d*) 3.

27. Zero watt cannot be chosen as zero deci- bel level because
(*a*) it is impossible to measure zero watt
(*b*) it is too small
(*c*) every power compared with it would be zero
(*d*) it would be impossible to define a decibel.

28. A minus 3 dB point on the gain versus frequency curve of an amplifier is that point where
(*a*) signal frequency drops to half the mid-band frequency
(*b*) voltage amplification becomes half of its maximum value
(*c*) power falls to half its maximum value
(*d*) upper cut-off frequency becomes twice the lower cut-off frequency

29. The bandwidth of an amplifier may be increased by
(*a*) decreasing the capacitance of its by pass capacitors
(*b*) minimizing its stray capacitances
(*c*) increasing input signal frequency
(*d*) cascading it.

30. Lower cut-off frequency of an amplifier is primarily determined by the
(*a*) interval capacitances of the active device used
(*b*) stray capacitance between its wiring and ground
(*c*) ac β value of its active devices
(*d*) capacitances of coupling and bypass capacitors.

31. The main reason for the variation of amp- lifier gain with frequency is
(*a*) the presence of capacitances, both ex- ternal and internal
(*b*) due to interstage transformers
(*c*) the logarithmic increase in its output power
(*d*) the Miller effect.

32. The gain-bandwidth product of an amp- lifier is given by
(*a*) $f_2 - f_1$ (*b*) $f_\alpha - f_\beta$
(*c*) f_T (*d*) βf_α

33. A Circuit which resonates at 1MHz has *a* of 100. Bandwidth between half-power points is
(*a*) 10 kHz (*b*) 100 kHz
(*c*) 10 Hz (*d*) 100 Hz

(UPSC Engg. Services 2002)
(Hint : BW = F_o/a)

ANSWERS

1. (*a*)	**2.** (*c*)	**3.** (*b*)	**4.** (*a*)	**5.** (*c*)	**6.** (*d*)	**7.** (*a*)	**8.** (*b*)	**9.** (*c*)	**10.** (*a*)	**11.** (*d*)
12. (*c*)	**13.** (*a*)	**14.** (*b*)	**15.** (*b*)	**16.** (*d*)	**17.** (*a*)	**18.** (*a*)	**19.** (*d*)	**20.** (*c*)	**21.** (*b*)	**22.** (*a*)
23. (*b*)	**24.** (*d*)	**25.** (*c*)	**26.** (*a*)	**27.** (*d*)	**28.** (*c*)	**29.** (*b*)	**30.** (*d*)	**31.** (*a*)	**32.** (*c*)	**33.** (*a*)

GO To FIRST