8.22 Cut off and Saturation Points

Fig. 8.49 (*i*) shows *CE* transistor circuit while Fig. 8.49 (*ii*) shows the output characteristcs along with the d.c. load line.

(*i*) Cut off. The point where the load line intersects the $I_B = 0$ curve is known as *cut off.* At this point, $I_B = 0$ and only small collector current (*i.e.* collector leakage current I_{CEO}) exists. At cut off, the base-emitter junction no longer remains forward biased and normal transistor action is lost. The collector-emitter voltage is nearly equal to V_{CC} *i.e.*

$$V_{CE\,(cut\,off)} = V_{CC}$$

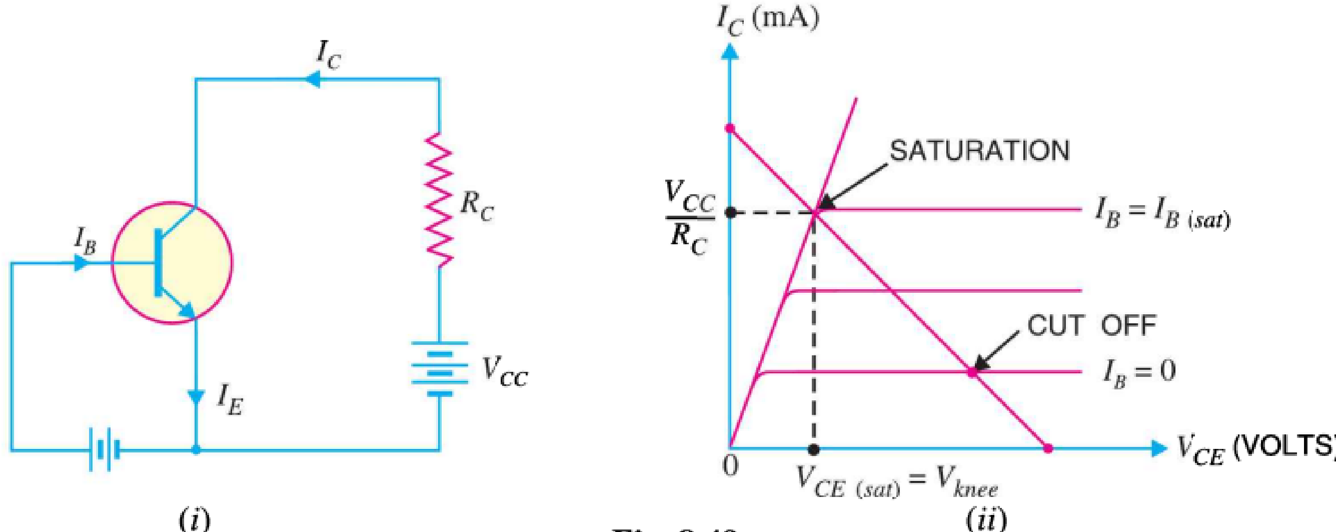


Fig. 8.49

(*ii*) Saturation. The point where the load line intersects the $I_B = I_{B(sat)}$ curve is called *saturation*. At this point, the base current is maximum and so is the collector current. At saturation, collector-base junction no longer remains reverse biased and normal transistor action is lost.

$$I_{C\,(sat)} \simeq \frac{V_{CC}}{R_C}\,; \quad V_{CE} = V_{CE(sat)} = V_{knee}$$

If base current is greater than $I_{B(sat)}$, then collector current cannot increase because collector-base junction is no longer reverse-biased.

(*iii*) Active region. The region between cut off and saturation is known as *active region*. In the active region, collector-base junction remains reverse biased while base-emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

Note. We provide biasing to the transistor to ensure that it operates in the active region. The reader may find the detailed discussion on transistor biasing in the next chapter.

Summary. A transistor has two *pn* junctions *i.e.*, it is like two diodes. The junction between base and emitter may be called *emitter diode*. The junction between base and collector may be called *collector diode*. We have seen above that transistor can act in one of the three states : **cut-off, saturated** and **active**. The state of a transistor is entirely determined by the states of the emitter diode and collector diode [See Fig. 8.50]. The relations between the diode states and the transistor states are :

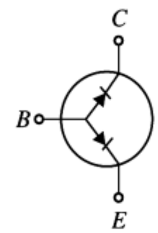


Fig. 8.50

CUT-OFF : Emitter diode and collector diode are **OFF.**

ACTIVE : Emitter diode is **ON** and collector diode is **OFF.**

SATURATED : Emitter diode and collector diode are **ON.**

In the **active state**, collector current [See Fig 8.51 (*i*)] is β times the base current (*i.e.* $I_C = \beta I_B$). If the transistor is **cut-off,** there is no base current, so there is no collector or emitter current. That is collector emitter pathway is open [See Fig. 8.51 (*ii*)]. In **saturation**, the collector and emitter are, in effect, shorted together. That is the transistor behaves as though a switch has been closed between the collector and emitter [See Fig. 8.51 (*iii*)].

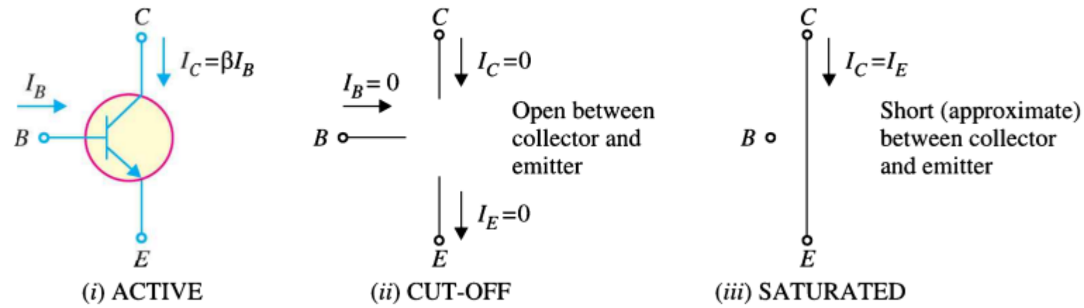


Fig. 8.51

Note. When the transistor is in the active state, $I_C = \beta I_B$. Therefore, a transistor acts as an amplifier when operating in the active state. Amplification means *linear amplification.* In fact, small signal amplifiers are the most common *linear devices*.

Example 8.32. *Determine the values of $V_{CE\,(off)}$ and $I_{C\,(sat)}$ for the circuit shown in Fig. 8.53.*

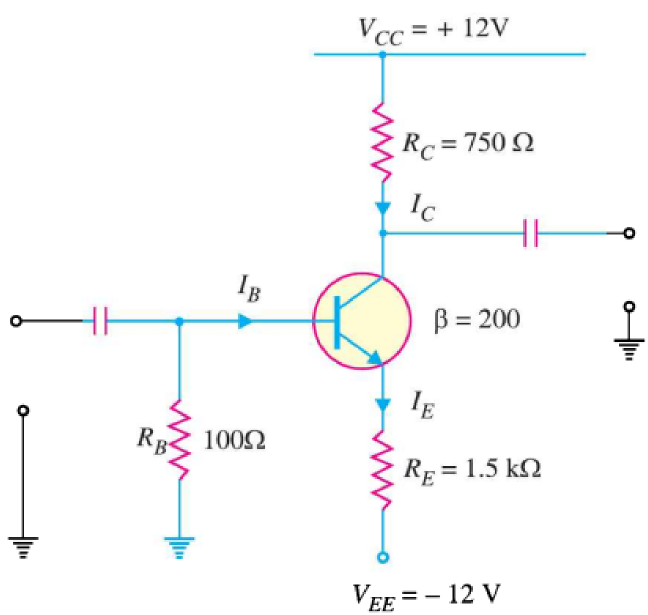


Fig. 8.53

Solution. Applying Kirchhoff's voltage law to the collector side of the circuit in Fig. 8.53, we have,

$$V_{CC} - I_C R_C - V_{CE} - {}^*I_C R_E + V_{EE} = 0$$

or $$V_{CE} = V_{CC} + V_{EE} - I_C (R_C + R_E) \quad \text{... } (i)$$

* Voltage across $R_E = I_E R_E$. Since $I_E \simeq I_C$, voltage across $R_E = I_C R_E$.

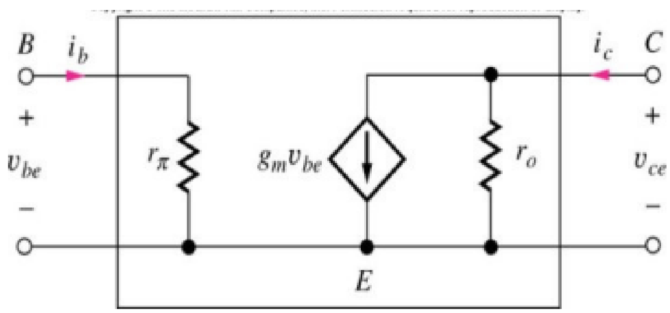
We have $V_{CE\,(off)}$ when $I_C = 0$. Therefore, putting $I_C = 0$ in eq. (*i*), we have,

$$V_{CE\,(off)} = V_{CC} + V_{EE} = 12 + 12 = \mathbf{24V}$$

We have $I_{C\,(sat)}$ when $V_{CE} = 0$.

$$\therefore \quad I_{C\,(sat)} = \frac{V_{CC} + V_{EE}}{R_C + R_E} = \frac{(12+12)\,V}{(750+1500)\,\Omega} = \mathbf{10.67\ mA}$$

Hybrid-Pi Small-Signal AC Model for the BJT



- The hybrid-pi small-signal model is the intrinsic low-frequency representation of the BJT.
- The small-signal parameters are controlled by the Q-point and are independent of the geometry of the BJT.

Transconductance:

$$g_m = \frac{I_C}{V_T} \cong 40 I_C$$

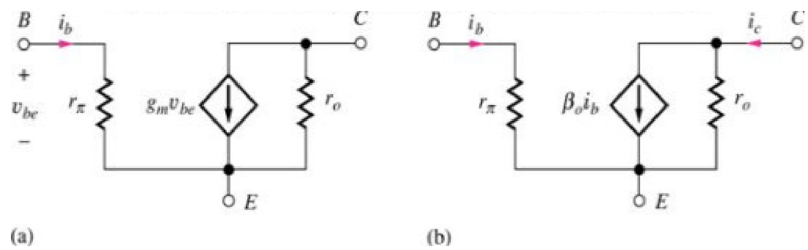
Input resistance:

$$r_\pi = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m}$$

Output resistance:

$$r_o = \frac{V_A + V_{CE}}{I_C}$$

Equivalent Forms of the Small-signal Model for the BJT



- The voltage-controlled current source $g_m v_{be}$ can be transformed into a current-controlled current source,

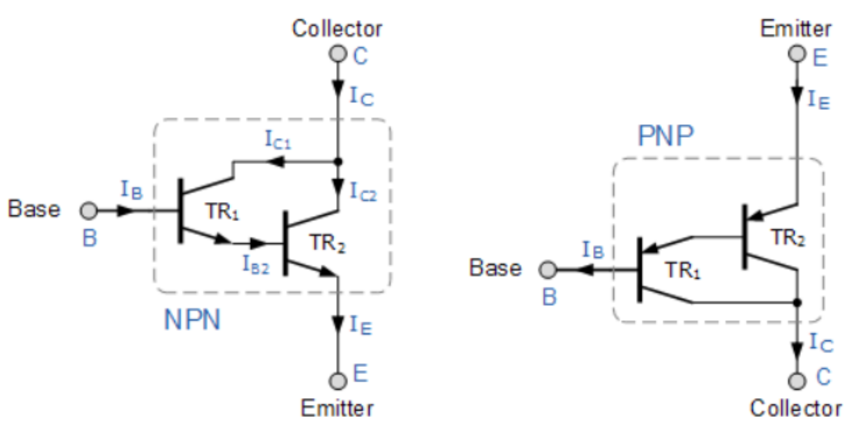
$$v_{be} = i_b r_\pi = i_b \frac{\beta_o}{g_m}$$

$$\therefore g_m v_{be} = g_m i_b r_\pi = \beta_o i_b$$

$$i_c = g_m v_{be} + \frac{v_{ce}}{r_o} \cong g_m v_{be} = \beta_o i_b$$

- The basic relationship $i_c = \beta i_b$ is useful in both dc and ac analysis when the BJT is biased in the forward-active region.

Basic Darlington Transistor Configuration



Using the NPN Darlington pair as the example, the collectors of two transistors are connected together, and the emitter of TR_1 drives the base of TR_2. This configuration achieves β multiplication because for a Base current i_b, the collector current is $\beta * i_b$ where the current gain is greater than one, or unity and this is defined as:

$$I_C = I_{C1} + I_{C2}$$

$$I_C = \beta_1 . I_B + \beta_2 . I_{B2}$$

But the base current, I_{B2} is equal to transistor TR1 emitter current, I_{E1} as the emitter of TR1 is connected to the base of TR2. Therefore:

$$I_{B2} = I_{E1} = I_{C1} + I_B = \beta_1.I_B + I_B = (\beta_1 + 1).I_B$$

Then substituting in the first equation:

$$I_C = \beta_1.I_B + \beta_2.(\beta_1 + 1).I_B$$

$$I_C = \beta_1.I_B + \beta_2.\beta_1.I_B + \beta_2.I_B$$

$$I_C = \left(\beta_1 + (\beta_2.\beta_1) + \beta_2\right).I_B$$

Where β_1 and β_2 are the gains of the individual transistors.

This means that the overall current gain, β is given by the gain of the first transistor multiplied by the gain of the second transistor as the current gains of the two transistors multiply. In other words, a pair of bipolar transistors combined together to make a single Darlington transistor pair can be regarded as a single transistor with a very high value of β and consequently a high input resistance.

14.6 Essentials of Transistor Oscillator

Fig. 14.7 shows the block diagram of an oscillator. Its essential components are :

(*i*) *Tank circuit.* It consists of inductance coil (L) connected in parallel with capacitor (C). The frequency of oscillations in the circuit depends upon the values of inductance of the coil and capacitance of the capacitor.

(*ii*) *Transistor amplifier.* The transistor amplifier receives d.c. power from the battery and changes it into a.c. power for supplying to the tank circuit. The oscillations occurring in the tank circuit are applied to the input of the transistor amplifier. Because of the amplifying properties of the transistor, we get increased output of these oscillations.

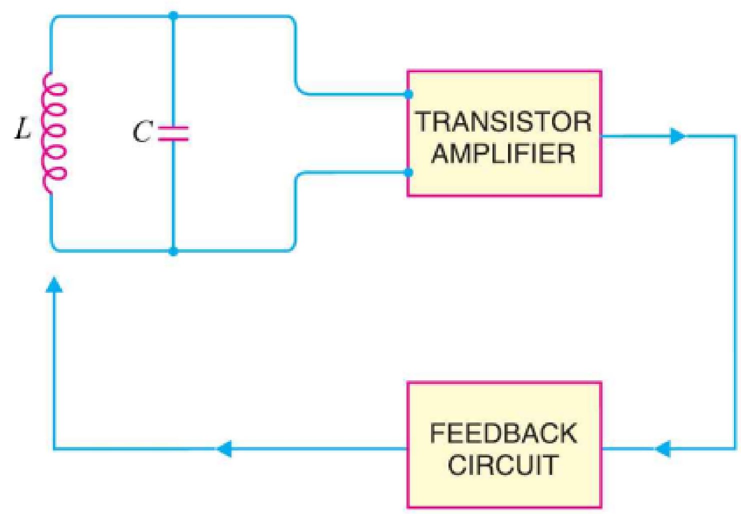


Fig. 14.7

This amplified output of oscillations is due to the d.c. power supplied by the battery. The output of the transistor can be supplied to the tank circuit to meet the losses.

(*iii*) Feedback circuit. The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillations *i.e.* it provides positive feedback.

$$m_v A_v = 1$$

where A_v = voltage gain of amplifer without feedback

m_v = feedback fraction

This relation is called *Barkhausen criterion*. This condition will be explained in the Art. 14.7.

14.7 Explanation of Barkhausen Criterion

Barkhausen criterion is that in order to produce continuous undamped oscillations at the output of an amplifier, the positive feedback should be such that :

$$m_v A_v = 1$$

Once this condition is set in the positive feedback amplifier, continuous undamped oscillations can be obtained at the output immediately after connecting the necessary power supplies.

(*i*) **Mathematical explanation.** The voltage gain of a positive feedback amplifier is given by;

$$A_{vf} = \frac{A_v}{1 - m_v A_v}$$

$$\text{If } m_v A_v = 1, \quad \text{then} \quad A_{vf} \to \infty.$$

We know that we cannot achieve infinite gain in an amplifier. So what does this result infer in physical terms? It means that a vanishing small input voltage would give rise to finite (*i.e.*, a definite amount of) output voltage even when the input signal is zero. Thus once the circuit receives the input trigger, it would become an oscillator, generating oscillations with no external signal source.

14.8 Different Types of Transistor Oscillators

A transistor can work as an oscillator to produce continuous undamped oscillations of any desired frequency if tank and feedback circuits are properly connected to it. All oscillators under different names have similar function *i.e.*, they produce continuous undamped output. However, the major difference between these oscillators lies in the method by which energy is supplied to the tank circuit to meet the losses. The following are the transistor oscillators commonly used at various places in electronic circuits :

(*i*) Tuned collector oscillator
(*ii*) Colpitt's oscillator
(*iii*) Hartley oscillator
(*iv*) Phase shift oscillator
(*v*) Wien Bridge oscillator
(*vi*) Crystal oscillator

14.9 Tuned Collector Oscillator

Fig.14.9 shows the circuit of tuned collector oscillator. It contains tuned circuit L_1-C_1 in the collector and hence the name. The frequency of oscillations depends upon the values of L_1 and C_1 and is given by :

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} \qquad \text{...}(i)$$

The feedback coil L_2 in the base circuit is magnetically coupled to the tank circuit coil L_1. In practice, L_1 and L_2 form the primary and secondary of the transformer respectively. The biasing is provided by potential divider arrangement. The capacitor C connected in the base circuit provides low reactance path to the oscillations.

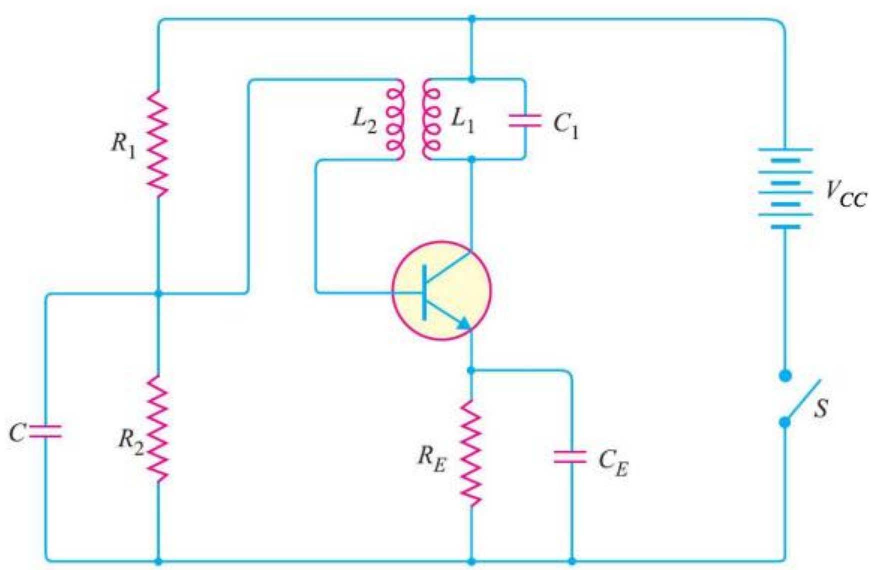


Fig. 14.9

Circuit operation. When switch S is closed, collector current starts increasing and charges the capacitor C_1. When this capacitor is fully charged, it discharges through coil L_1, setting up oscillations of frequency determined by exp. (*i*). These oscillations induce some voltage in coil L_2 by mutual induction. The frequency of voltage in coil L_2 is the same as that of tank circuit but its magnitude depends upon the number of turns of L_2 and coupling between L_1 and L_2. The voltage across L_2 is applied between base and emitter and appears in the amplified form in the collector circuit, thus overcoming the losses occurring in the tank circuit. The number of turns of L_2 and coupling between L_1 and L_2 are so adjusted that oscillations across L_2 are amplified to a level just sufficient to supply losses to the tank circuit.

It may be noted that the phase of feedback is correct *i.e.* energy supplied to the tank circuit is in phase with the generated oscillations. A phase shift of 180° is created between the voltages of L_1 and L_2 due to transformer *action. A further phase shift of 180° takes place between base-emitter and collector circuit due to transistor properties. As a result, the energy fedback to the tank circuit is in phase with the generated oscillations.

14.10 Colpitt's Oscillator

Fig. 14.10 shows a Colpitt's oscillator. It uses two capacitors and placed across a common inductor L and the centre of the two capacitors is tapped. The tank circuit is made up of C_1, C_2 and L. The frequency of oscillations is determined by the values of C_1, C_2 and L and is given by ;

$$f = \frac{1}{2\pi\sqrt{LC_T}} \qquad \text{....}(i)$$

where

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

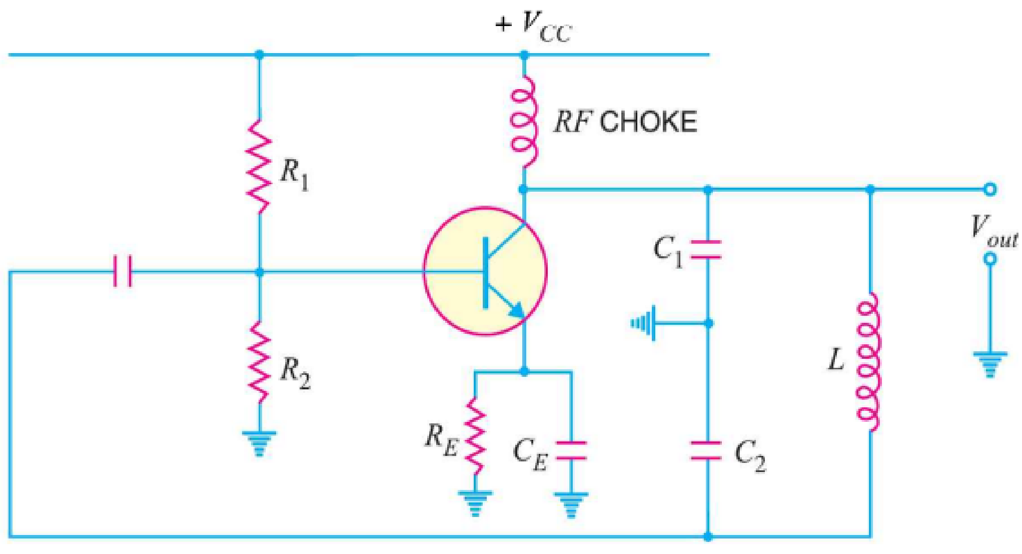


Fig. 14.10

*Note that $C_1 - C_2 - L$ is also the feedback circuit that produces a phase shift of 180°.

Circuit operation. When the circuit is turned on, the capacitors C_1 and C_2 are charged. The capacitors discharge through L, setting up oscillations of frequency determined by exp.** (*i*). The output voltage of the amplifier appears across C_1 and feedback voltage is developed across C_2. The voltage across it is 180° out of phase with the voltage developed across C_1 (V_{out}) as shown in Fig. 14.11. It is easy to see that voltage fedback (voltage across C_2) to the transistor provides positive feedback. A phase shift of 180° is produced by the transistor and a further phase shift of 180° is produced by $C_1 - C_2$ voltage divider. In this way, feedback is properly phased to produce continuous undamped oscillation.

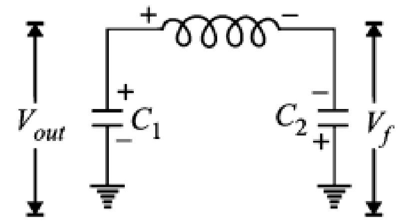


Fig. 14.11

25.2 Differential Amplifier (DA)

Since differential amplifier (*DA*) is key to the operation of *OP*-Amp, we shall discuss this circuit in detail. So far in the book we have considered general-purpose amplifiers. In these conventional amplifiers, the signal (generally single input) is applied at the input terminals and amplified output is obtained at the output terminals. However, we can design an amplifier circuit that accepts two input signals and amplifies the difference between these two signals. Such an amplifier is called a **differential amplifier* (*DA*).

A **differential amplifier** *is a circuit that can accept two input signals and amplify the difference between these two input signals.*

Fig. 25.2 shows the block diagram of an ordinary amplifier. The input voltage v is amplified to Av where A is the voltage gain of the amplifier. Therefore, the ouput voltage is $v_0 = Av$.

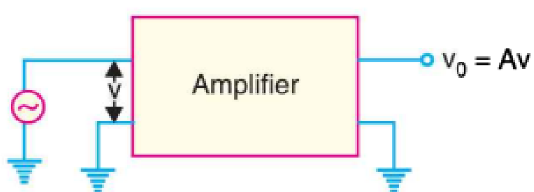


Fig. 25.2

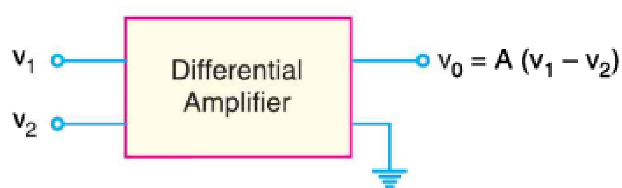


Fig.25.3

Fig. 25.3 shows the block diagram of a differential amplifier. There are two input voltages v_1 and v_2. This amplifier amplifies the difference between the two input voltages. Therefore, the output voltage is $v_0 = A(v_1 - v_2)$ where A is the voltage gain of the amplifier.

Example 25.1. *A differential amplifier has an open-circuit voltage gain of 100. The input signals are 3.25 V and 3.15V. Determine the output voltage.*

Solution.

Output voltage, $v_0 = A(v_1 - v_2)$

Here, $A = 100$; $v_1 = 3.25$ V : $v_2 = 3.15$V

$\therefore$ $v_0 = 100(3.25 - 3.15) = \mathbf{10V}$

25.15 Operational Amplifier (OP- Amp)

Fig. 25.38 shows the block diagram of an operational amplifier (*OP*-amp). The input stage of an *OP*- amp is a differential stage followed by more stages of gain and a class *B* push-pull emitter follower.

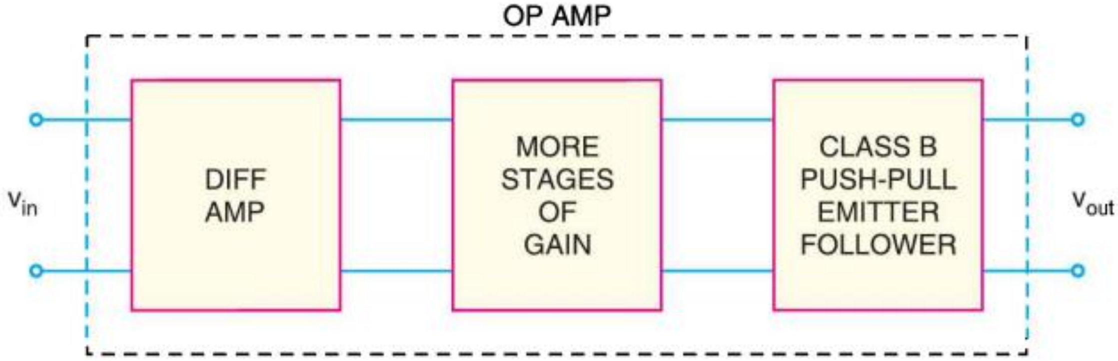


Fig. 25.38

The following are the important properties common to all operational amplifiers (*OP*-amps):

(*i*) An operational amplifier is a multistage amplifier. The input stage of an *OP*-amp is a differential amplifier stage.

(*ii*) An inverting input and a noninverting input.

(*iii*) A high input impedance (usually assumed infinite) at both inputs.

(*iv*) A low output impedance (< 200 Ω).

(*v*) A large open-loop voltage gain, typically 10^5.

(*vi*) The voltage gain remains constant over a wide frequency range.

(*vii*) Very large *CMRR* (> 90 dB).

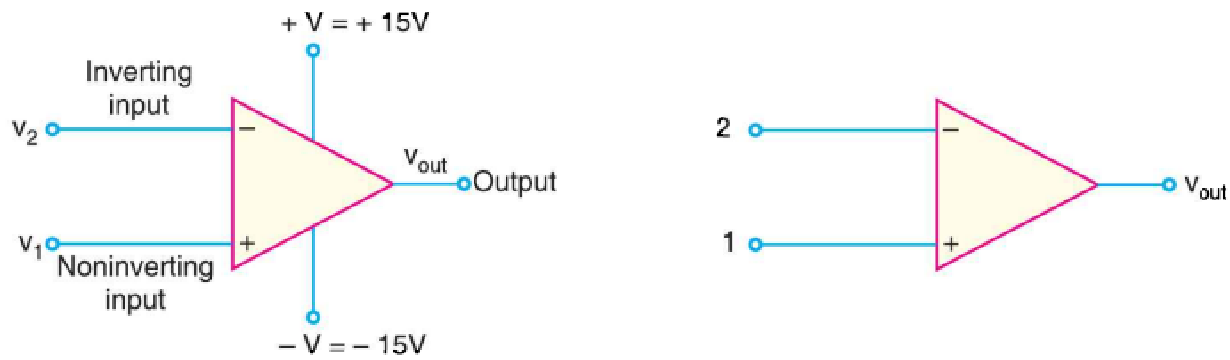
25.16 Schematic Symbol of Operational Amplifier

Fig.25.39(*i*) shows the schematic symbol of an operational amplifier. The following points are worth noting :

(*i*) The basic operational amplifier has *five terminals: two terminals for supply voltages +V and –V; two input terminals (inverting input and noninverting input) and one output terminal.

(ii) Note that the input terminals are marked + and –. These are not polarity signs. The – sign indicates the ***inverting input*** while the + sign indicates the ***noninverting input.*** A signal applied to plus terminal will appear in the same phase at the output as at the input. A signal applied to the minus terminal will be shifted in phase 180° at the output.

(iii) The voltages v_1, v_2 and v_{out} are node voltages. This means that they are always measured w.r.t. ground. The differential input v_{in} is the difference of two node voltages v_1 and v_2. We normally do not show the ground in the symbol.



(*i*) (*ii*)

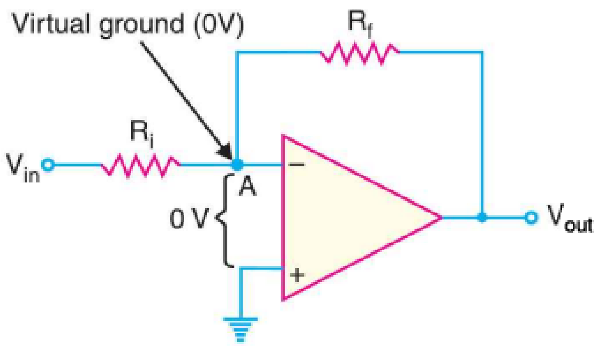
Fig. 25.39

(iv) For the sake of *simplicity, + *V* and – *V* terminals are often omitted from the symbol as shown in Fig. 25.39(*ii*). The two input leads are always shown on the symbol regardless of whether they are both used.

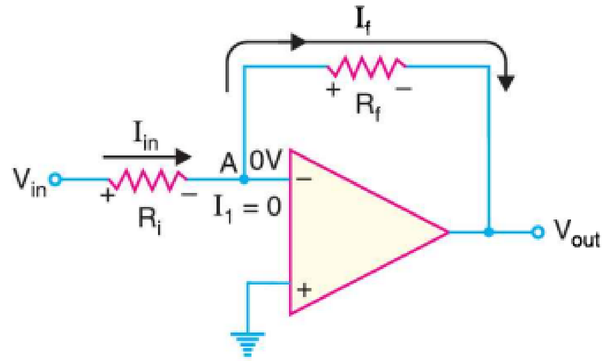
(v) In most cases, if only one input is required for an *OP*-amp circuit, the input not in use will be shown connected to ground. A single-input *OP*-amp is generally classified as either inverting or noninverting.

(vi) The *OP*-amp is produced as an integrated circuit (*IC*). Because of the complexity of the internal circuitry of an *OP*-amp, the *OP*-amp symbol is used exclusively in circuit diagrams.

Voltage gain. An OP-amp has an infinite input impedance. This means that there is zero current at the inverting input. If there is zero current through the input impedance, then there must be *no* voltage drop between the inverting and non-inverting inputs. This means that voltage at the inverting input (–) is zero (point A) because the other input (+) is grounded. The 0V at the inverting input terminal (point A) is referred to as **virtual ground.** This condition is illustrated in Fig. 25.47. The point A is said to be at virtual ground because it is at 0V but is not physically connected to the ground (*i.e.* $V_A = 0V$).



(*i*)



(*ii*)

Fig. 25.47

Referring to Fig. 25.47 (*ii*), the current I_1 to the inverting input is zero. Therefore, current I_{in} flowing through R_i entirely flows through feedback resistor R_f. In other words, $I_f = I_{in}$.

Now $$I_{in} = \frac{\text{Voltage across } R_i}{R_i} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

and $$I_f = \frac{\text{Voltage across } R_f}{R_f} = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

$$\text{Since } I_f = I_{in}, \quad -\frac{V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

$$\therefore \quad \text{Voltage gain, } A_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

Example 25.25. *Given the OP-amp configuration in Fig. 25.49, determine the value of R_f required to produce a closed-loop voltage gain of –100.*

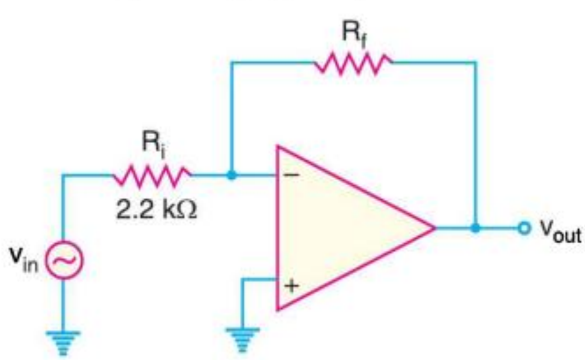


Fig. 25.49

Solution. $$A_{CL} = -\frac{R_f}{R_i} \quad \text{or} \quad -100 = -\frac{R_f}{2.2}$$

$\therefore$ $$R_f = 100 \times 2.2 = \mathbf{220\ k\Omega}$$

Example 25.29. *For the circuit shown in Fig. 25.53, find (i) closed-loop voltage gain (ii) input impedance of the circuit (iii) the maximum operating frequency. The slew rate is 0.5V/μs.*

Solution.

(*i*) Closed-loop voltage gain, $A_{CL} = -\frac{R_f}{R_i} = -\frac{100\ k\Omega}{10\ k\Omega} = \mathbf{-10}$

(*ii*) The input impedance Z_i of the circuit is

$$Z_i \simeq R_i = \mathbf{10\ k\Omega}$$

(*iii*) To calculate the maximum operating frequency (f_{max}) for this inverting amplifier, we need to determine its peak output voltage. With values of $V_{in} = 1\ V_{pp}$ and $A_{CL} = 10$, the peak-to-peak output voltage is

$$V_{out} = (1V_{pp})\,(A_{CL})$$
$$= (1V_{pp}) \times 10 = 10\ V_{pp}$$

Therefore, the peak output voltage is

$$V_{pk} = 10/2 = 5\ V$$

$$\therefore \quad f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\ V/\mu s}{2\pi \times 5}$$

$$= \frac{500\ kHz}{2\pi \times 5} = \mathbf{15.9\ kHz}$$

$(\because\ 0.5\ V/\mu s = 500\ kHz)$

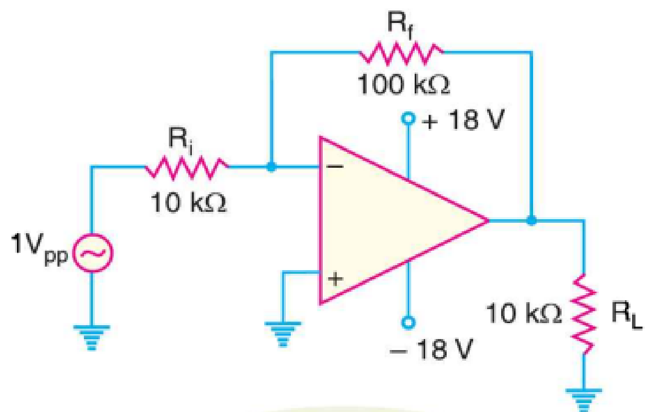


Fig. 25.53

25.26 Noninverting Amplifier

There are times when we wish to have an output signal of the same polarity as the input signal. In this case, the *OP*-amp is connected as noninverting amplifier as shown in Fig. 25.55. The input signal is applied to the noninverting input (+). The output is applied back to the input through the feedback circuit formed by feedback resistor R_f and input resistance R_i. Note that resistors R_f and R_i form a voltage divide at the inverting input (–). This produces **negative feedback* in the circuit. Note that R_i is grounded. Since the input signal is applied to the noninverting input (+), the output signal will be noninverted i.e., the output signal will be in phase with the input signal. Hence, the name non-inverting amplifier.

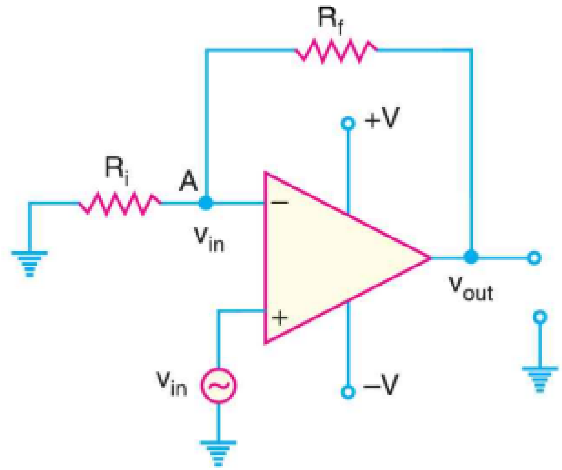


Fig. 25.55

Voltage gain. If we assume that we are not at saturation, the potential at point A is the same as V_{in}. Since the input impedance of *OP*-amp is very high, all of the current that flows through R_f also flows through R_i. Keeping these things in mind, we have,

$$\text{Voltage across } R_i = V_{in} - 0 \;;\; \text{Voltage across } R_f = V_{out} - V_{in}$$

Now $\quad$ Current through R_i = Current through R_f

or $$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

or $$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

or $$V_{in}(R_f + R_i) = V_{out} R_i$$

or $$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

$\therefore$ Closed-loop voltage gain, $A_{CL} = \dfrac{V_{out}}{V_{in}} = 1 + \dfrac{R_f}{R_i}$

The following points may be noted about the noninverting amplifier :

(i) $$A_{CL} = 1 + \frac{R_f}{R_i}$$

Example 25.34. *For the noninverting amplifier circuit shown in Fig. 25.59, find peak-to-peak output voltage.*

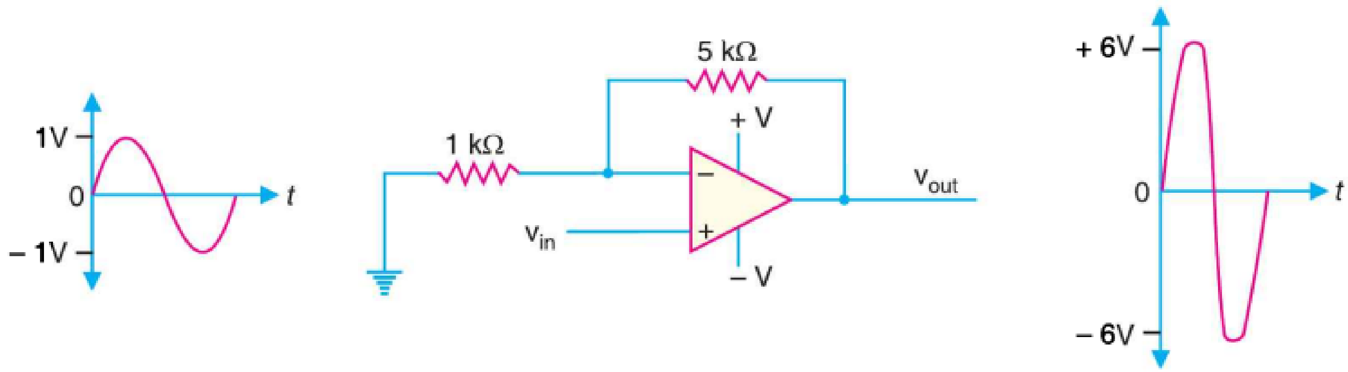


Fig. 25.59

Solution. The input signal is 2 V peak-to-peak.

$$\text{Voltage gain, } A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{5\text{ k}\Omega}{1\text{ k}\Omega} = 1 + 5 = 6$$

$\therefore$ Peak-to-peak output voltage $= A_{CL} \times v_{inpp} = 6 \times 2 = \mathbf{12\ V}$

Example 25.35. *For the noninverting amplifier circuit shown in Fig. 25.60, find (i) closed-loop voltage gain (ii) maximum operating frequency. The slew rate is 0.5 V/µs.*

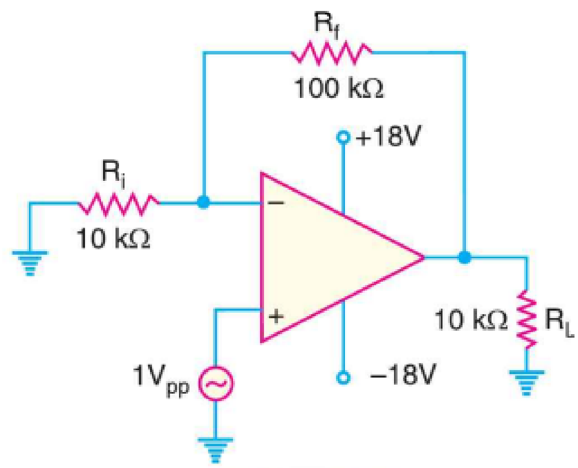


Fig. 25.60

Solution.

(i) Voltage gain, $A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\ \text{k}\Omega}{10\ \text{k}\Omega} = 1 + 10 = \mathbf{11}$

(ii) To determine the value of maximum operating frequency (f_{max}), we need to calculate the peak output voltage for the amplifier. The peak-to-peak output voltage is

$$v_{out} = A_{CL} \times v_{in} = 11 \times (1V_{pp}) = 11V_{pp}$$

$\therefore$ Peak output voltage, $V_{pk} = 11/2 = 5.5\ \text{V}$

$$\therefore \quad f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5\ \text{V}/\mu\text{s}}{2\pi \times 5.5}$$

$$= \frac{500\ \text{kHz}}{2\pi \times 5.5} = \mathbf{14.47\ kHz} \qquad (\because\ 0.5\ \text{V}/\mu\text{s} = 500\ \text{kHz})$$