18.12 Transistor Astable Multivibrator

A multivibrator which generates square waves of its own (i.e. without any external triggering pulse) is known as an **astable** *or* **free running multivibrator.**

The *astable multivibrator has no stable state. It switches back and forth from one state to the other, remaining in each state for a time determined by circuit constants. In other words, at first one transistor conducts (*i.e.* ON state) and the other stays in the OFF state for some time. After this period of time, the second transistor is automatically turned ON and the first transistor is turned OFF. Thus the multivibrator will generate a square wave output of its own. The width of the square wave and its frequency will depend upon the circuit constants.

Circuit details. Fig. 18.13 shows the circuit of a typical transistor astable multivibrator using two identical transistors Q_1 and Q_2. The circuit essentially consists of two symmetrical *CE* amplifier stages, each providing a feedback to the other. Thus collector loads of the two stages are equal *i.e.* $R_1 = R_4$ and the biasing resistors are also equal *i.e.* $R_2 = R_3$. The output of transistor Q_1 is coupled to the input of Q_2 through C_1 while the output of Q_2 is fed to the input of Q_1 through C_2. The square wave output can be taken from Q_1 or Q_2.

Operation. When V_{CC} is applied, collector currents start flowing in Q_1 and Q_2. In addition, the coupling capacitors C_1 and C_2 also start charging up. As the characteristics of no two transistors (*i.e.* β, V_{BE}) are *exactly* alike, therefore, one transistor, say Q_1, will conduct more rapidly than the other. The rising collector current in Q_1 drives its collector more and more positive. The increasing positive output at point *A* is applied to the base of transistor Q_2 through C_1. This establishes a reverse

* A means not. Hence astable means that it has no stable state.

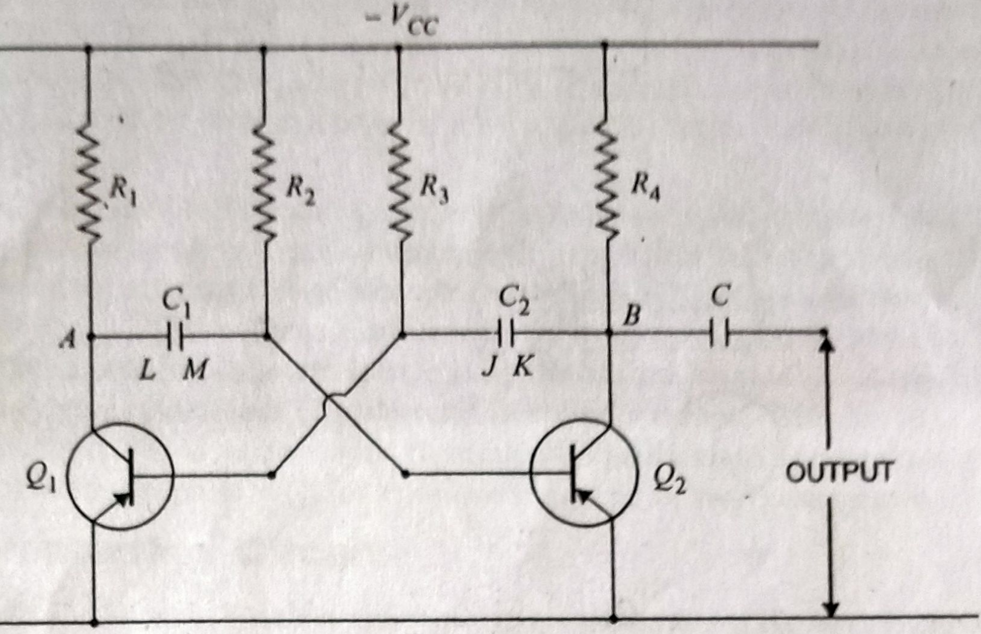


Fig. 18.13

bias on Q_2 and its collector current starts decreasing. As the collector of Q_2 is connected to the base of Q_1 through C_2, therefore, base of Q_1 becomes more negative *i.e.* Q_1 is more forward biased. This further increases the collector current in Q_1 and causes a further decrease of collector current in Q_2. This series of actions is repeated until the circuit drives Q_1 to saturation and Q_2 to cut off. These actions occur very rapidly and may be considered practically instantaneous. The output of Q_1 (ON state) is approximately zero and that of Q_2 (OFF state) is approximately V_{CC}. This is shown by *ab* in Fig. 18.14.

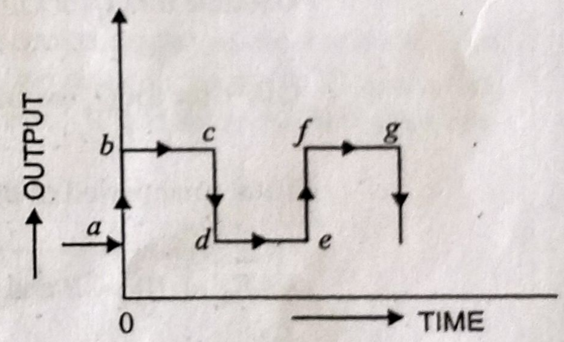


Fig. 18.14

When Q_1 is at saturation and Q_2 is cut off, the full voltage V_{CC} appears across R_1 and voltage across R_4 will be zero. The charges developed across C_1 and C_2 are sufficient to maintain the saturation and cut off conditions at Q_1 and Q_2 respectively. This condition is represented by time interval *bc* in Fig. 18.14. However, the capacitors will not retain the charges indefinitely but will discharge through their respective circuits. The discharge path for C_1, with plate *L* negative and Q_1 conducting, is $LAQ_1V_{CC}R_2M$ as shown in Fig. 18.15 (*i*).

The discharge path for C_2, with plate *K* negative and Q_2 cut off, is KBR_4R_3J as shown in Fig. 18.15 (*ii*). As the resistance of the discharge path for C_1 is lower than that of C_2, therefore, C_1 will discharge more rapidly.

As C_1 discharges, the base bias at Q_2 becomes less positive and at a time determined by R_2 and C_1, forward bias is re-established at Q_2. This causes the collector current to start in Q_2. The increasing positive potential at collector of Q_2 is applied to the base of Q_1 through the capacitor C_2. Hence the base of Q_1 will become more positive *i.e.* Q_1 is reverse biased. The decrease in collector current in Q_1 sends a negative voltage to the base of Q_2 through C_1, thereby causing fu ther increase in the collector current of Q_2. With this set of actions taking place, Q_2 is quickly driven o saturation and Q_1 to cut off. This condition is represented by *cd* in Fig. 18.14. The period of tir ie during which Q_2 remains at saturation and Q_1 at cut off is determined by C_2 and R_3.

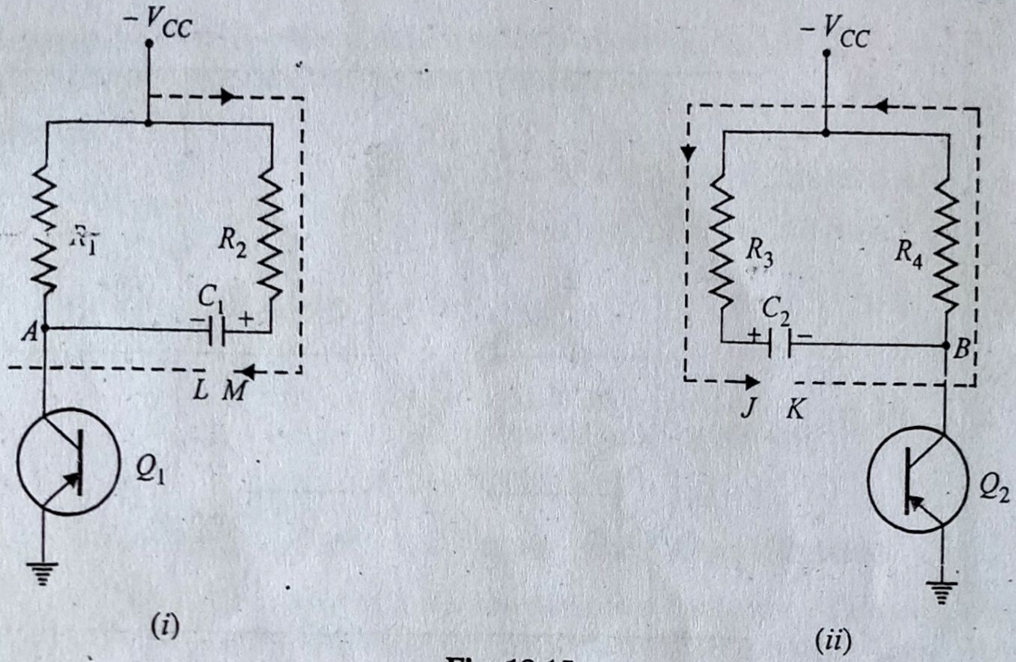


Fig. 18.15

ON or OFF time. The time for which either transistor remains ON or OFF is given by :

ON time for Q_1 (or OFF time for Q_2) is

$$T_1 = 0.694 R_2 C_1$$

OFF time for Q_1 (or ON time for Q_2) is

$$T_2 = 0.694 R_3 C_2$$

Total time period of the square wave is

$$T = T_1 + T_2 = 0.694 (R_2 C_1 + R_3 C_2)$$

As $R_2 = R_3 = R$ and $C_1 = C_2 = C$,

$$\therefore \quad T = 0.694 (RC + RC) \simeq 1.4 \, RC \text{ seconds}$$

Frequency of the square wave is

$$f = \frac{1}{T} \simeq \frac{0.7}{RC} \text{ Hz}$$

It may be noted that in these expressions, R is in ohms and C in farad.

Example 18.4. *In the astable multivibrator shown in Fig. 18.13, $R_2 = R_3 = 10 \text{ k}\Omega$ and $C_1 = C_2 = 0.01 \mu F$. Determine the time period and frequency of the square wave.*

Solution.

Here $R = 10 \text{ k}\Omega = 10^4 \Omega$; $C = 0.01 \mu\text{F} = 10^{-8}$ F

Time period of the square wave is

$$T = 1.4 \, RC = 1.4 \times 10^4 \times 10^{-8} \text{ second}$$
$$= 1.4 \times 10^{-4} \text{ second} = 1.4 \times 10^{-4} \times 10^3 \text{ m sec}$$
$$= \mathbf{0.14 \text{ m sec}}$$

Frequency of the square wave is

$$f = \frac{1}{T \text{ in second}} \text{ Hz} = \frac{1}{1.4 \times 10^{-4}} \text{ Hz}$$
$$= 7 \times 10^3 \text{ Hz} = \mathbf{7 \text{ kHz}}$$

18.13 Transistor Monostable Multivibrator

A multivibrator in which one transistor is always conducting (i.e. in the ON state) and the other is non-conducting (i.e. in the OFF state) is called a **monostable multivibrator.**

A *monostable multivibrator has only one state stable. In other words, if one transistor is conducting and the other is non-conducting, the circuit will remain in this position. It is only with the application of external pulse that the circuit will interchange the states. However, after a certain time, the circuit will automatically switch back to the original stable state and remains there until another pulse is applied. Thus a monostable multivibrator cannot generate square waves of its own like an astable multivibrator. Only external pulse will cause it to generate the square wave.

Circuit details. Fig. 18.16 shows the circuit of a transistor monostable multivibrator. It consists of two similar transistors Q_1 and Q_2 with equal collector loads *i.e.* $R_1 = R_4$. The values of V_{BB} and R_5 are such as to reverse bias Q_1 and keep it at cut off. The collector supply V_{CC} and R_2 forward bias Q_2 and keep it at saturation. The input pulse is given through C_2 to obtain the square wave. Again output can be taken from Q_1 or Q_2.

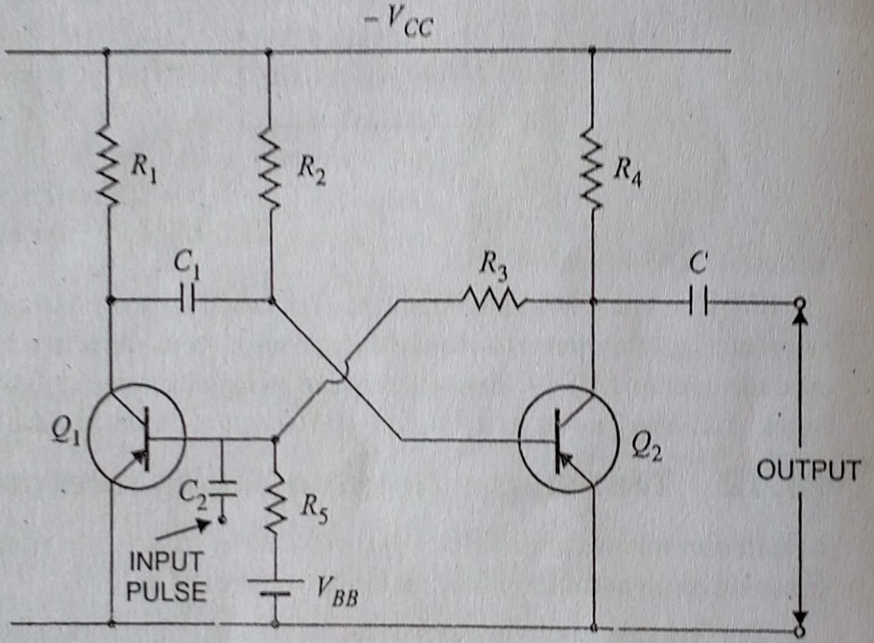
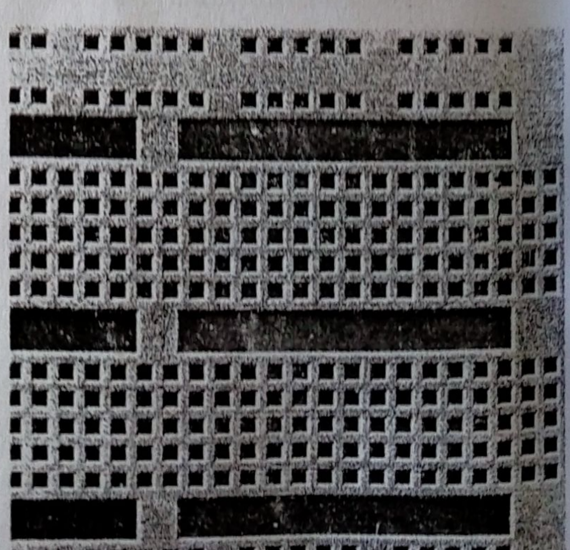


Fig. 18.16

Operation. With the circuit arrangement shown, Q_1 is at cut off and Q_2 is at saturation. This is the stable state for the circuit and it will continue to stay in this state until a triggering pulse is applied at C_2. When a negative pulse of short duration and sufficient magnitude is applied to the base of Q_1 through C_2, the transistor Q_1 starts conducting and positive potential is established at its collector. The positive potential at the collector of Q_1 is coupled to the base of Q_2 through capacitor C_1. This decreases the forward bias on Q_2 and its collector current decreases. The increasing negative potential on the collector of Q_2 is applied to the base of Q_1 through R_3. This further increases the forward bias on Q_1 and hence its collector current. With this set of actions taking place, Q_1 is quickly driven to saturation and Q_2 to cut off.



Monostable Multivibrator

* Mono means single.

With Q_1 at saturation and Q_2 at cut off, the circuit will come back to the original stage (*i.e.* Q_2 at saturation and Q_1 at cut off) after some time as explained in the following discussion. The capacitor C_1 (charged to approximately V_{CC}) discharges through the path $R_2 V_{CC} Q_1$. As C_1 discharges, it sends a voltage to the base of Q_2 to make it less positive. This goes on until a point is reached when forward bias is re-established on Q_2 and collector current starts to flow in Q_2. The step by step events already explained occur and Q_2 is quickly driven to saturation and Q_1 to cut off. This is the stable state for the circuit and it remains in this condition until another pulse causes the circuit to switch over the states.

18.14 Transistor Bistable Multivibrator

A multivibrator which has both the states stable is called a **bistable multivibrator.**

The bistable multivibrator has both the states stable. It will remain in whichever state it happens to be until a trigger pulse causes it to switch to the other state. For instance, suppose at any particular instant, transistor Q_1 is conducting and transistor Q_2 is at cut off. If left to itself, the bistable multivibrator will stay in this position forever. However, if an external pulse is applied to the circuit in such a way that Q_1 is cut off and Q_2 is turned on, the circuit will stay in the new position. Another trigger pulse is then required to switch the circuit back to its original state.

Circuit details. Fig. 18.17 shows the circuit of a typical transistor bistable multivibrator. It consists of two identical *CE* amplifier stages with output of one fed to the input of the other. The feedback is coupled through resistors (R_2, R_3) shunted by capacitors C_1 and C_2. The main purpose of capacitors C_1 and C_2 is to improve the switching characteristics of the circuit by passing the high frequency components of the square wave. This allows fast rise and fall times and hence distortionless square wave output. The output can be taken across either transistor.

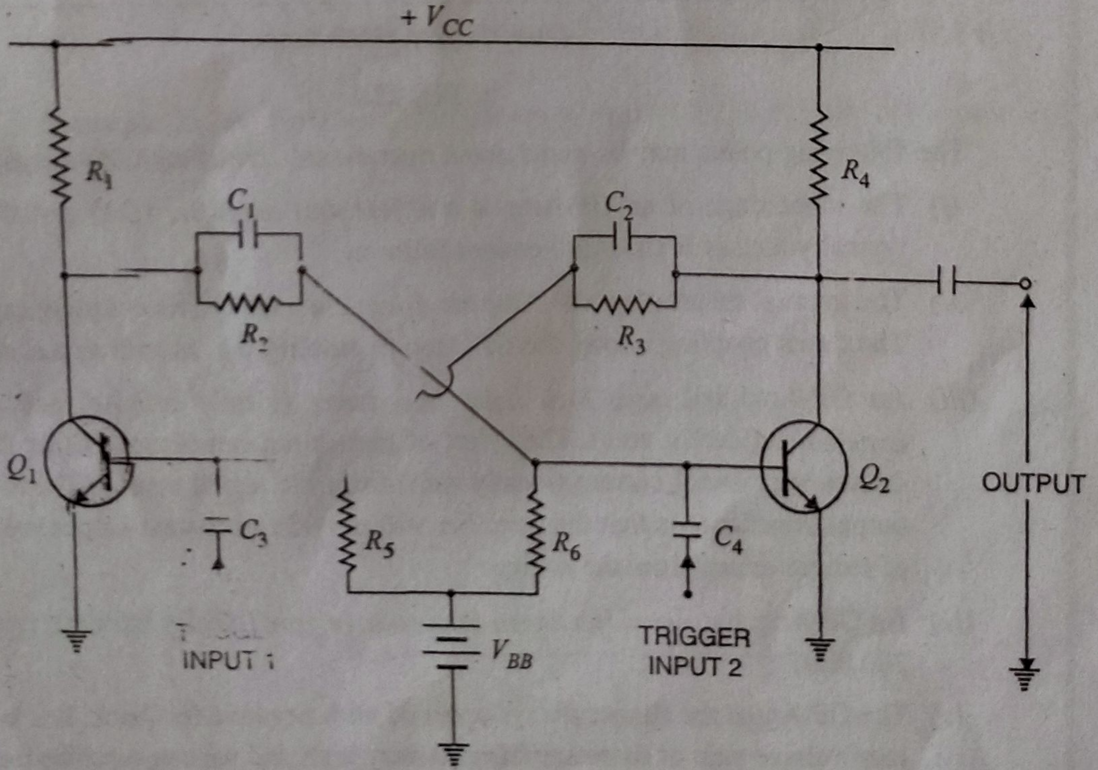


Fig. 18.17

Operation. When V_{CC} is applied, one transistor will start conducting slightly ahead of the other due to some differences in the characteristics of the transistors. This will drive one transistor to saturation and the other to cut off in a manner described for the astable multivibrator. Assume that Q_1 is turned ON and Q_2 is cut OFF. If left to itself, the circuit will stay in this condition. In order to switch the multivibrator to its other state, a trigger pulse must be applied. A negative pulse applied to the base of Q_1 through C_3 will cut it off or a positive pulse applied to the base of Q_2 through C_4 will cause it to conduct.

Suppose a negative pulse of sufficient magnitude is applied to the base of Q_1 through C_3. This will reduce the forward bias on Q_1 and cause a decrease in its collector current and an increase in collector voltage. The rising collector voltage is coupled to the base of Q_2 where it forward biases the base-emitter junction of Q_2. This will cause an increase in its collector current and decrease in collector voltage. The decreasing collector voltage is applied to the base of Q_1 where it further reverse biases the base-emitter junction of Q_1 to decrease its collector current. With this set of actions taking place, Q_2 is quickly driven to saturation and Q_1 to cut off. The circuit will now remain stable in this state until a negative trigger pulse at Q_2 (or a positive trigger pulse at Q_1) changes this state.

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.

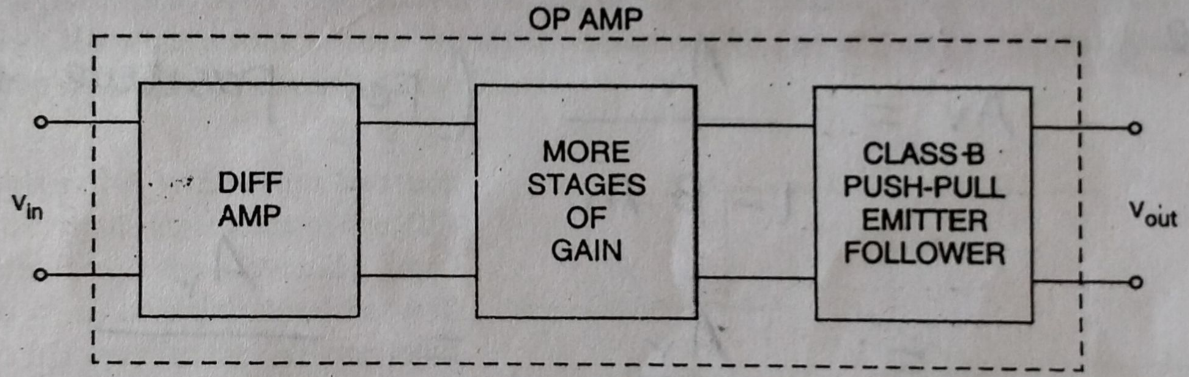


Fig. 25.38

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 ($< 200\ \Omega$).

(*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.

* Two other terminals, the *offset null terminals*, are used to ensure zero output when the two inputs are equal. These are normally used when small d.c. signals are involved.

25.23 Applications of OP-Amps

The operational amplifiers have many practical applications. The *OP*-amp can be connected in a large number of circuits to provide various operating characteristics. In the sections to follow, we shall discuss important applications of *OP*-amps.

25.24 Inverting Amplifier

An *OP* amplifier can be operated as an inverting amplifier as shown in Fig. 25.46. An input signal v_{in} is applied through input resistor R_i to the minus input (inverting input). The output is fed back to the same minus input through feedback resistor R_f. The plus input (noninverting input) is grounded. Note that the resistor R_f provides the **negative feedback*. Since the input signal is applied to the inverting input (–), the output will be inverted (*i.e.* 180° out of phase) as compared to the input. Hence the name inverting amplifier.

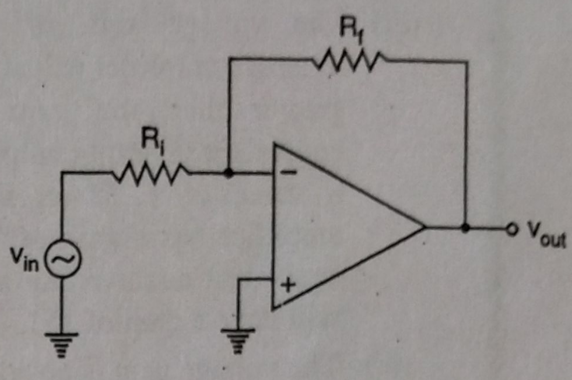
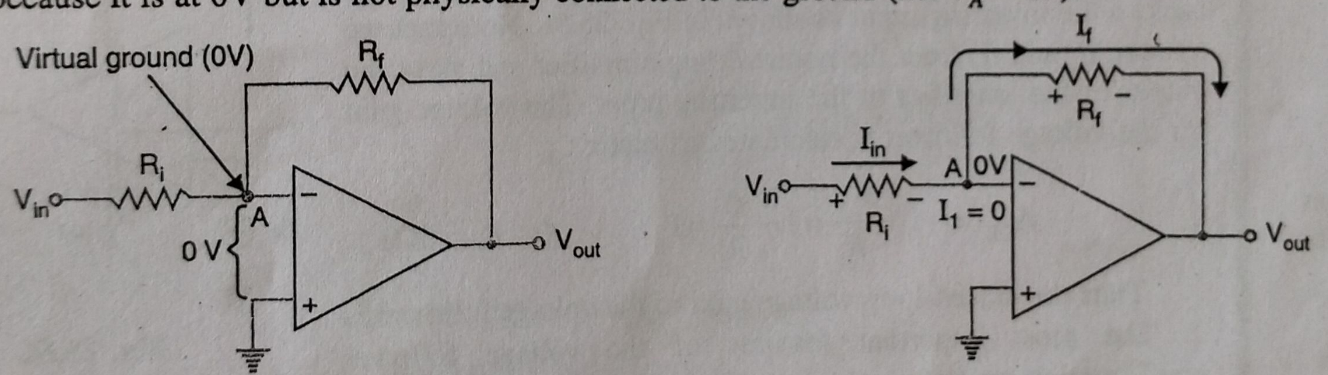


Fig. 25.46

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

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

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

* The output voltage is 180° out of phase with the input. Since the voltage drop across R_f is of the opposite polarity to the applied voltage, the circuit is providing negative feedback.

The negative sign indicates that output signal is inverted as compared to the input signal. The following points may be noted about the inverting amplifier :

(*i*) The closed-loop voltage gain (A_{CL}) of an inverting amplifier is the ratio of the feedback resistance R_f to the input resistance R_i. *The closed-loop voltage gain is independent of the OP-amp's internal open-loop voltage gain.* Thus the negative feedback stabilises the voltage gain.

(*ii*) The inverting amplifier can be designed for unity gain. Thus if $R_f = R_i$, then voltage gain, $A_{CL} = -1$. Therefore, the circuit provides a unity voltage gain with 180° phase inversion.

(*iii*) If R_f is some multiple of R_i, the amplifier gain is constant. For example, if $R_f = 10\ R_i$, then $A_{CL} = -10$ and the circuit provides a voltage gain of exactly 10 along with a 180° phase inversion from the input signal. If we select precise resistor values for R_f and R_i, we can obtain a wide range of voltage gains. *Thus the inverting amplifier provides constant voltage gain.*

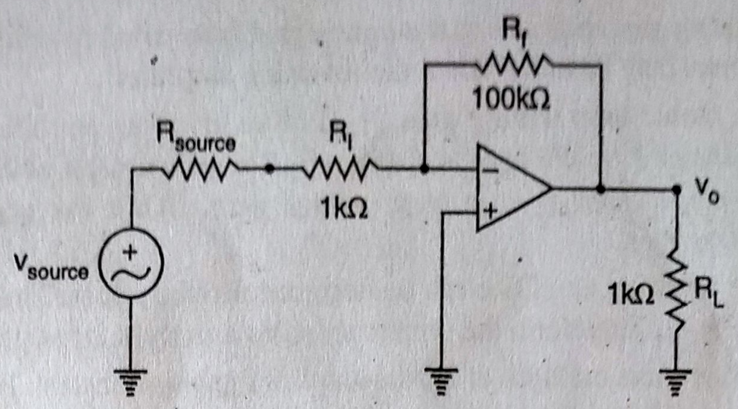


Fig. 25.54

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.

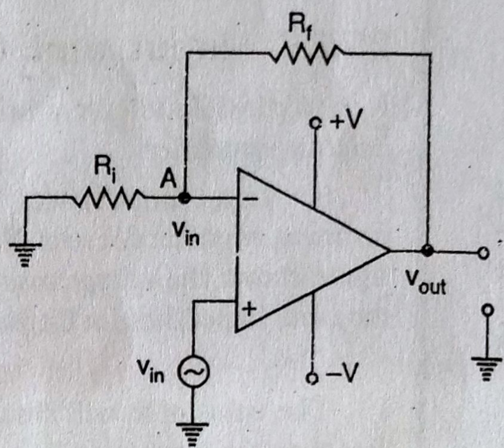


Fig. 25.55

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

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

The following points may be noted about the noninverting amplifier :

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

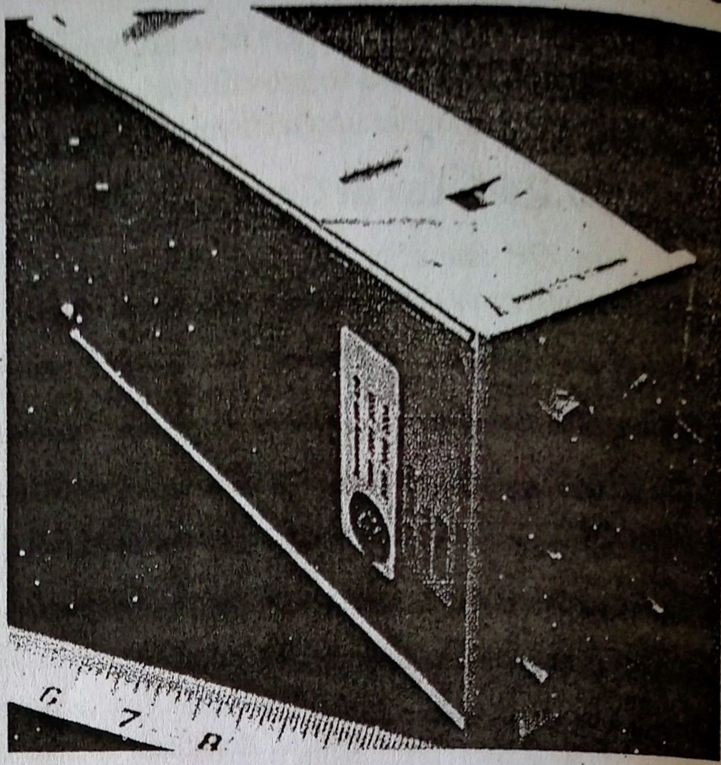
* If the output voltage increases, the voltage at the inverting input will also increase. Since the voltage being amplified is the difference between the voltages at the two input terminals, the differential voltage will decrease when the output voltage increases. Therefore, the circuit provides negative feedback.

The voltage gain of noninverting amplifier also depends upon the values of R_f and R_i.

(ii) The voltage gain of a non-inverting amplifier can be made equal to or greater than 1.

(iii) The voltage gain of a non-inverting amplifier will always be greater than the gain of an equivalent inverting amplifier by a value of 1. If an inverting amplifier has a gain of 150, the equivalent noninverting amplifier will have a gain of 151.

(iv) The voltage gain is positive. This is not surprising because output signal is in phase with the input signal.



Non-inverting operational amplifier.

25.27 Voltage Follower

The voltage follower arrangement is a special case of noninverting amplifier where all of the output voltage is fed back to the inverting input as shown in Fig. 25.56. Note that we remove R_i and R_f from the noninverting amplifier and short the output of the amplifier to the inverting input. The voltage gain for the voltage follower is calculated as under :

$$A_{CL} = 1+\frac{R_f}{R_i}=1+\frac{0}{R_i}=1 \qquad (\because R_f = 0\Omega)$$

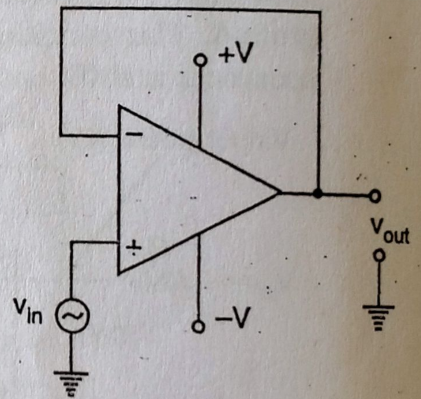


Fig. 25.56

Thus the closed-loop voltage gain of the voltage follower is 1. The most important features of the voltage follower configuration are its *very high input impedance* and its *very low output impedance*. These features make it a nearly ideal buffer amplifier to be connected between high-impedance sources and low-impedance loads.

Example 25.32. *Calculate the output voltage from the noninverting amplifier circuit shown in Fig. 25.57 for an input of 120 μV.*

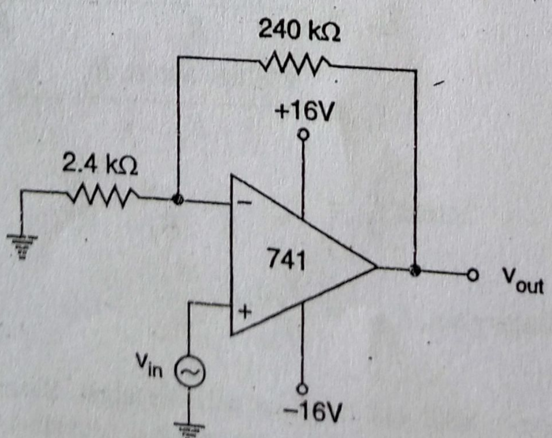


Fig. 25.57

25.33 Applications of Summing Amplifiers

By proper modifications, a summing amplifier can be made to perform many useful functions. There are a number of applications of summing amplifiers. However, we shall discuss the following two applications by way of illustration:

1. As averaging amplifier
2. As subtractor

1. As averaging amplifier. By using the proper input and feedback resistor values, a summing amplifier can be designed to provide an output voltage that is equal to the *average* of input voltages. A summing amplifier will act as an averaging amplifier when *both* of the following conditions are met:

(*i*) All input resistors (R_1, R_2 and so on) are *equal in value.*

(*ii*) The ratio of any input resistor to the feedback resistor is equal to the number of input circuits.

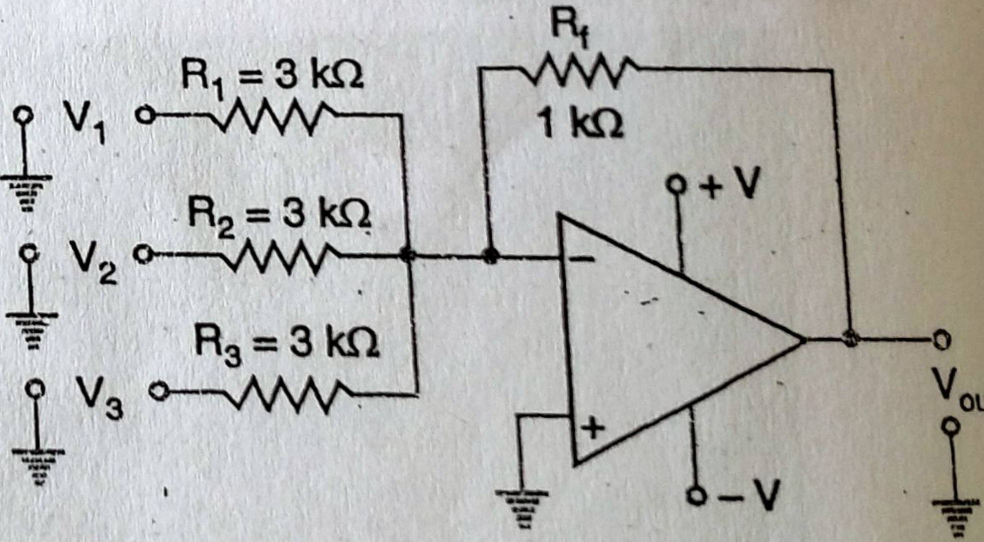


Fig. 25.77

Fig. 25.77 shows the circuit of averaging amplifier. Note that it is a summing amplifier meeting the above two conditions. All input resistors are equal in value (3 kΩ). If we take the ratio of any input resistor to the feedback resistor, we get 3 kΩ/ 1 kΩ = 3. This is equal to the number of inputs to the circuit. Referring to the circuit in Fig. 25.77, the output voltage is given by;

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

Now $$\frac{R_f}{R_1} = \frac{R_f}{R_2} = \frac{R_f}{R_3} = \frac{1\,\text{k}\Omega}{3\,\text{k}\Omega} = \frac{1}{3}$$

$\therefore$ $$V_{out} = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

Note that V_{out} is equal to the average of the three inputs. The negative sign shows the phase reversal.

2. **As subtractor.** A summing amplifier can be used to provide an output voltage that is equal to the difference of two voltages. Such a circuit is called a **subtractor** and is shown in Fig. 25.78. As we shall see, this circuit will provide an output voltage that is equal to the difference between V_1 and V_2.

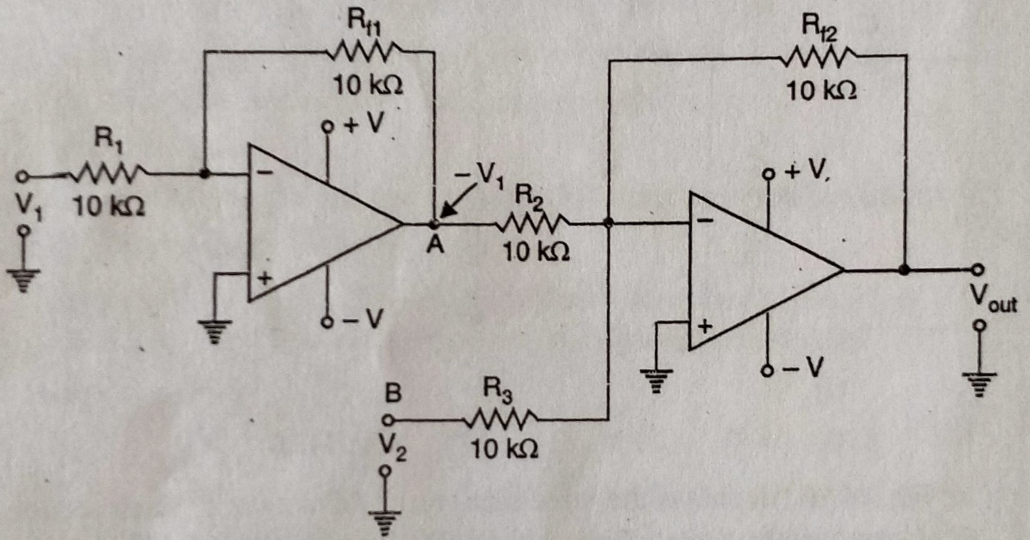


Fig. 25.78

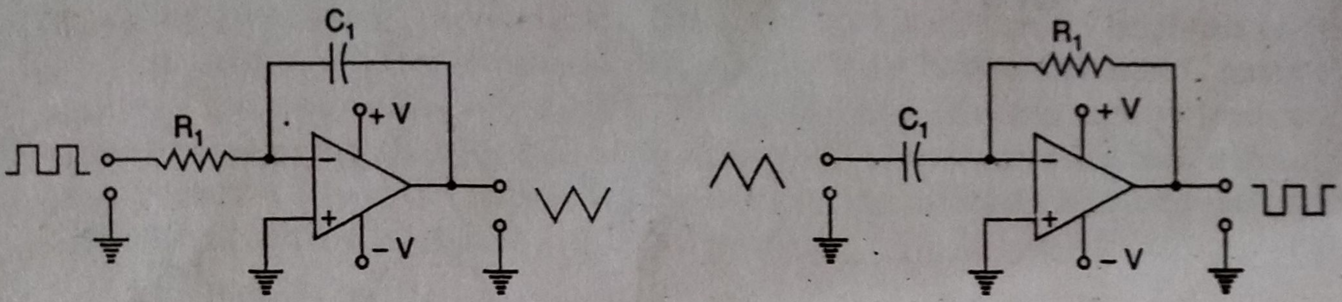
The voltage V_1 is applied to a standard inverting amplifier that has *unity gain*. Because of this; the output from the inverting amplifier will be equal to $-V_1$. This output is then applied to the summing amplifier (also having unity gain) along with V_2. Thus output from second *OP*-amp is given by;

$$V_{out} = -(V_A + V_B) = -(-V_1 + V_2) = V_1 - V_2$$

It may be noted that the gain of the second stage in the subtractor can be varied to provide an output that is proportional to (rather than equal to) the difference between the input voltages. However, if the circuit is to act as a subtractor, the input inverting amplifier *must* have unity gain. Otherwise, the output will not be proportional to the true difference between V_1 and V_2.

25.34 OP-Amp Integrators and Differentiators

A circuit that performs the mathematical integration of input signal is called an *integrator*. The output of an integrator is proportional to the area of the input waveform over a period of time. A circuit that performs the mathematical differentiation of input signal is called a *differentiator*. The output of a differentiator is proportional to the rate of change of its input signal. Note that the two operations are opposite.



OP-amp Integrator
(*i*)

OP-amp differentiator
(*ii*)

Fig. 25.79

Fig.25.79 shows *OP*-amp integrator and differentiator. As you can see, the two circuits are nearly identical in terms of their construction. Each contains a single *OP*-amp and an *RC* circuit. However, the difference in resistor/capacitor placement in the two circuits causes them to have input/output relationships that are exact opposites. For example, if the input to the integrator is a square wave, the output will be a triangular wave as shown in Fig. 25.79 (*i*). However, the differentiator will convert a triangular wave into square wave as shown in Fig. 25.79 (*ii*).

25.35 *OP*-Amp Integrator

As discussed above, an integrator is a circuit that performs integration of the input signal. The most popular application of an integrator is to produce a *ramp* output voltage (*i.e.* a linearly increasing or decreasing voltage). Fig. 25.80 shows the circuit of an *OP*-amp integrator. It consists of an *OP*-amp, input resistor *R* and feedback capacitor *C*. Note that the feedback component is a capacitor instead of a resistor.

As we shall see, when a signal is applied to the input of this circuit, the output-signal waveform will be the integration of input-signal waveform.

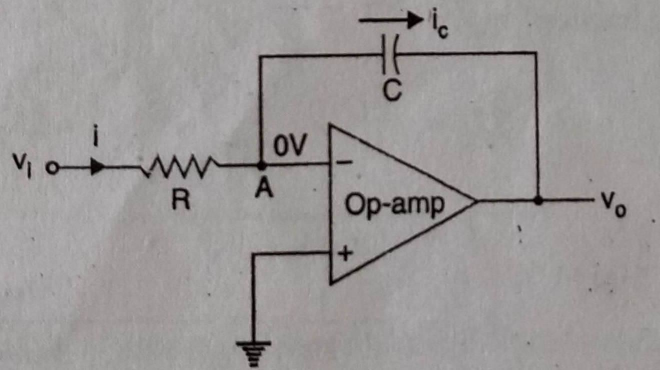


Fig. 25.80

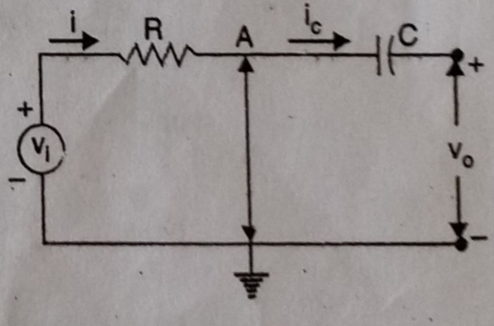


Fig. 25.81

Circuit Analysis. Since point *A* in Fig. 25.80 is at virtual ground, the *virtual-ground equivalent circuit of operational integrator will be as shown in Fig. 25.81. Because of virtual ground and infinite impedance of the *OP*-amp, all of the input current *i* flows through the capacitor *i.e.* $i = i_c$.

Now $$i = \frac{v_i - 0}{R} = \frac{v_i}{R} \qquad ...(i)$$

Also voltage across capacitor is $v_c = 0 - v_o = -v_o$

$$\therefore \quad i_c = \frac{C\,dv_c}{dt} = -C\frac{dv_o}{dt} \qquad ...(ii)$$

* Recall that virtual ground means that point *A* is 0V but it is not mechanically grounded. Therefore, no current flows from point *A* to ground.

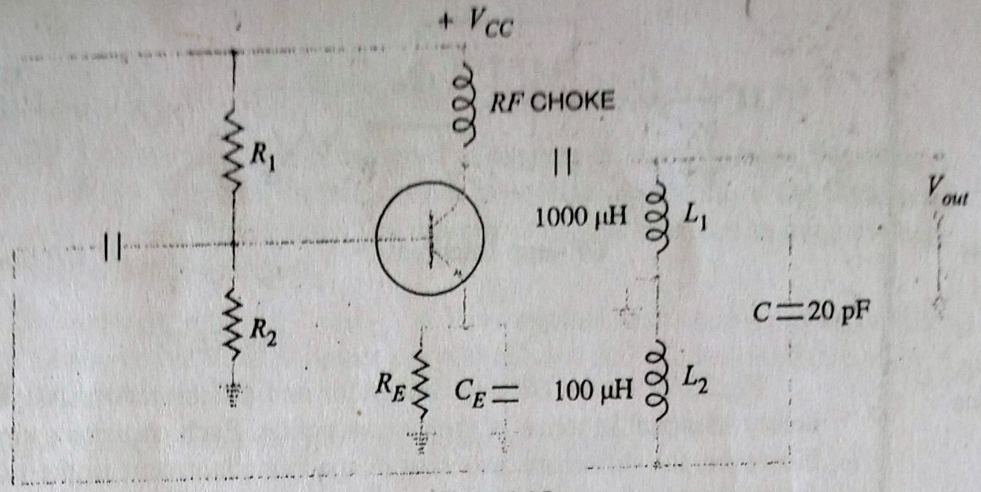


Fig. 14.15

$$\therefore \quad \text{Operating frequency, } f = \frac{1}{2\pi\sqrt{L_T C}} = \frac{1}{2\pi\sqrt{1140 \times 10^{-6} \times 20 \times 10^{-12}}} \text{ Hz}$$

$$= 1052 \times 10^3 \text{ Hz} = 1052 \text{ kHz}$$

(ii) $$\text{Feedback fraction, } m_v = \frac{L_2}{L_1} = \frac{100\ \mu H}{1000\ \mu H} = 0.1$$

Example 14.6. *A 1 pF capacitor is available. Choose the inductor values in a Hartley oscillator so that f = 1 MHz and m_v = 0.2.*

Solution.

$$\text{Feedback fraction, } m_v = \frac{L_2}{L_1}$$

or $$0.2 = \frac{L_2}{L_1} \qquad \therefore L_1 = 5L_2$$

Now $$f = \frac{1}{2\pi\sqrt{L_T C}}$$

or $$L_T = \frac{1}{C(2\pi f)^2} = \frac{1}{(1 \times 10^{-12})(2\pi \times 1 \times 10^6)^2}$$

$$= 25.3 \times 10^{-3} \text{ H} = 25.3 \text{ mH}$$

or $$L_1 + L_2 = 25.3 \text{ mH} \qquad (\because L_T = L_1 + L_2)$$

or $$5L_2 + L_2 = 25.3 \qquad \therefore L_2 = 25.3/6 = \mathbf{4.22\ mH}$$

and $$L_1 = 5\,L_2 = 5 \times 4.22 = \mathbf{21.1\ mH}$$

14.12 Principle of Phase Shift Oscillators

One desirable feature of an oscillator is that it should feed back energy of correct phase to the tank circuit to overcome the losses occurring in it. In the oscillator circuits discussed so far, the tank circuit employed inductive (*L*) and capacitive (*C*) elements. In such circuits, a phase shift of 180° was obtained due to inductive or capacitive coupling and a further phase shift of 180° was obtained due to transistor properties. In this way, energy supplied to the tank circuit was in phase with the generated oscillations. The oscillator circuits employing *L-C* elements have two general drawbacks. Firstly, they suffer from frequency instability and poor waveform. Secondly, they cannot be used for very low frequencies because they become too much bulky and expensive.

Good frequency stability and waveform can be obtained from oscillators employing resistive and capacitive elements. Such amplifiers are called *R-C* or *phase shift oscillators* and have the additional advantage that they can be used for very low frequencies. In a phase shift oscillator, a phase shift of 180° is obtained with a phase shift circuit instead of inductive or capacitive coupling. A further phase-shift of 180° is introduced due to the transistor properties. Thus, energy supplied back to the tank circuit is assured of correct phase.

Phase shift circuit. A phase-shift circuit essentially consists of an *R-C* network. Fig. 14.16 (*i*) shows a single section of *RC* network. From the elementary theory of electrical engineering, it can be shown that alternating voltage V_1' across *R* leads the applied voltage V_1 by ϕ°. The value of ϕ depends upon the values of *R* and *C*. If resistance *R* is varied, the value of ϕ also changes. If *R* were reduced to zero, V_1' will lead V_1 by 90° *i.e.* $\phi = 90°$. However, adjusting *R* to zero would be impracticable because it would lead to no voltage across *R*. Therefore, in practice, *R* is varied to such a value that makes V_1' to lead V_1 by 60°.

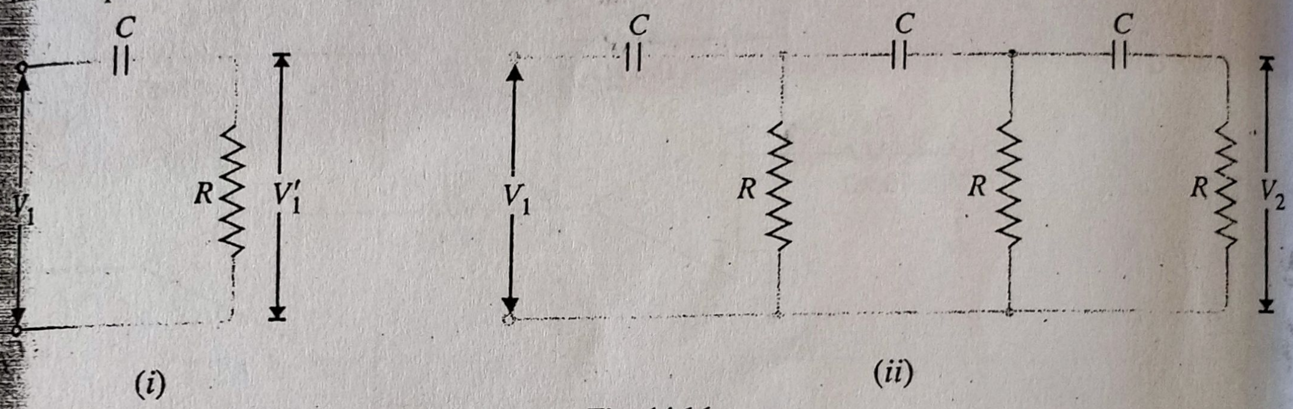


Fig. 14.16

Fig. 14.16 (*ii*) shows the three sections of *RC* network. Each section produces a phase shift of 60°. Consequently, a total phase shift of 180° is produced *i.e.* voltage V_2 leads the voltage V_1 by 180°.

14.13 Phase Shift Oscillator

Fig.14.17 shows the circuit of a phase shift oscillator. It consists of a conventional single transistor amplifier and a *RC* phase shift network. The phase shift network consists of three sections R_1C_1, R_2C_2 and R_3C_3. At some particular frequency f_0, the phase shift in each *RC* section is 60° so that the total phase-shift produced by the *RC* network is 180°. The frequency of oscillations is given by :

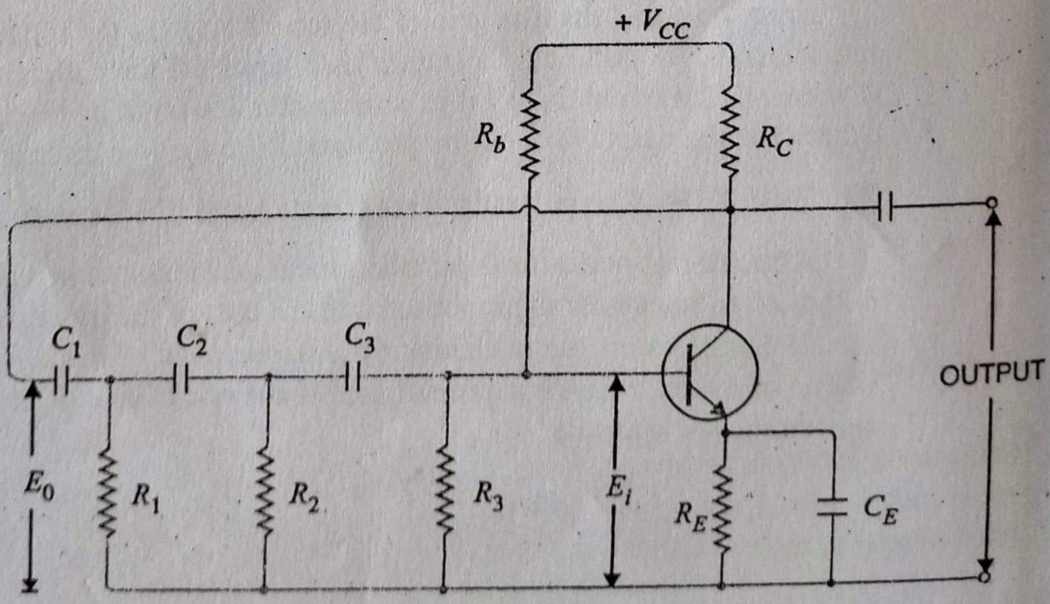


Fig. 14.17

$$f_0 = \frac{1}{2\pi RC\sqrt{6}} \qquad \ldots(i)$$

where

$$R_1 = R_2 = R_3 = R$$
$$C_1 = C_2 = C_3 = C$$

Circuit operation. When the circuit is switched on, it produces oscillations of frequency determined by exp. (*i*). The output E_0 of the amplifier is fed back to *RC* feedback network. This network produces a phase shift of 180° and a voltage E_i appears at its output which is applied to the transistor amplifier.

Obviously, the feedback fraction $m = E_i/E_0$. The feedback phase is correct. A phase shift of 180° is produced by the transistor amplifier. A further phase shift of 180° is produced by the *RC* network. As a result, the phase shift around the entire loop is 360°.

Advantages

(*i*) It does not require transformers or inductors.

(*ii*) It can be used to produce very low frequencies.

(*iii*) The circuit provides good frequency stability.

Disadvantages

(*i*) It is difficult for the circuit to start oscillations as the feedback is generally small.

(*ii*) The circuit gives small output.

Example 14.7. *In the phase shift oscillator shown in Fig. 14.17, $R_1 = R_2 = R_3 = 1M\Omega$ and $C_1 = C_2 = C_3 = 68\ pF$. At what frequency does the circuit oscillate ?*

Solution.

$$R_1 = R_2 = R_3 = R = 1\ M\Omega = 10^6\ \Omega$$
$$C_1 = C_2 = C_3 = C = 68\ pF = 68 \times 10^{-12}\ F$$

Frequency of oscillations is

$$f_o = \frac{1}{2\pi RC\sqrt{6}}$$
$$= \frac{1}{2\pi \times 10^6 \times 68 \times 10^{-12}\sqrt{6}}\ \text{Hz}$$
$$= \mathbf{954\ Hz}$$

Example 14.8. *A phase shift oscillator uses 5 pF capacitors. Find the value of R to produce a frequency of 800 kHz.*

Solution.

$$f_o = \frac{1}{2\pi RC\sqrt{6}}$$

or

$$R = \frac{1}{2\pi f_o C\sqrt{6}} = \frac{1}{2\pi \times 800 \times 10^3 \times 5 \times 10^{-12} \times \sqrt{6}}$$
$$= 16.2 \times 10^3\ \Omega = \mathbf{16.2\ k\Omega}$$

14.14 Wien Bridge Oscillator

The Wien-bridge oscillator is the standard oscillator circuit for all frequencies in the range of 10 Hz to about 1 MHz. It is the most frequently used type of audio oscillator as the output is free from circuit fluctuations and ambient temperature. Fig. 14.18 shows the circuit of Wien bridge oscillator. It is essentially a two-stage amplifier with *R-C* bridge circuit. The bridge circuit has the arms R_1C_1,

R_2C_2 and tungsten lamp L_p. Resistances R_3 and L_p are used to stabilise the amplitude of the output. The transistor T_1 serves as an oscillator and amplifier while the other transistor T_2 serves as inverter (*i.e.* to produce a phase shift of 180°). The circuit uses positive and negative feedbacks. The positive feedback is through R_1C_1, C_2R_2 to the transistor T_1. The negative feedback is through the voltage divider to the input of transistor T_2. The frequency of oscillations is determined by the series element R_1C_1 and parallel element R_2C_2 of the bridge.

$$f = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

If $R_1 = R_2 = R$

and $C_1 = C_2 = C$, then,

$$f = \frac{1}{2\pi RC} \qquad ...(i)$$

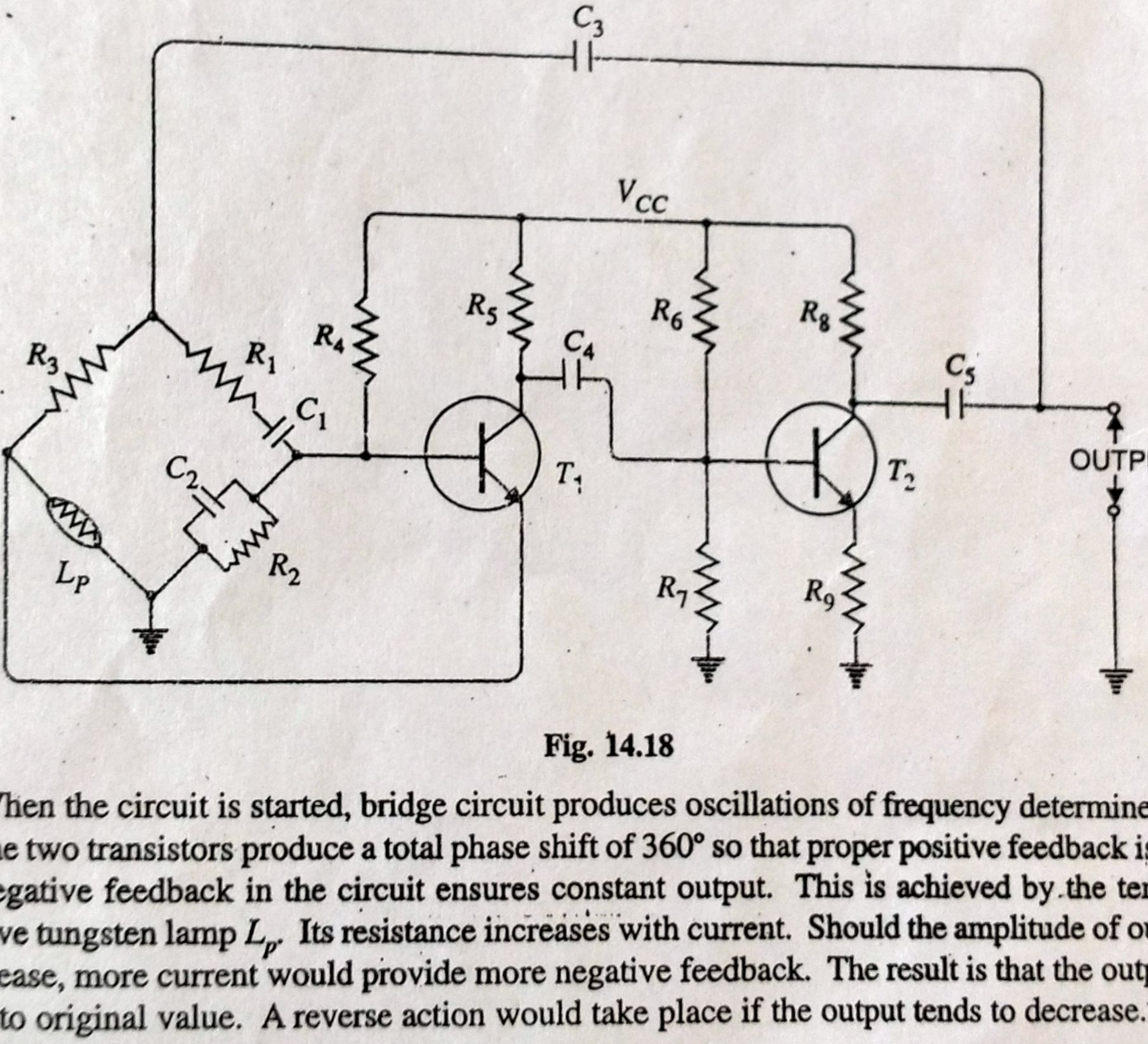


Fig. 14.18

When the circuit is started, bridge circuit produces oscillations of frequency determined by exp. (*i*). The two transistors produce a total phase shift of 360° so that proper positive feedback is ensured. The negative feedback in the circuit ensures constant output. This is achieved by the temperature sensitive tungsten lamp L_p. Its resistance increases with current. Should the amplitude of output tend to increase, more current would provide more negative feedback. The result is that the output would return to original value. A reverse action would take place if the output tends to decrease.

Advantages

(*i*) It gives constant output.

(*ii*) The circuit works quite easily.

(*iii*) The overall gain is high because of two transistors.

(*iv*) The frequency of oscillations can be easily changed by using a potentiometer.

Disadvantages

(*i*) The circuit requires two transistors and a large number of components.

(*ii*) It cannot generate very high frequencies.

(*ii*) Since $A_{CL} = 1$ for the circuit, $v_{out} = v_{in}$. Therefore, peak output voltage (V_{pk}) is one-half of $6V_{pp}$ *i.e.*, $V_{pk} = 6/2 = 3$ V. The maximum operating frequency (f_{max}) is given by ;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}} = \frac{0.5 \text{ V}/\mu\text{s}}{2\pi \times 3}$$

$$= \frac{500 \text{ kHz}}{2\pi \times 3} = \mathbf{26.53 \text{ kHz}} \qquad (\because 0.5 \text{ V}/\mu\text{s} = 500 \text{ kHz})$$

25.28 Multi-stage OP-Amp Circuits

When a number of OP-amp stages are connected in series, the overall voltage gain is equal to the product of individual stage gains. Fig. 25.63 shows connection of three stages. The first stage is connected to provide noninverting gain. The next two stages provide inverting gains.

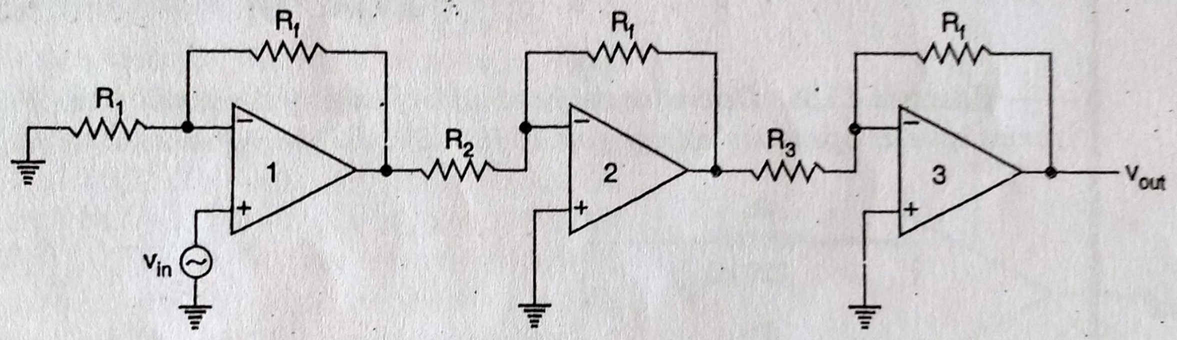


Fig. 25.63

The overall voltage gain A of this circuit is given by;

$$A = A_1 A_2 A_3$$

where A_1 = Voltage gain of first stage = $1 + (R_f/R_1)$

A_2 = Voltage gain of second stage = $-R_f/R_2$

A_3 = Voltage gain of third stage = $-R_f/R_3$

Since the overall voltage gain is positive, the circuit behaves as a noninverting amplifier.

Example 25.38. *Fig. 25.63 shows the multi-stage OP-amp circuit. The resistor values are : R_f = 470 kΩ ; R_1 = 4.3 kΩ ; R_2 = 33 kΩ and R_3 = 33 kΩ. Find the output voltage for an input of 80 μV.*

Solution. Voltage gain of first stage, $A_1 = 1 + (R_f/R_1) = 1 + (470 \text{ k}\Omega/4.3 \text{ k}\Omega) = 110.3$

Voltage gain of second stage, $A_2 = -R_f/R_2 = -470 \text{ k}\Omega/33 \text{ k}\Omega = -14.2$

Voltage gain of third stage, $A_3 = -R_f/R_3 = -470 \text{ k}\Omega/33 \text{ k}\Omega = -14.2$

$\therefore$ Overall voltage gain, $A = A_1 A_2 A_3 = (110.3) \times (-14.2) \times (-14.2) = 22.2 \times 10^3$

Output voltage, $v_{out} = A \times v_{in} = 22.2 \times 10^3 \times (80 \ \mu\text{V}) = \mathbf{1.78V}$