18

Solid-State Switching Circuits

INTRODUCTION

In practice, it is often required to make or break an electrical circuit in many operations. In some applications, it is desirable and necessary that this make and break should be very quick and without sparking. The mechanical switches cannot be used for the purpose for two main reasons. Firstly, a mechanical switch has high inertia which limits its speed of operation. Secondly, there is sparking at the contacts during breaking operation which results in the burning of the contacts.

The researches in the past years have revealed that tubes and transistors can serve as switching devices. They can turn ON or OFF power in an electrical circuit at a very high speed without any sparking. Such switches are known as electronic switches. The electronic switches are being extensively used to produce non-si-

nusoidal waves *e.g.*, square, rectangular, triangular or saw-tooth waves. Solid-state switching circuits are finding increasing applications. For example, solid-state switching circuits are the fundamental components of modern computer systems. In this chapter, we shall confine our attention to transistor as a switch. Once the reader gets acquainted with the switching action of a transistor, he can continue to study digital electronics on his/her own.

18.1 Switching Circuit

A circuit which can turn ON or OFF current in an electrical circuit is known as a **switching circuit.**

A switching circuit essentially consists of two parts *viz.* **(*i*)** a switch and **(*ii*)** associated circuitry. The switch is the most important part of the switching circuit. It actually makes or breaks the electrical circuit. The function of associated circuitry is to help the switch in turning ON or OFF current in the circuit. It may be worthwhile to mention here that associated circuitry is particularly used with electronic switches.

18.2 Switch

A switch is a device that can turn ON or OFF current in an electrical circuit. It is the most important part of a switching circuit. The switches can be broadly classified into the following three types :

  (*i*) Mechanical switch

 (*ii*) Electro-mechanical switch or Relay

(*iii*) Electronic switch

Although the basic purpose of this chapter is to discuss the switching action of a transistor, yet a brief description of mechanical and electromechanical switches is being presented. This will help the reader to understand the importance of transistor as a switch.

18.3 Mechanical Switch

A switch which is operated mechanically to turn ON or OFF current in an electrical circuit is known as a **mechanical switch.**

The familiar example of a mechanical switch is the tumbler switch used in homes to turn ON or OFF power supply to various appliances such as fans, heaters, bulbs etc. The action of a mechanical switch can be beautifully understood by referring to Fig. 18.1 where a load R_L is

Fig. 18.1

connected in series with a battery and a mechanical switch *S*. As long as the switch is open, there is no current in the circuit. When switch is closed, the current flow is established in the circuit. It is easy to see that the whole current flows through the load as well as the switch.
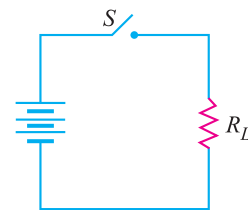
Limitations. A mechanical switch suffers from the following drawbacks :

 (*i*) In the closed position, the switch carries the whole of the load current. For a large load current, the switch contacts have to be made heavy to enable them to carry the necessary current without overheating. This increases the size of the switch.

 (*ii*) If the load current carried by the circuit is large, there will be sparking at the contacts of the switch during breaking operation. This results in the wear and tear of the contacts.

(*iii*) Due to high inertia of a mechanical switch, the speed of operation is very small.

Mechanical Switches

Due to above limitations, the use of mechanical switches is restricted to situations where switching speed is small and the load current to be handled is not very heavy.

18.4 Electro-mechanical Switch or Relay

It is a mechanical switch which is operated electrically to turn ON or OFF current in an electrical circuit.

The electro-mechanical switch or relay is an improved form of simple mechanical switch. Fig. 18.2 shows the schematic diagram of a typical relay. It consists of lever L carrying armature A and a solenoid C. The spring pulls the lever upwards while the solenoid when energised pulls it downwards. The solenoid circuit is so designed that when switch S is closed, the downward pull of the solenoid exceeds the upward pull of the spring.

When the switch S is closed, the lever is pulled downward and the armature A closes the relay contacts 1 and 2. This turns ON current in the circuit. However, when switch S is opened, the so-

Fig. 18.2

lenoid is de-energised and the spring pulls the lever and hence the armature A upwards. Consequently, the relay contacts 1 and 2 are opened and current flow in the circuit is interrupted. In this way, a relay acts as a switch.
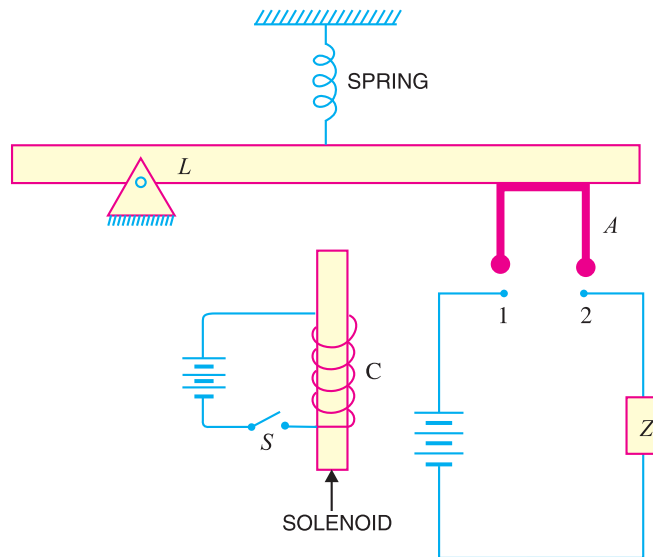
Advantages. A relay possesses the following advantages over a simple mechanical switch :

(*i*) The relay or electro-mechanical switch requires a small power for its operation. This permits to control a large power in the load by a small power to the relay circuit. Thus a relay acts as a power amplifier *i.e.* it combines control with power amplification.

(*ii*) The switch in the relay coil carries a small current as compared to the load current. This permits the use of a smaller switch in the relay coil circuit.

(*iii*) The operator can turn ON or OFF power to a load even from a distance. This is a very important advantage when high voltages are to be handled.

(*iv*) There is no danger of sparking as the turning ON or OFF is carried by the relay coil switch which carries a small current.

However, a relay has two principal limitations. First, the speed of operation is very small; less than 5 operations per second. Secondly, a relay has moving parts and hence there is considerable wear and tear.

18.5 Electronic Switches

It is a device which can turn ON or OFF current in an electrical circuit with the help of electronic devices e.g., transistors or tubes.

Electronic switches have become very popular because of their high speed of operation and absence of sparking. A transistor can be used as a switch by driving it back and forth between *saturation* and *cut off.* This is illustrated in the discussion below :
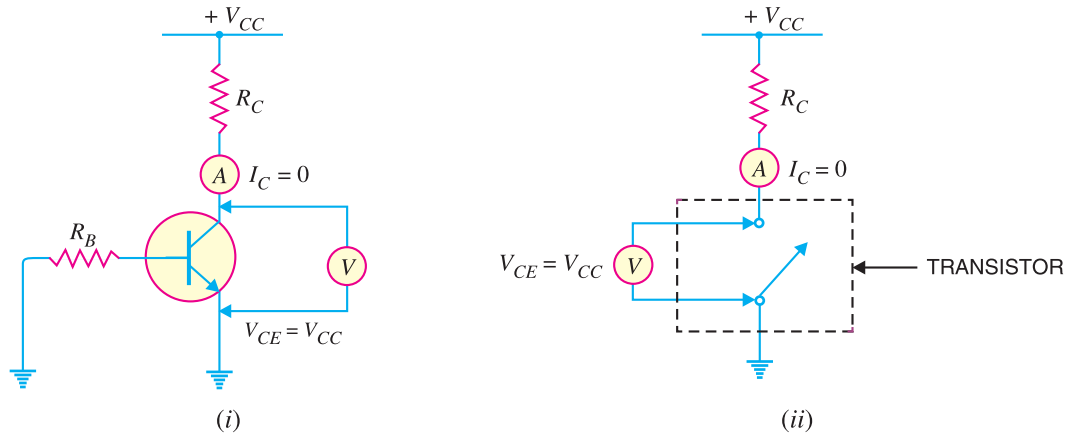

Fig. 18.3

(*i*) When the base input voltage is enough negative, the transistor is cut off and no current flows in collector load [See Fig. 18.3 (*i*)]. As a result, there is no voltage drop acorss R_C and the output voltage is *ideally V_{CC}. *i.e.*,

$$I_C = 0 \quad \text{and} \quad V_{CE} = V_{CC}$$

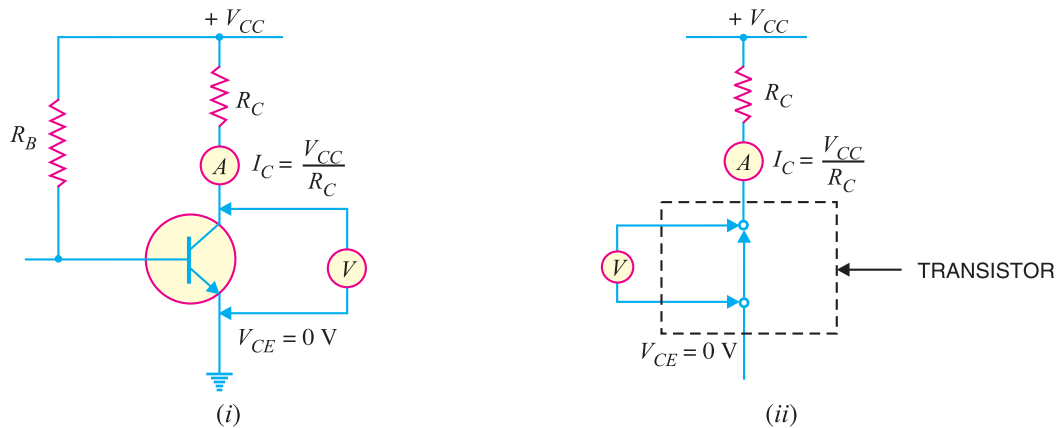This condition is similar to that of an open switch (*i.e.*, OFF state) as shown in Fig. 18.3 (*ii*).

Fig. 18.4

(*ii*) When the input base voltage is positive enough that transistor saturates, then $I_{C(sat)}$ will flow through R_C. Under such conditions, the entire V_{CC} will drop across collector load R_C and output

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* The collector current will not be zero since a little leakage current always flows even when the base input voltage is negative or zero.

∴ Output voltage $= V_{CC} - I_{leakage} R_C.$ If $I_{leakage} = 0$, then output voltage $= V_{CC}$

voltage is ideally zero *i.e.*,

$$I_C = I_{C(sat)} = \frac{V_{CC}}{R_C} \quad \text{and} \quad V_{CE} = 0$$

This condition is similar to that of a closed switch (*i.e.*, ON state) as shown in Fig. 18.4 (*ii*).

Conclusion. The above discussion leads to the conclusion that a transistor can behave as a switch under proper conditions. In other words, if the input base voltages are enough negative and positive, the transistor will be driven between *cut off* and *saturation*. These conditions can be easily fulfilled in a transistor circuit. Thus a transistor can act as a switch. Fig. 18.5 shows the switching action of a transistor in terms of dc load line. The
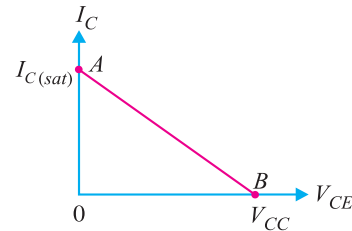

Fig. 18.5

point *A* of the load line represents the ON condition while point *B* represents the OFF condition.

Example 18.1. *Determine the minimum high input voltage (+V) required to saturate the transistor switch shown in Fig. 18.6.*

Solution. Assuming the transistor to be ideal,

Electronic Switches

$$I_{C(sat)} = V_{CC}/R_C = 10 \text{ V}/1 \text{ k}\Omega = 10 \text{ mA}$$

$$\therefore \quad I_B = \frac{I_{C(sat)}}{\beta} = \frac{10 \text{ mA}}{100} = 0.1 \text{ mA}$$

Now
$$+V = I_B R_B + V_{BE}$$
$$= (0.1 \text{ mA}) (47 \text{ k}\Omega) + 0.7$$
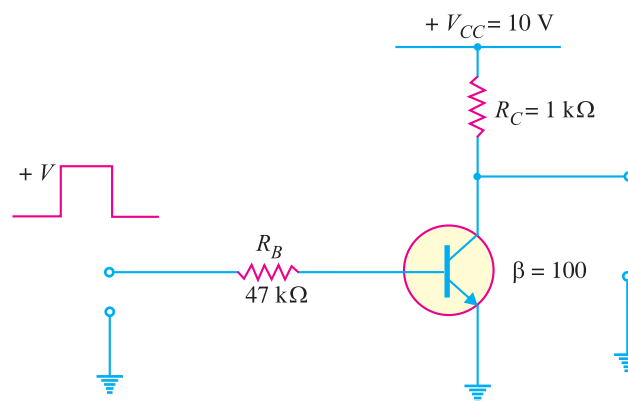$$= 4.7 + 0.7 = \textbf{5.4 V}$$

Fig. 18.6

Hence in order to saturate the transistor, we require + 5.4 V.

18.6 Advantages of Electronic Switches

The following are the advantages of transistor switch over other types of switches :

(*i*) It has no moving parts and hence there is little wear and tear. Therefore, it gives noiseless operation.

(*ii*) It has smaller size and weight.

(*iii*) It gives troublefree service because of solid state.

(*iv*) It is cheaper than other switches and requires little maintenance.

(*v*) It has a very fast speed of operation say upto 10^9 operations per second. On the other hand, the mechanical switches have a small speed of operation *e.g.* less than 5 operations in a second.

18.7. Important Terms

So far we have considered the transistor to be an ideal one. An ideal transistor has $V_{CE} = V_{CC}$ (or I_C = 0) in the OFF state and $V_{CE} = 0$ (or $I_C = I_{C(sat)}$) in the ON state. However, such ideal conditions are not realised in practice. In a practical transistor, the output voltage is neither V_{CC} in the OFF state nor it is zero in the ON state. While designing a transistor switching circuit, these points must be taken into consideration.

(*i*) **Collector leakage current.** When the input circuit is reverse biased or input voltage is zero, a small current (a few μA) flows in the collector. This is known as collector leakage current and is due to the minority carriers. The value of this leakage current is quite large in *Ge* transistors, but in modern silicon transistors, the value of leakage current is low enough to be ignored.

(*ii*) **Saturation collector current.** *It is the maximum collector current for a particular load in a transistor.*

Fig. 18.7

Consider an *npn* transistor having a load R_C in its collector circuit as shown in Fig. 18.7. As the input forward bias is increased, the collector current I_C also increases because $I_C = \beta I_B$. However, with the increase in I_C, the voltage drop across R_C increases. This results in the *decrease of V_{CE}. When V_{CE} drops to knee voltage (V_{knee}), any further increase in collector current is not possible since β decreases sharply when V_{CE} falls below knee voltage. This maximum current is known as saturation collector current.

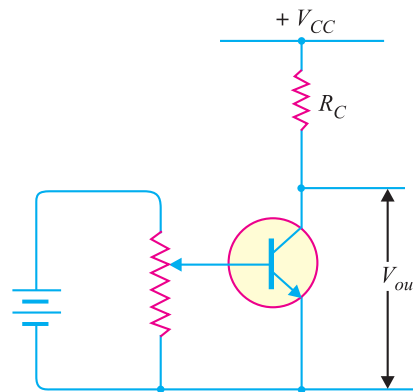∴ Saturation collector current, $I_{C(sat)} = \dfrac{V_{CC} - V_{knee}}{R_C}$

18.8 Switching Transistors

A transistor which is used as a switch is known as a **switching transistor.**

In general, switching transistor is fabricated by the same process as an ordinary transistor except that it has special design features to reduce switch-off time and saturation voltage. It is so arranged in the circuit that either maximum current (called saturation collector current) flows through the load or

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* $V_{CE} = V_{CC} - I_C R_C$

minimum current (called collector leakage current) flows through the load. In other words, a switching transistor has two states *viz.* (*i*) ON state or when collector saturation current flows through the load (*ii*) OFF state or when collector leakage current flows through the load. In the discussion that follows transistor means the switching transistor.

18.9 Switching Action of a Transistor

The switching action of a transistor can also be explained with the help of output characteristics. Fig. 18.8 shows the output characteristics of a typical transistor for a *CE* configuration. The load line is drawn for load R_C and collector supply V_{CC}. The characteristics are arranged in three regions : OFF, ON or saturation and active regions.
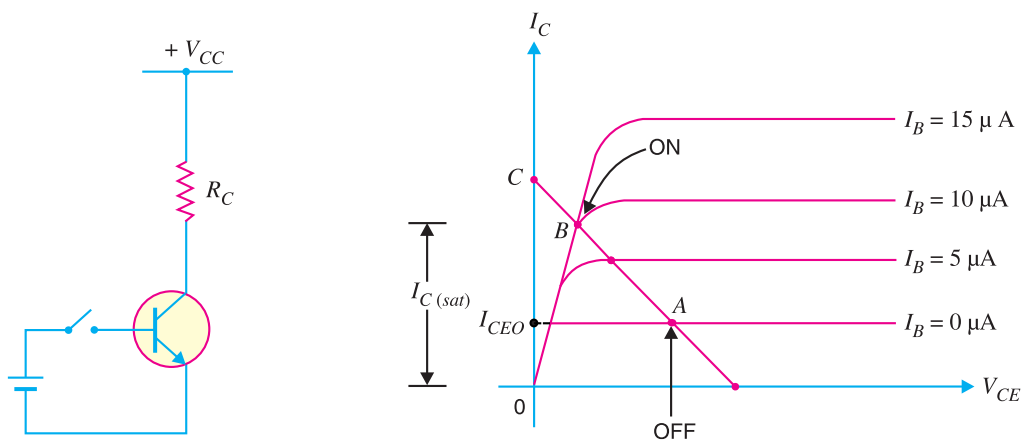

Fig. 18.8

(*i*) **OFF region.** When the input base voltage is zero or *negative, the transistor is said to be in the OFF condition. In this condition, $I_B = 0$ and the collector current is equal to the collector leakage current I_{CEO}. The value of I_{CEO} can be obtained from the characteristics if we know V_{CE}.

$$\text{Power loss} = \text{Output voltage} \times \text{Output current}$$

As already noted, in the OFF condition, the output voltage $= V_{CC}$ since voltage drop in the load due to I_{CEO} is negligible.

∴ $$\text{Power loss} = V_{CC} \times I_{CEO}$$

Since I_{CEO} is very small as compared to full-load current that flows in the ON condition, power loss in the transistor is quite small in the OFF condition. It means that the transistor has a high efficiency as a switch in the OFF condition.

(*ii*) **ON or saturation region.** When the input voltage is made so much positive that saturation collector current flows, the transistor is said to be in the ON condition. In this condition, the saturation collector current is given by :

$$I_{C(sat)} = \frac{V_{CC} - V_{knee}}{R_C}$$

$$\text{Power loss} = \text{Output voltage} \times \text{Output current}$$

. . . .

* If a small negative voltage is given to the input, the base-emitter junction is reverse biased and load current becomes I_{CBO} instead of I_{CEO}.

The output voltage in the ON condition is equal to V_{knee} and output current is $I_{C(sat)}$.

$$\therefore \quad \text{Power loss} = V_{knee} \times I_{C(sat)}$$

Again the efficiency of transistor as a switch in the ON condition is high. It is because the power loss in this condition is quite low due to small value of V_{knee}.

(*iii*) **Active region.** *It is the region that lies between OFF and ON conditions.*

The OFF and ON regions are the stable regions of operation. The active region is the unstable (or transient) region through which the operation of the transistor passes while changing from OFF state to the ON state. Thus referring to Fig. 18.8, the path *AB* is the active region. The collector current increases from I_{CEO} to $I_{C(sat)}$ along the path *AB* as the transistor is switched ON. However, when the transistor is switched OFF, the collector current decreases from $I_{C(sat)}$ to I_{CEO} along *BA*.

Conclusions

(*a*) In the **active region,** the transistor operates as a *linear amplifier* where small changes in input current (ΔI_B) cause relatively large changes in output current (ΔI_C).

(*b*) In the **saturation state,** the transistor behaves like a virtual short (collector – emitter shorted), where V_{CE} is approximately zero and I_C is maximum, limited only by the resistance R_C in the collector. In the cut off state, the transistor behaves like an open circuit (collector-emitter open), where I_C is practically zero and V_{CE} is equal to supply voltage V_{CC}. **Thus transistor in the saturation and cut off states behaves as a switch**—saturation state corresponds to the closure of switch and cut off state corresponding to opening of switch.

Note. Transistor switch is inferior to mechanical switch or relay in one respect. When the mechanical switch or relay is in the OFF condition, the load current is exactly zero. But when transistor switch is in the OFF condition, the collector current is not zero but is equal to small collector leakage current. However, for all practical purposes, this small collector leakage current may be neglected.

Example 18.2. *A transistor is used as a switch. If V_{CC} = 10V, R_C = 1 kΩ and I_{CBO} = 10 μA, determine the value of V_{CE} when the transistor is (i) cut off and (ii) saturated.*

Solution.

(*i*) *At cut off*

$$I_C = I_{CBO} = 10 \text{ μA}$$

$$\therefore \quad V_{CE} = V_{CC} - I_{CBO} R_C$$

$$= 10 \text{ V} - 10 \text{ μA} \times 1 \text{ kΩ} = 10\text{V} - 10 \text{ mV} = \mathbf{9.99V}$$

(*ii*) *At saturation*

$$I_{C\,(sat)} = \frac{V_{CC} - V_{knee}}{R_C}$$

$$\therefore \quad V_{CE} = V_{knee} = \mathbf{0.7V}$$

Example 18.3. *Fig. 18.9 shows the transistor switching circuit. Given that R_B = 2.7 kΩ, V_{BB} = 2V, V_{BE} = 0.7V and V_{knee} = 0.7V.*

(*i*) *Calculate the minimum value of β for saturation.*

(*ii*) *If V_{BB} is changed to 1V and transistor has minimum β = 50, will the transistor be saturated.*

Solution.

(*i*)

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

$$= \frac{2\text{V} - 0.7\text{V}}{2.7 \text{ kΩ}} = \frac{1.3 \text{ V}}{2.7 \text{ kΩ}} = 0.48 \text{ mA}$$

Now

$$I_{C\,(sat)} = \frac{V_{CC} - V_{knee}}{R_C}$$

+ $V_{CC} = 10V$

$R_C = 1\ k\Omega$

$R_B = 2.7\ k\Omega$

V_{BE}

V_{BB}
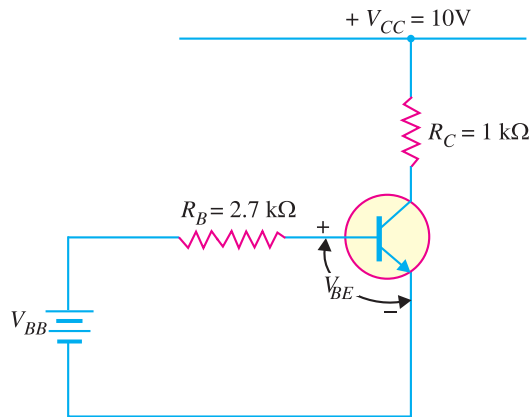
Fig. 18.9

$$= \frac{10V - 0.7V}{1\ k\Omega} = \frac{9.3V}{1\ k\Omega} = 9.3\ mA$$

$\therefore$ Minimum $\beta = \dfrac{I_{C(sat)}}{I_B} = \dfrac{9.3\ mA}{0.48\ mA} = \mathbf{19.4}$

(ii) $I_B = \dfrac{V_{BB} - V_{BE}}{R_B}$

$$= \frac{1V - 0.7V}{2.7\ k\Omega} = \frac{0.3V}{2.7\ k\Omega} = 0.111\ mA$$

$\therefore$ $I_C = \beta I_B = 50 \times 0.111 = 5.55\ mA$

Since the collector current is less than saturation current (= 9.3 mA), **the transistor will not be saturated.**

18.10 Multivibrators

*An electronic circuit that generates square waves (or other non-sinusoidals such as rectangular, saw-tooth waves) is known as a *****multivibrator.**

FEEDBACK

FEEDBACK

FIRST STAGE TRANSISTOR Q_1

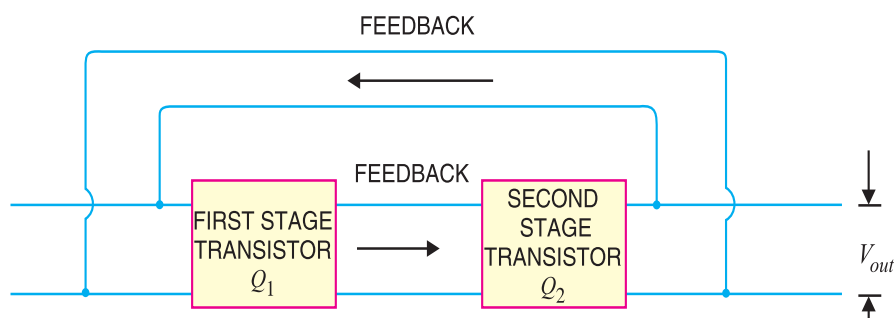SECOND STAGE TRANSISTOR Q_2

V_{out}

Fig. 18.10

A multivibrator is a switching circuit which depends for operation on positive feedback. It is basically a two-stage amplifier with output of one fedback to the input of the other as shown in Fig. 18.10.

* The name multivibrator is derived from the fact that a square wave actually consists of a large number of (fourier series analysis) sinusoidals of different frequencies.

The circuit operates in two states (*viz* ON and OFF) controlled by circuit conditions. Each amplifier stage supplies feedback to the other in such a manner that will drive the transistor of one stage to saturation (ON state) and the other to cut off (OFF state).

After a certain time controlled by circuit conditions, the action is reversed *i.e.* saturated stage is driven to cut off and the cut off stage is driven to saturation. The output can be taken across either stage and may be rectangular or square wave depending upon the circuit conditions.

Fig. 18.10 shows the block diagram of a multivibrator. It is a two-stage amplifier with 100% positive feedback. Suppose output is taken across the transistor Q_2. At any particular instant, one transistor is ON and conducts $I_{C(sat)}$ while the other is OFF. Suppose Q_2 is ON and Q_1 is OFF. The collector current in Q_2 will be $I_{C(sat)}$ as shown in

Fig. 18.11

Fig. 18.11. This condition will prevail for a time (*bc* in this case) determined by circuit conditions. After this time, transistor Q_2 is cut off and Q_1 is turned ON. The collector current in Q_2 is now I_{CEO} as shown. The circuit will stay in this condition for a time *de*. Again Q_2 is turned ON and Q_1 is driven to cut off. In this way, the output will be a square wave.
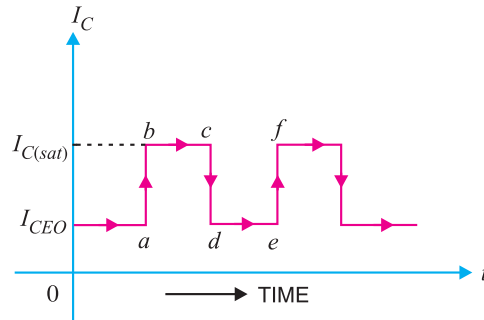
18.11 Types of Multivibrators

A multivibrator is basically a two-stage amplifier with output of one fedback to the input of the other. At any particular instant, one transistor is ON and the other is OFF. After a certain time depending upon the circuit components, the stages reverse their conditions – the conducting stage suddenly cuts off and the non-conducting stage suddenly starts to conduct. The two possible states of a multivibrator are :

	ON	**OFF**
First State	Q_1	Q_2
Second State	Q_2	Q_1

Depending upon the manner in which the two stages interchange their states, the multivibrators are classified as :

  (i) Astable or free running multivibrator

 (ii) Monostable or one-shot multivibrator

(iii) Bi-stable or flip-flop multivibrator

Fig. 18.12 shows the input/output relations for the three types of multivibrators.

  (i) The astable or free running multivibrator alternates automatically between the two states and remains in each for a time dependent upon the circuit constants. Thus it is just an oscillator since it requires no external pulse for its operation. Of course, it does require a source of d.c. power. Because it continuously produces the square-wave output, it is often referred to as a *free running multivibrator*.

 (ii) The monostable or one-shot multivibrator has one state stable and one quasi-stable (*i.e.* half-stable) state. The application of input pulse triggers the circuit into its quasi-stable state, in which it remains for a period determined by circuit constants. After this period of time, the circuit returns to its initial stable state, the process is repeated upon the application of each trigger pulse. Since the monostable multivibrator produces a single output pulse for each input trigger pulse, it is generally called *one-shot multivibrator*.
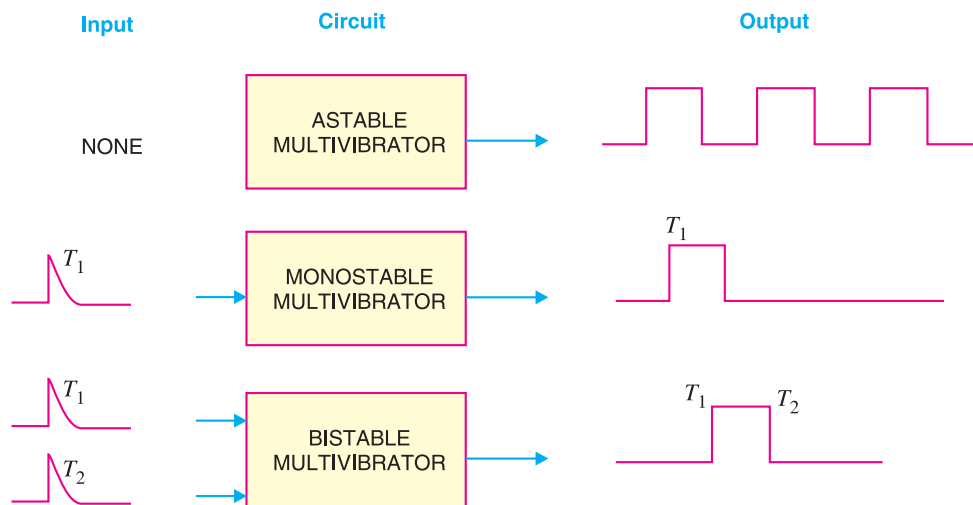
Input   Circuit   Output

NONE

ASTABLE MULTIVIBRATOR

T_1

MONOSTABLE MULTIVIBRATOR

T_1

T_1

T_2

BISTABLE MULTIVIBRATOR

T_1 T_2

Fig. 18.12

(*iii*) The bistable multivibrator has both the two states stable. It requires the application of an external triggering pulse to change the operation from either one state to the other. Thus one pulse is used to generate half-cycle of square wave and another pulse to generate the next half-cycle of square wave. It is also known as a *flip-flop multivibrator* because of the two possible states it can assume.

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

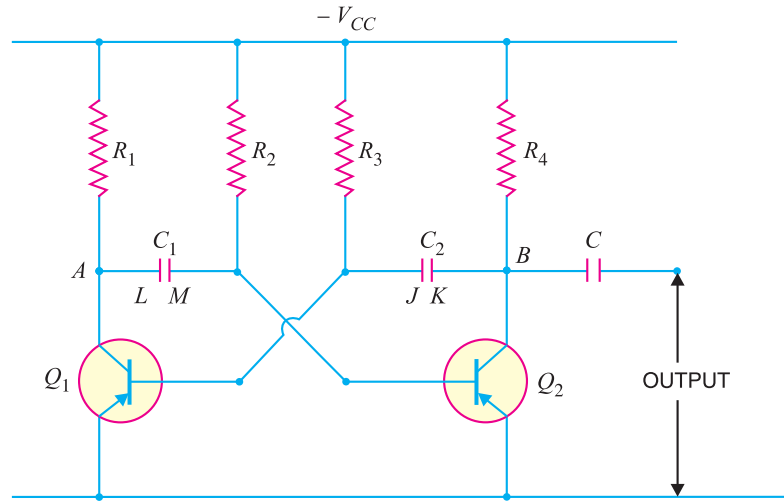* A means not. Hence astable means that it has no stable state.

Fig. 18.13

Fig. 18.14

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.
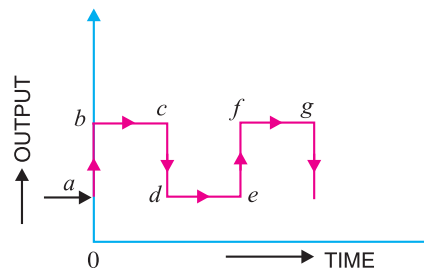
When Q_1 is at saturation and Q_2 is cut off, the full voltage V_{CC} appears across R_1 and voltage across R_4 will be zero. The charges developed across C_1 and C_2 are sufficient to maintain the saturation and cut off conditions at Q_1 and Q_2 respectively. This condition is represented by time interval *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 further increase in the collector current of Q_2. With this set of actions taking place, Q_2 is quickly driven to saturation and Q_1 to cut off. This condition is represented by *cd* in Fig. 18.14. The period of time during which Q_2 remains at saturation and Q_1 at cut off is determined by C_2 and R_3.
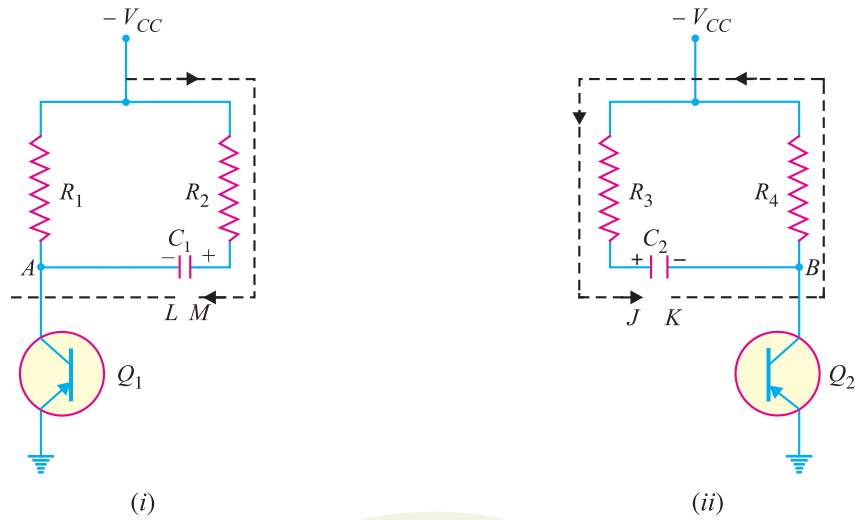
(i)   (ii)

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 $C_1 = C_2 = C$,

∴ $T = 0.694 \, (RC + RC) \simeq 1.4 \, RC$ seconds

Frequency of the square wave is

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

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, $R_2 = R_3 = 10 \, k\Omega$ and $C_1 = C_2$ = 0.01 μF. Determine the time period and frequency of the square wave.*

Solution.

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

Time period of the square wave is

$$
\begin{aligned}
T &= 1.4 \, RC = 1.4 \times 10^4 \times 10^{-8} \text{ second} \\
&= 1.4 \times 10^{-4} \text{ second} = 1.4 \times 10^{-4} \times 10^3 \text{ m sec} \\
&= \textbf{0.14 m sec}
\end{aligned}
$$

Frequency of the square wave is

$$
f = \frac{1}{T \text{ in second}} \, \text{Hz} = \frac{1}{1.4 \times 10^{-4}} \, \text{Hz}
$$

$$
= 7 \times 10^3 \, \text{Hz} = \textbf{7 kHz}
$$

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.
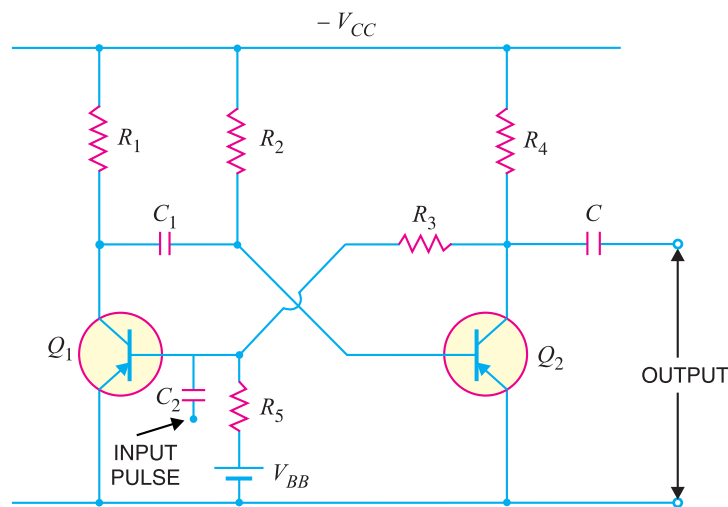
Fig. 18.16

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.
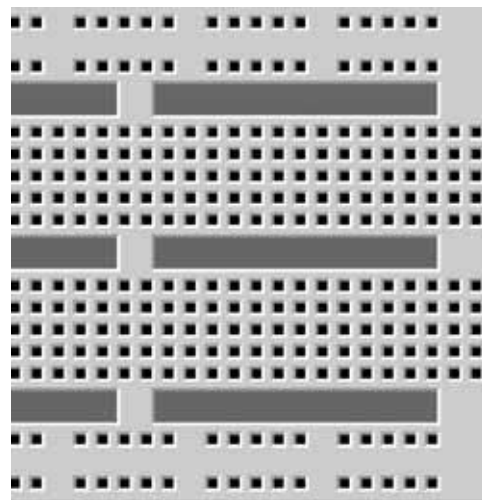
Monostable Multivibrator

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* 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.
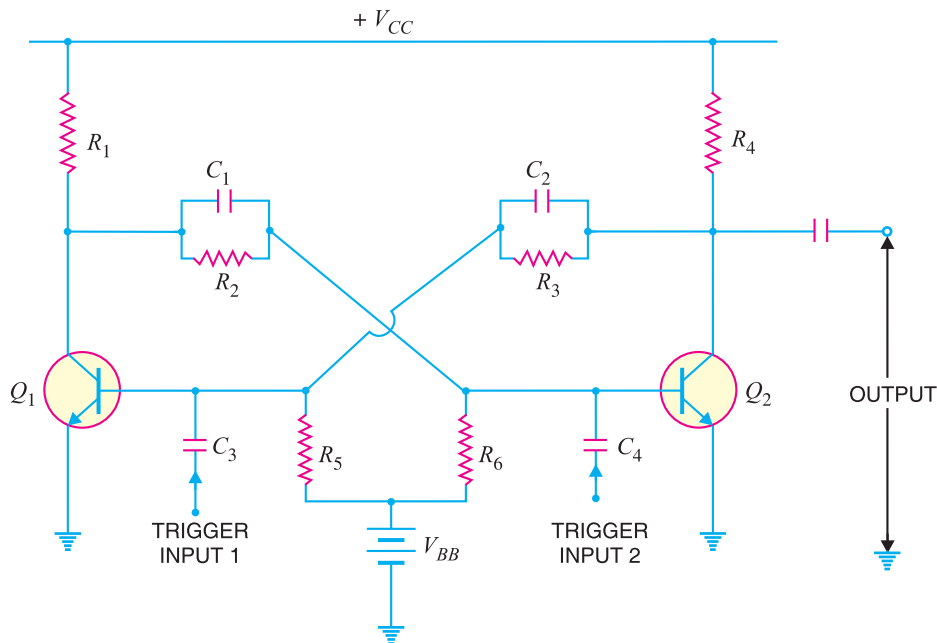

Fig. 18.17

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.

18.15 Differentiating Circuit

A circuit in which output voltage is directly proportional to the derivative of the input is known as a **differentiating circuit.**

$$\text{Output} \ \propto \ \frac{d}{dt} (\text{Input})$$

A differentiating circuit is a simple RC series circuit with output taken across the resistor R. The circuit is suitably designed so that output is proportional to the derivative of the input. Thus if a d.c. or constant input is applied to such a circuit, the output will be zero. It is because the derivative of a constant is zero.
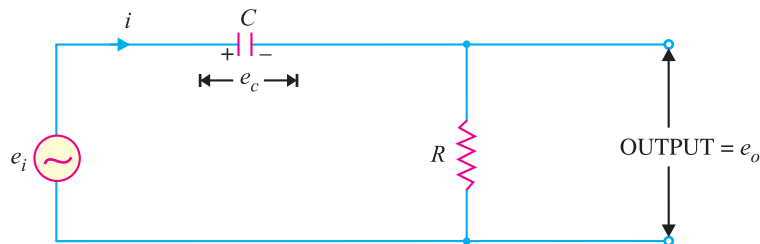
Fig. 18.18

Fig. 18.18 shows a typical differentiating circuit. The output across R will be the derivative of the input. It is important to note that merely using voltage across R does not make the circuit a differentiator; it is also necessary to set the proper circuit values. In order to achieve good differentiation, the following two conditions should be satisfied :

(*i*) The time constant RC of the circuit should be much smaller than the time period of the input wave.

(*ii*) The value of X_C should be 10 or more times larger than R at the operating frequency.

Fulfilled these conditions, the output across R in Fig. 18.18 will be the derivative of the input.

Let e_i be the input alternating voltage and let i be the resulting alternating current. The charge q on the capacitor at any instant is

$$q \ = \ C \, e_c$$

Now
$$i \ = \ \frac{dq}{dt} \ = \ \frac{d}{dt}(q) \ = \ \frac{d}{dt}(C \, e_c)$$

or $\qquad i \;=\; C\dfrac{d}{dt}(e_c)$

Since the capacitive reactance is very much larger than R, the input voltage can be considered equal to the capacitor voltage with negligible error *i.e.* $e_c = e_i$.

$\therefore \qquad\qquad\qquad i \;=\; C\dfrac{d}{dt}(e_i)$

Output voltage, $\; e_o \;=\; i\,R$

$\qquad\qquad\qquad\qquad =\; RC\dfrac{d}{dt}(e_i)$

$\qquad\qquad\qquad\qquad \propto\; \dfrac{d}{dt}(e_i) \qquad\qquad\qquad\qquad (\because RC \text{ is constant})$

$\therefore \qquad\qquad$ Output voltage $\propto \dfrac{d}{dt}$ (Input)

Output waveforms. The output waveform from a differentiating circuit depends upon the time constant and shape of the input wave. Three important cases will be considered.

(*i*) **When input is a square wave.** When the input fed to a differentiating circuit is a square wave, output will consist of sharp narrow pulses as shown in Fig. 18.19. During the *OC* part of input wave, its amplitude changes abruptly and hence the differentiated wave will be a sharp narrow pulse as shown in Fig. 18.19. However, during the constant part *CB* of the input, the output will be zero because the derivative of a constant is zero.
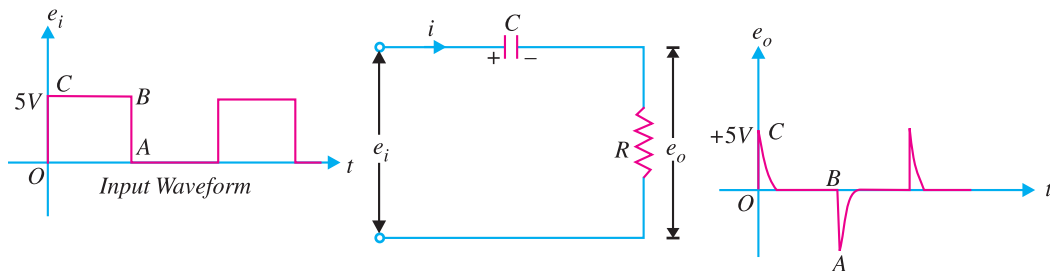
Fig. 18.19

Let us look at the physical explanation of this behaviour of the circuit. Since time constant RC of the circuit is very small *w.r.t.* time period of input wave and $X_C >> R$, the capacitor will become fully charged during the early part of each half-cycle of the input wave. During the remainder part of the half-cycle, the output of the circuit will be zero because the capacitor voltage (e_c) neutralises the input voltage and there can be no current flow through R. Thus we shall get sharp pulse at the output during the start of each half-cycle of input wave while for the remainder part of the half-cycle of input wave, the output will be zero. In this way, a symmetrical output wave with sharp positive and negative peaks is produced. Such pulses are used in many ways in electronic circuits *e.g.* in television transmitters and receivers, in multivibrators to initiate action etc.

(*ii*) **When input is a triangular wave.** When the input fed to a differentiating circuit is a triangular wave, the output will be a rectangular wave as shown in Fig. 18.20. During the period *OA*
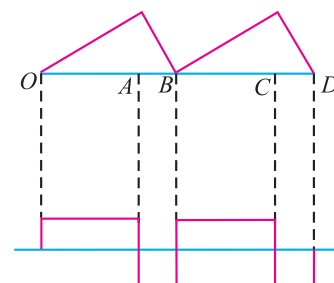

Fig. 18.20

of the input wave, its amplitude changes at a constant rate and, therefore, the differentiated wave has a constant value for each constant rate of change. During the period *AB* of the input wave, the change is less abrupt so that the output will be a very narrow pulse of rectangular form. Thus when a triangular wave is fed to a differentiating circuit, the output consists of a succession of rectangular waves of equal or unequal duration depending upon the shape of the input wave.

(*iii*) **When input is a sine wave.** A sine wave input becomes a cosine wave and a cosine wave input becomes an inverted sine wave at the output.

Example 18.5. (*i*) *What is the effect of time constant of an RC circuit on the differentiated wave?*

(*ii*) *Sketch the output waveform from the differentiating circuit when input is square wave for* $T = 100\,RC, T = 10\,RC, T = RC.$

Solution.

(*i*) In an *RC* differentiating circuit, the output voltage is taken across *R* and the waveform of the output depends upon the time constant of the circuit. The circuit will function as a differentiator if the product *RC* is many times smaller than the time period of the input wave.

(*ii*) **Square wave input.** Fig. 18.21 shows the input square wave fed to a differentiating circuit. Fig. 18.22 shows the output waveforms for different values of time period of the input wave.
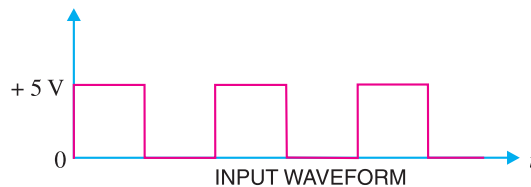
Fig. 18.21

It may be noted that *RC* coupling circuit is the same as a differentiating circuit except that it has a long time constant—in excess of 5 *RC*. Therefore, a coupling circuit does not noticeably differentiate the input wave.
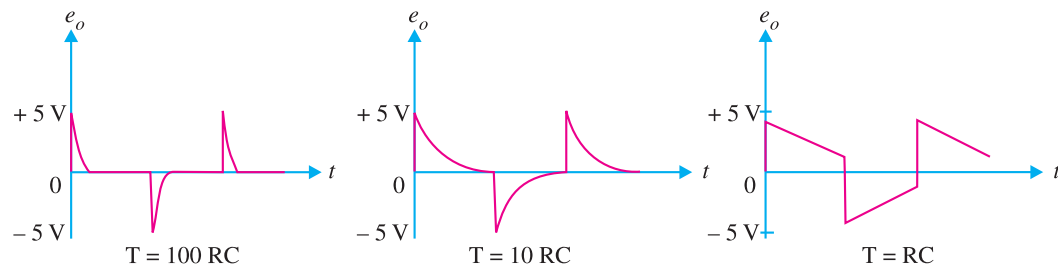
Fig. 18.22

Example 18.6. *In a differentiating circuit, R = 10 kΩ and C = 2.2 μF. If the input voltage goes from 0 V to 10 V at a constant rate in 0.4 s, determine the output voltage.*

Solution.

$$e_o = RC\frac{d}{dt}(e_i) = RC\frac{de_i}{dt} \qquad \text{... See Art. 18.15}$$

Here $\qquad R = 10\text{ k}\Omega\,;\ C = 2.2\text{ μF}\,;\ \dfrac{de_i}{dt} = \dfrac{10-0}{0.4} = 25\text{ V/s}$

$\therefore \qquad e_o = (10\times 10^3)\times(2.2\times 10^{-6})\times 25 = \textbf{0.55 V}$

18.16 Integrating Circuit

A circuit in which output voltage is directly proportional to the integral of the input is known as an **integrating circuit** *i.e.*

$$\text{Output} \propto \int \text{Input}$$

An integrating circuit is a simple RC series circuit with output taken across the capacitor C as shown in Fig. 18.23. It may be seen that R and C of the differentiating circuit have changed places. In order that the circuit renders good integration, the following conditions should be fulfilled :
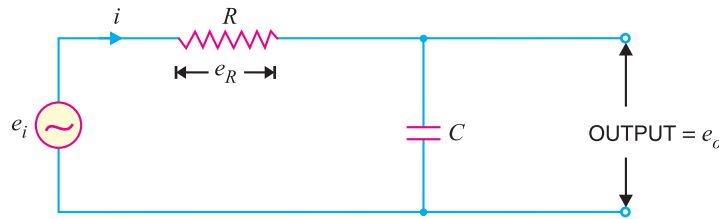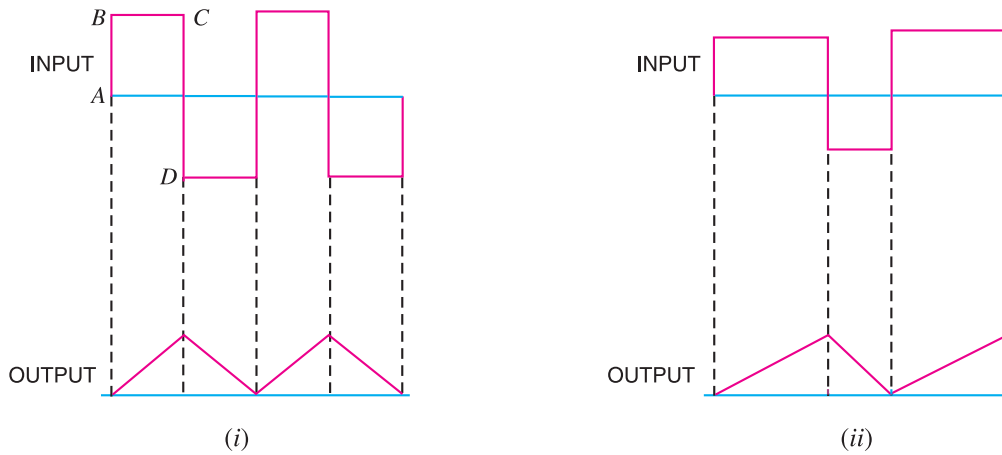

Fig. 18.23

(**i**) The time constant RC of the circuit should be very large as compared to the time period of the input wave.

(**ii**) The value of R should be 10 or more times larger than X_C.

Let e_i be the input alternating voltage and let i be the resulting alternating current. Since R is very large as compared to capacitive reactance X_C of the capacitor, it is reasonable to assume that voltage across R (*i.e.* e_R) is equal to the input voltage *i.e.*

$$e_i = e_R$$

Now
$$i = \frac{e_R}{R} = \frac{e_i}{R}$$

The charge q on the capacitor at any instant is

$$q = \int i\, dt$$

$$\text{Output voltage, } e_o = \frac{q}{C} = \frac{\int i\, dt}{C}$$

$$= \frac{\int \frac{e_i}{R}\, dt}{C} \qquad\qquad \left(Q\ i = \frac{e_i}{R} \right)$$

$$= \frac{1}{RC} \int e_i\, dt$$

$$\propto \int e_i\, dt \qquad\qquad (\because RC \text{ is constant})$$

$$\therefore \qquad \text{Output voltage} \propto \int \text{Input}$$

Output waveforms. The output waveform from an integrating circuit depends upon time constant and shape of the input wave. Two important cases will be discussed :

(**i**) **When input is a square wave.** When the input fed to an integrating circuit is a square wave, the output will be a triangular wave as shown in Fig. 18.24 (*i*). As integration means summation, therefore, output from an integrating circuit will be the sum of all the input waves at any instant. This sum is zero at A and goes on increasing till it becomes maximum at C. After this, the summation goes on decreasing to the onset of negative movement CD of the input.

Fig. 18.24

(ii) When input is rectangular wave. When the input fed to an integrating circuit is a rectangular wave, the output will be a triangular wave as shown in Fig. 18.24 (*ii*).

18.17 Important Applications of Diodes

We have seen that diodes can be used as rectifiers. Apart from this, diodes have many other applications. However, we shall confine ourselves to the following two applications of diodes :

(*i*) as a clipper   (*ii*) as a clamper

A clipper (or limiter) is used to clip off or remove a portion of an a.c. signal. The half-wave rectifier is basically a clipper that eliminates one of the alternations of an a.c. signal.

A clamper (or *dc* restorer) is used to restore or change the *dc* reference of an *ac* signal. For example, you may have a 10 V_{pp} *ac* signal that varies equally above and below 2 V *dc*.

18.18 Clipping Circuits

The circuit with which the waveform is shaped by removing (or clipping) a portion of the applied wave is known as a **clipping circuit.**

Clippers find extensive use in radar, digital and other electronic systems. Although several clipping circuits have been developed to change the wave shape, we shall confine our attention to diode clippers. These clippers can remove signal voltages above or below a specified level. The important diode clippers are (*i*) positive clipper (*ii*) biased clipper (*iii*) combination clipper.

(*i*) **Positive clipper.** A positive clipper is that which removes the positive half-cycles of the input voltage. Fig. 18.25 shows the typical circuit of a positive clipper using a diode. As shown, the output voltage has all the positive half-cycles removed or clipped off.
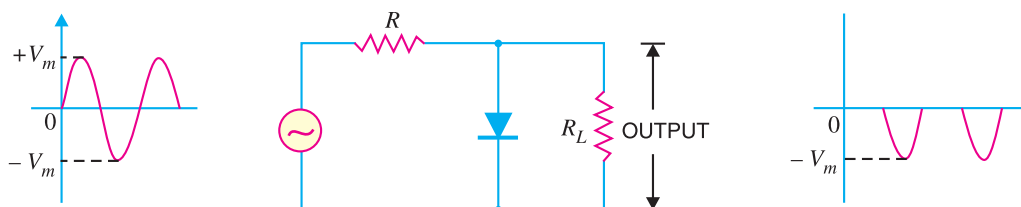
Fig. 18.25

The circuit action is as follows. During the positive half-cycle of the input voltage, the diode is forward biased and conducts heavily. Therefore, the voltage across the diode (which behaves as a short) and hence across the load R_L is zero. Hence *output voltage during positive half-cycles is zero.

During the negative half-cycle of the input voltage, the diode is reverse biased and behaves as an open. In this condition, the circuit behaves as a voltage divider with an output given by :

$$\text{Output voltage} \ = \ -\frac{R_L}{R + R_L} V_m$$

Generally, R_L is much greater than R.

∴   Output voltage $\ = \ - V_m$

It may be noted that if it is desired to remove the negative half-cycle of the input, the only thing to be done is to reverse the polarities of the diode in the circuit shown in Fig. 18.25. Such a clipper is then called a *negative clipper*.

(ii) Biased clipper. Sometimes it is desired to remove a small portion of positive or negative half-cycle of the signal voltage. For this purpose, biased clipper is used. Fig. 18.26 shows the circuit of a biased clipper using a diode with a battery of V volts. With the polarities of battery shown, a portion of each positive half-cycle will be clipped. However, the negative half-cycles will appear as such across the load. Such a clipper is called *biased positive clipper.*

The circuit action is as follows. The diode will conduct heavily so long as input voltage is greater than $+V$. When input voltage is greater than $+V$, the diode behaves as a short and the output equals $+V$. The output will stay at $+V$ so long as the input voltage is greater than $+V$. During the period the input voltage is less than $+V$, the diode is reverse biased and behaves as an open. Therefore, most of the input voltage appears across the output. In this way, the biased positive clipper removes input voltage above $+V$.

During the negative half-cycle of the input voltage, the diode remains reverse biased. Therefore, almost entire negative half-cycle appears across the load.
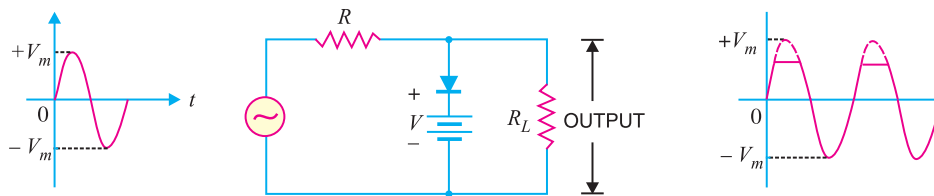
Fig. 18.26

If it is desired to clip a portion of negative half-cycles of input voltage, the only thing to be done is to reverse the polarities of diode or battery. Such a circuit is then called a *biased negative clipper.*

(iii) Combination clipper. It is a combination of biased positive and negative clippers. With a combination clipper, a portion of both positive and negative half-cycles of input voltage can be removed or clipped as shown in Fig. 18.27.
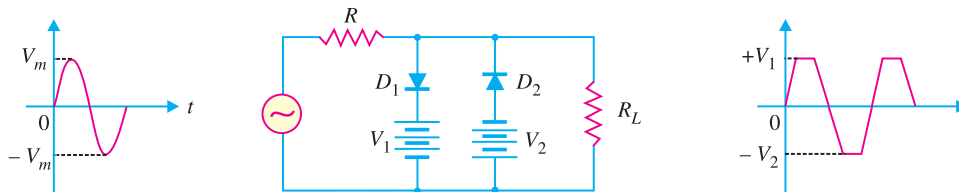

Fig. 18.27

*   It may be noted that all the input voltage during this half-cycle is dropped across R.

The circuit action is as follows. When positive input voltage is greater than $+V_1$, diode D_1 conducts heavily while diode D_2 remains reverse biased. Therefore, a voltage $+V_1$ appears across the load. This output stays at $+V_1$ so long as the input voltage exceeds $+V_1$. On the other hand, during the negative half-cycle, the diode D_2 will conduct heavily and the output stays at $-V_2$ so long as the input voltage is greater than $-V_2$. Note that $+V_1$ and $-V_2$ are less than $+V_m$ and $-V_m$ respectively.

Between $+V_1$ and $-V_2$ neither diode is on. Therefore, in this condition, most of the input voltage appears across the load. It is interesting to note that this clipping circuit can give square wave output if V_m is much greater than the clipping levels.

Example 18.7. *For the negative series clipper shown in Fig.18.28, what is the peak output voltage from the circuit ?*

Solution. When the diode is connected in series with the load, it is called a series clipper. Since it is a negative clipper, it will remove negative portion of input a.c. signal.
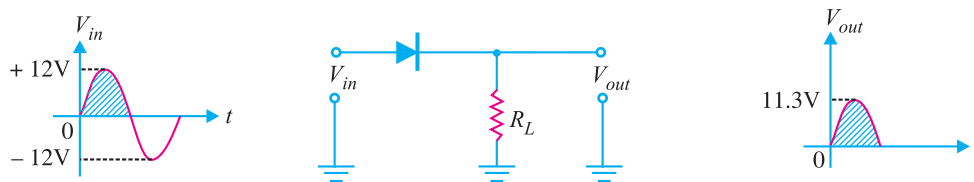
Fig. 18.28

During the positive half-cycle of input signal, the dioide is forward biased. As a result, the diode will conduct. The output voltage is

$$V_{out\,(peak)} = V_{in\,(peak)} - 0.7 = 12 - 0.7 = \textbf{11.3 V}$$

During the negative half-cycle of input signal, the diode is reverse biased and consequently it will not conduct. Therefore, $V_{out} = 0$. Note that under this condition, the entire input voltage will appear across the diode.

Example 18.8. *The negative shunt clipper shown in Fig. 18.29 (i) has a peak input voltage of + 10 V. What is the peak output voltage from this circuit ?*
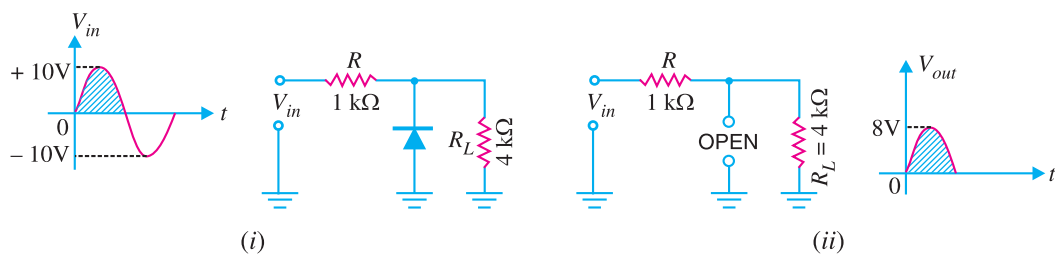
Fig. 18.29

Solution. When the diode is connected in parallel with the load, it is called a shunt clipper. During the positive half-cycle of input ac signal, the diode is reverse biased and it will behave as an open. This is shown in Fig. 18.29 (*ii*). With diode as an open,

$$V_{out\,(peak)} = \text{Peak voltage across } R_L$$

$$= \frac{R_L}{R + R_L} V_{in\,(peak)} = \frac{4}{1+4} \times 10 = \textbf{8V}$$

Note that peak output voltage is somewhat less than the peak input voltage.

Example 18.9. *In example 18.8, what will be the output voltage and voltage across R when the input voltage is –10 V ?*
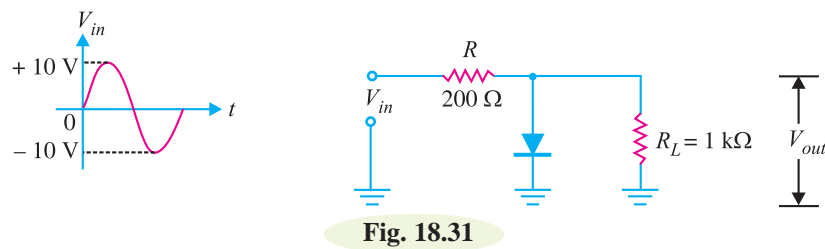
Solution. During the negative half-cycle of input signal, the diode is forward biased. Therefore, diode can be replaced by its simplified equivalent circuit as shown in Fig. 18.30. Since load is connected in parallel with the diode,
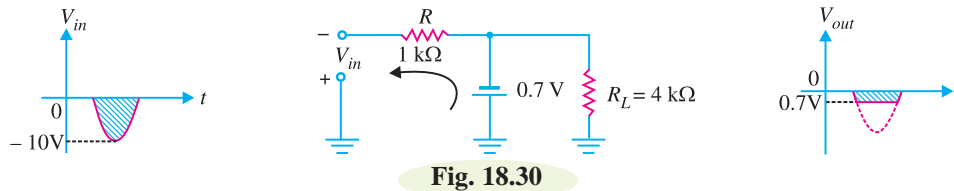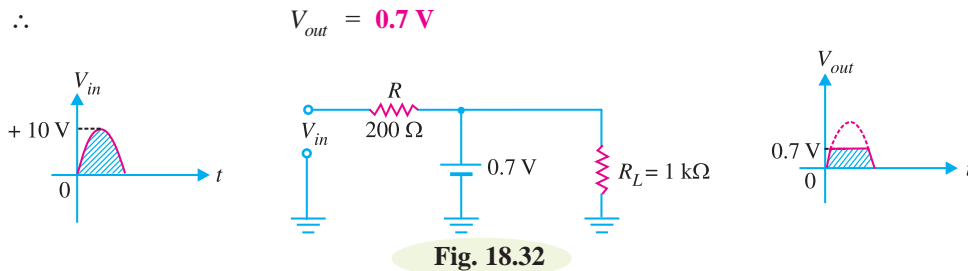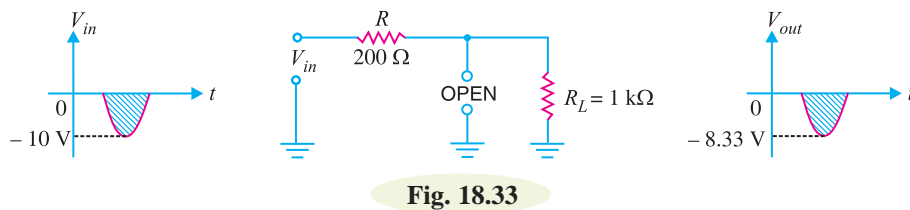

Fig. 18.30

$$\therefore \qquad V_{out} = -0.7 \text{ V}$$

$$\text{Voltage across } R, \ V_R = (-10) - (-0.7) = -10 + 0.7 = -9.3 \text{ V}$$

Example 18.10. *The positive shunt clipper shown in Fig. 18.31 has the input waveform as indicated. Determine the value of V_{out} for each of the input alternations.*

Fig. 18.31

Solution.

Positive half-cycle. During the positive half-cycle of the input ac signal, the diode is forward biased. Therefore, diode can be replaced by its simplified equivalent circuit as shown in Fig. 18.32. Since the load is connected in parallel with the diode,

$$\therefore \qquad V_{out} = 0.7 \text{ V}$$

Fig. 18.32

Negative half-cycle. During the negative half-cycle of the input a.c. signal, the diode is reverse biased and it conducts no current. Therefore, the diode will behave as an open as shown in Fig. 18.33.

Fig. 18.33

$$\therefore \qquad V_{out(peak)} = \frac{R_L}{R + R_L} V_{in(peak)}$$

$$= \left(\frac{1000}{200 + 1000}\right)(-10 \text{ V}) = -\textbf{8.33 V}$$

Again the peak output voltage is somewhat less than the peak input voltage.

Example 18.11. *In Fig. 18.31, what is the purpose of using the series resistance R ?*

Solution. The purpose of series resistance R is to protect the diode from damage. Let us explain this point. Suppose the series resistance R is not in the circuit. The circuit then becomes as shown in Fig. 18.34.

During the positive half-cycle of the input signal, the diode is forward biased. Since series resistance R is not present, it is easy to see that the diode will short the signal source to the ground. As a result, excessive current will flow through the diode as well as through the signal source. This large current may damage/destroy either the diode or the signal source.
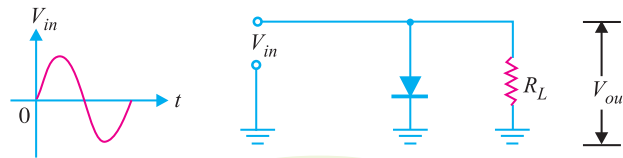
Fig. 18.34

Note. The series resistance R protects the diode and signal source when diode is forward biased. However, the presence of this resistance affects the output voltage to a little extent. It is because in a practical clipper circuit, the value of R is much lower than R_L. Consequently, output voltage will be approximately equal to V_{in} when the diode is reverse biased.

Example 18.12. *For the input wave to the clipping circuit shown in Fig. 18.35, find the output waveform.*
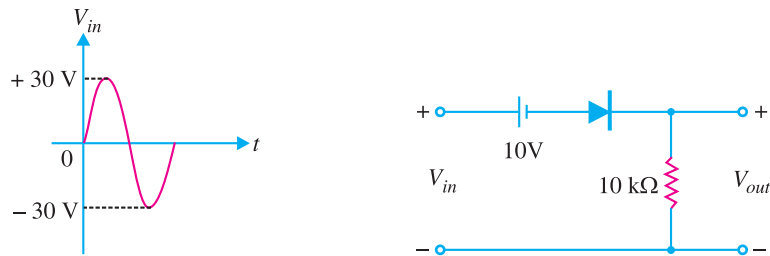
Fig. 18.35

Solution. For any value of $V_{in} > 10$V, the ideal diode is forward biased and $V_{out} = V_{in} - 10$. For example, at $V_{in} = 15$V [See Fig. 18.36 (*i*)], $V_{out} = 15 - 10 = 5$V.
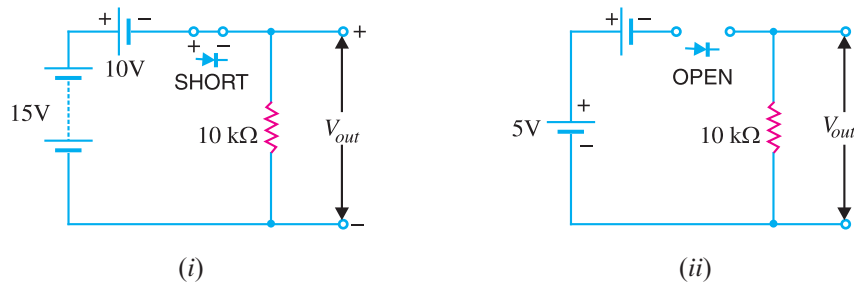
(*i*)   (*ii*)

Fig. 18.36

For any value of $V_{in} < 10V$, the ideal diode is reverse biased. Therefore, circuit current is zero and hence $V_{out} = 0$. For example, with $V_{in} = 5V$ [See Fig. 18.36 (ii)], $V_{out} = 0$ and V_d (drop across diode) = 5V
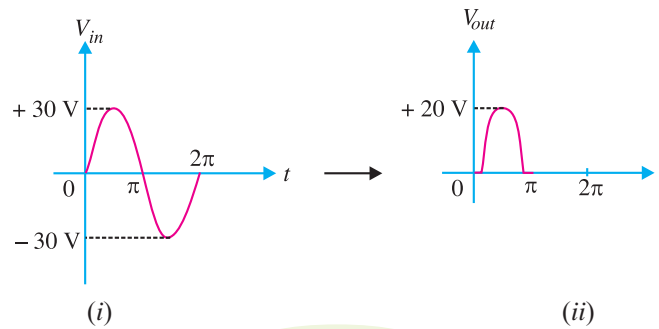

(i)   (ii)

Fig. 18.37

The output waveform will be as shown in Fig. 18.37 (ii).

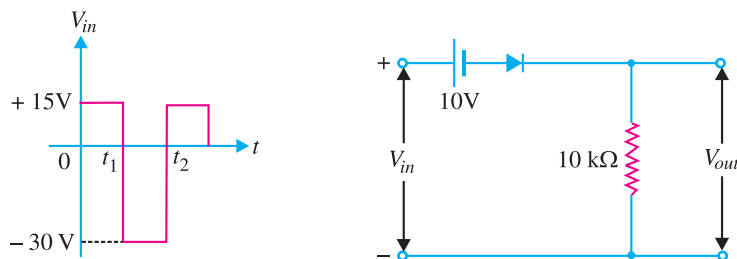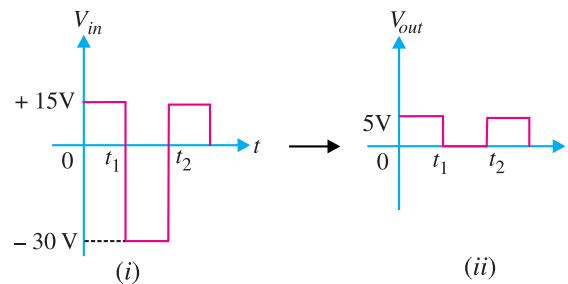**Example 18.13.** *For the input wave to the clipping circuit in Fig. 18.38, find the output wave-form.*

Fig. 18.38

Solution. For any value of $V_{in} > 10V$, the ideal diode is forward biased and $V_{out} = V_{in} - 10$. For any value of $V_{in} < 10V$, the ideal diode is reverse biased and $V_{out} = 0$.

(i)   (ii)

Fig. 18.39

The output waveform will be as shown in Fig. 18.39 (ii).

Example 18.14. *For the input waveform to the clipping circuit in Fig. 18.40, find the output voltage waveform.*

Solution. The battery of 5V reverse biases the diode. The point *A must go positive to 5V before the diode turns on. For all voltages at point A equal to or greater than 5V, the diode conducts and the

* Assuming the diode to be ideal. Actually point A must go positive to 5.6V before the diode turns on. Here 0.6V accounts for potential barrier.

output voltage stays at 5V. For all negative voltages at A and positive voltages less than 5V, the diode is reverse biased. When reverse biased, the diode acts like an open circuit and $V_{out} = V_{in}$. Thus circuit in Fig. 18.40 is an adjustable positive peak clipper that clips all positive peaks greater than battery voltage (*i.e.* 5V).
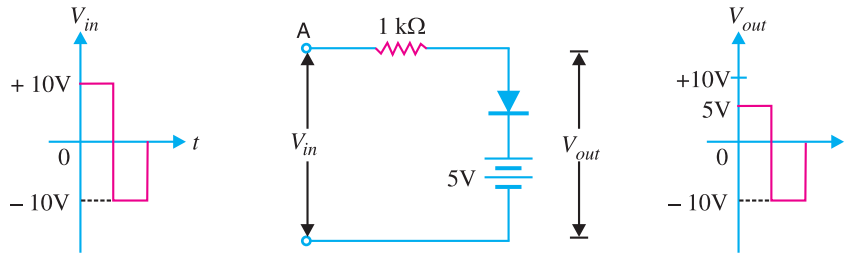

Fig. 18.40

Example 18.15. *For the input wave to the symmetrical clipper shown in Fig. 18.41, find the output voltage waveform. Assume that the barrier voltage of each diode is 0.6V.*

Solution. Fig. 18.41 shows the symmetrical clipper.

(*i*)   Diode D_1 is reverse biased for all positive inputs and negative inputs less than 0.6V. Diode D_2 is reverse biased for all negative inputs and positive inputs less than 0.6V.

(*ii*)   For all positive inputs greater than 0.6V, D_2 is forward biased and output voltage stays at 0.6V. For all negative inputs greater than –0.6V, D_1 is forward biased and output stays at – 0.6V.
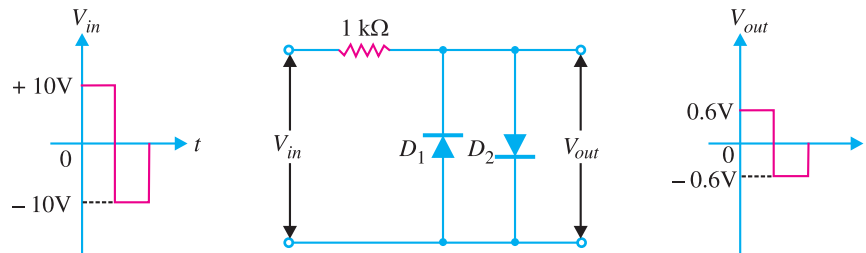
Fig. 18.41

Thus for the input voltage waveform, the output voltage varies between – 0.6V and 0.6V. This circuit is sometimes used to convert a sine-wave input to a reasonably square-wave output signal.

Example 18.16. *Fig. 18.42 shows a zener shunt clipper with sine wave input. Determine the output waveform.*
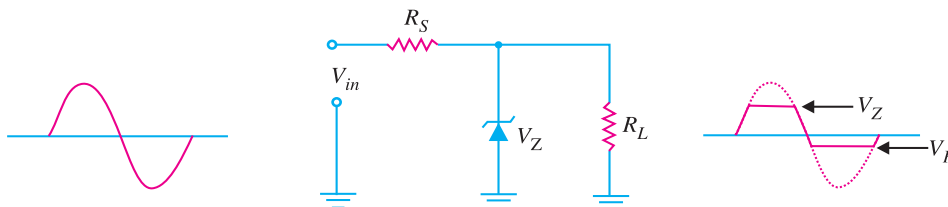
Fig. 18.42

Solution. The *zener shunt clipper* uses a zener diode in place of the ordinary diode. The zener shunt clipper uses both the forward and reverse characteristics of the zener diode. Thus when the zener diode is forward biased, this clipper acts just like the standard shunt clipper.

When the input signal in Fig. 18.42 goes positive, the zener is reverse biased. Therefore, the zener diode will remain OFF until the value of V_{in} reaches the value of V_Z. At that time, the zener diode will turn ON, clipping the input signal. As long as V_{in} is greater than V_Z, the zener will remain ON and the output voltage is

$$V_{out} = V_Z$$

When the input signal goes negative, the zener is forward biased. Therefore, the zener is clipped off at 0.7 V.

Example 18.17. *Fig. 18.43 shows a symmetrical zener shunt clipper with sine wave input. Determine the output waveform.*
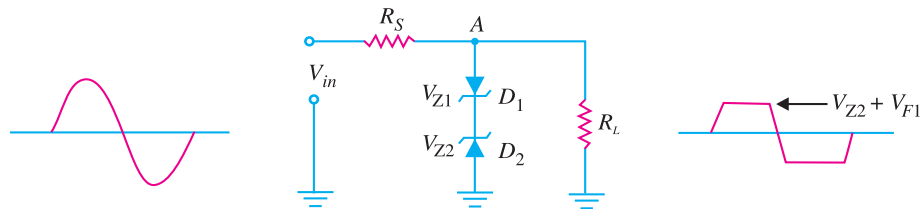
Fig. 18.43

Solution. The *symmetrical zener clipper* uses two zener diodes that are connected as shown in Fig. 18.43. When the input is positive, D_1 is forward biased and D_2 is reverse biased (assuming that the value of V_{in} is high enough to turn both diodes ON). When both diodes are conducting, the voltage from point A to ground will be equal to the sum of V_{Z2} and the forward voltage drop of D_1 *i.e.*, $V_{F1} = 0.7V$.

$$\therefore \quad V_{out} = V_{Z2} + V_{F1} = V_{Z2} + 0.7V$$

When the input is negative, D_1 is reverse biased and D_2 is forward biased. The output voltage in this case is

$$V_{out} = -V_{Z1} - V_{F2} = -(V_{Z1} + 0.7V)$$

In practice, the two zeners have the same voltage rating *i.e.* $V_{Z1} = V_{Z2} = V_Z$.

$$\therefore \quad V_{out} = \pm(V_Z + 0.7V)$$

18.19 Applications of Clippers

There are numerous clipper applications and it is not possible to discuss all of them. However, in general, clippers are used to perform one of the following two functions :

(**i**) Changing the shape of a waveform

(**ii**) Circuit transient protection

(**i**) **Changing the shape of waveform.** Clippers can alter the shape of a waveform. For example, a clipper can be used to convert a sine wave into a rectangular wave, square wave etc. They can limit either the negative or positive alternation or both alternations of an a.c. voltage.

(**ii**) **Circuit Transient protection.** *Transients can cause considerable damage to many types of circuits *e.g.*, a digital circuit. In that case, a clipper diode can be used to prevent the transient form reaching that circuit.

. . . .

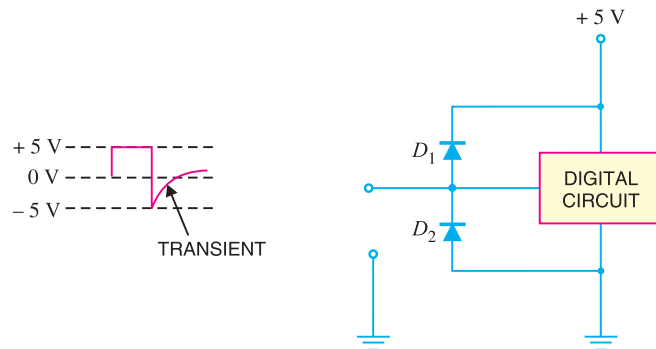*   A transient is a sudden current or voltage rise that has an extremely short duration.

Fig. 18.44

Fig. 18.44 shows the protection of a typical digital circuit against transients by the diode clipper. When the transient shown in Fig. 18.44 occurs on the input line, it causes diode D_2 to be forward biased. The diode D_2 will conduct; thus shorting the transient to the ground. Consequently, the input of the circuit is protected from the transient.

18.20 Clamping Circuits

A circuit that places either the positive or negative peak of a signal at a desired d.c. level is known as a **clamping circuit.**

Fig. 18.45

A clamping circuit (or a clamper) essentially adds a *d.c.* component to the signal. Fig. 18.45 shows the key idea behind clamping. The input signal is a sine wave having a peak-to-peak value of 10 V. The clamper adds the *d.c.* component and pushes the signal upwards so that the negative peaks fall on the zero level. As you can see, the waveform now has peak values of +10 V and 0 V.

It may be seen that the shape of the original signal has not changed; only there is vertical shift in the signal. Such a clamper is called a *positive clamper.* The *negative clamper* does the reverse *i.e.* it pushes the signal downwards so that the positive peaks fall on the zero level.

The following points may be noted carefully :

(***i***) The clamping circuit does not change the peak-to-peak or r.m.s. value of the waveform. Thus referring to Fig. 18.45 above, the input waveform and clamped output have the same peak-to-peak value *i.e.*, 10 V in this case. If you measure the input voltage and clamped output with an a.c. voltmeter, the readings will be the same.

(***ii***) A clamping circuit changes the peak and average values of a waveform. This point needs explanation. Thus in the above circuit, it is easy to see that input waveform has a peak value of 5 V and average value over a cycle is zero. The clamped output varies between 10 V and 0 V. Therefore, the peak value of clamped output is 10 V and *average value is 5 V. Hence we arrive at a very

---

*   Average value (or *dc* value) $= \dfrac{10 + 0}{2} = 5$ V

important conclusion that *a clamper changes the peak value as well as the average value of a wave-form.*

18.21 Basic Idea of a Clamper

A clamping circuit should not change peak-to-peak value of the signal; it should only change the *dc* level. To do so, a clamping circuit uses a capacitor, together with a diode and a load resistor R_L. Fig. 18.46 shows the circuit of a positive clamper. *The operation of a clamper is based on the principle that charging time of a capacitor is made very small as compared to its discharging time.* Thus referring to Fig. 18.46,
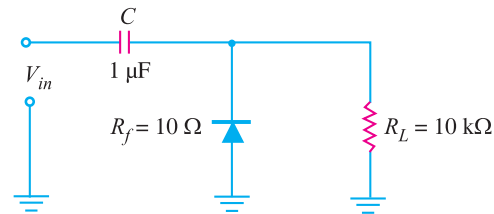
Fig. 18.46

$$\text{*Charging time constant, } \tau = R_f C = (10\ \Omega) \times (10^{-6}\ F) = 10\ \mu s$$
$$\text{Total charging time, } \tau_C = \text{**}5R_f C = 5 \times 10 = 50\ \mu s$$
$$\text{***Discharging time constant, } \tau = R_L C = (10 \times 10^3) \times (1 \times 10^{-6}) = 10\ ms$$
$$\text{Total discharging time, } \tau_D = 5\,R_L C = 5 \times 10 = 50\ ms$$

It may be noted that charging time (*i.e.*, 50 μs) is very small as compared to the discharging time (*i.e.*, 50 ms). This is the basis of clamper circuit operation. In a practical clamping circuit, the values of C and R_L are so chosen that discharging time is very large.

18.22 Positive Clamper

Fig. 18.47 shows the circuit of a †positive clamper. The input signal is assumed to be a square wave with time period T. The clamped output is obtained across R_L. The circuit design incorporates two main features. Firstly, the values of C and R_L are so selected that time constant $\tau = CR_L$ is very large. This means that voltage across the capacitor will not discharge significantly during the interval the diode is non-conducting. Secondly, $R_L C$ time constant is deliberately made much greater than the time period T of the incoming signal.
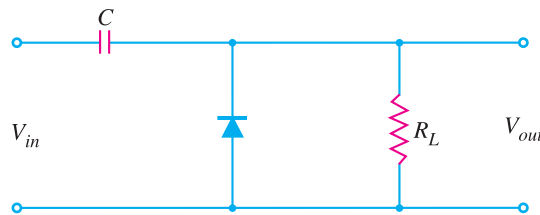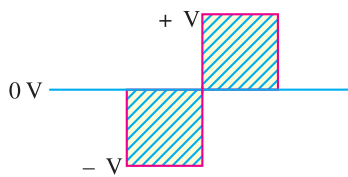

Fig. 18.47

Operation

    (*i*)   During the negative half-cycle of the input signal, the diode is forward biased. Therefore,

. . . .

*	When diode is forward biased.
**	From the knowledge of electrical engineering, we know that charging time of a capacitor is ≃ 5 *RC*.
***	When diode is reverse biased.
†	If you want to determine what type of clamper you are dealing with, here is an easy memory trick. If the diode is pointing up (away from ground), the circuit is a positive clamper. On the other hand, if diode is pointing down (towards ground), the circuit is a negative clamper.

the diode behaves as a short as shown in Fig. 18.48. The charging time constant ($= CR_f$, where $R_f =$ forward resistance of the diode) is very small so that the capacitor will charge to V volts very quickly. It is easy to see that during this interval, the output voltage is directly across the short circuit. Therefore, $V_{out} = 0$.
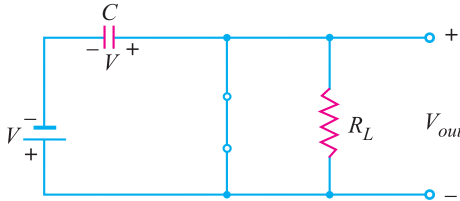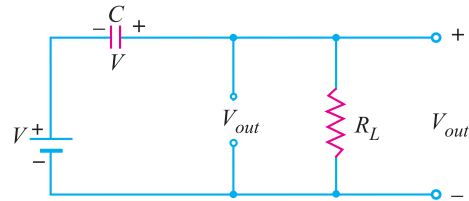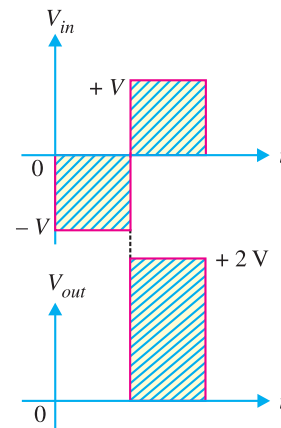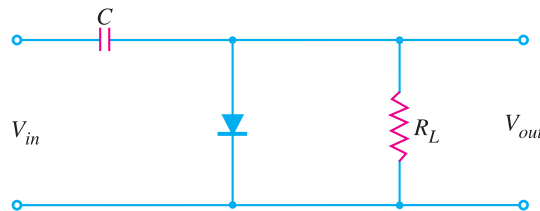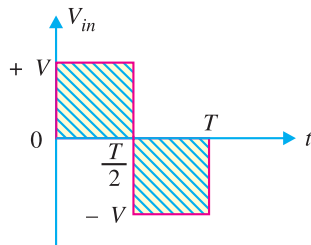

Fig. 18.48

Fig. 18.49

(*ii*) When the input switches to $+V$ state (*i.e.*, positive half-cycle), the diode is reverse biased and behaves as an open as shown in Fig. 18.49. Since the discharging time constant ($= CR_L$) is much greater than the time period of the input signal, the capacitor remains almost fully charged to V volts during the off time of the diode. Referring to Fig. 18.49 and applying Kirchhoff 's voltage law to the input loop, we have,

$$V + V - V_{out} = 0$$

or

$$V_{out} = 2V$$

The resulting waveform is shown in Fig. 18.50. It is clear that it is a positively clamped output. That is to say the input signal has been pushed upward by V volts so that negative peaks fall on the zero level.

18.23 Negative Clamper

Fig. 18.51 shows the circuit of a negative clamper. The clamped output is taken across R_L. Note that only change from the positive clamper is that the connections of diode are reversed.

(*i*) During the positive half-cycle of the input signal, the diode is forward biased. Therefore, the diode behaves as a short as shown in Fig. 18.52. The charging time constant ($= CR_f$) is very small so that the capacitor will charge to V volts very quickly. It is easy to see that during this interval, the output voltage is directly across the short circuit. Therefore, $V_{out} = 0$.

Fig. 18.50

Fig. 18.51

(*ii*) When the input switches to $-V$ state (*i.e.*, negative half-cycle), the diode is reverse biased
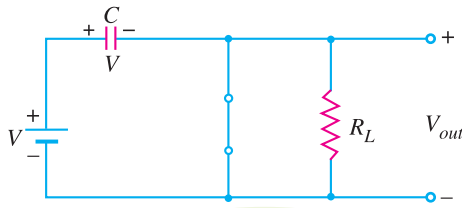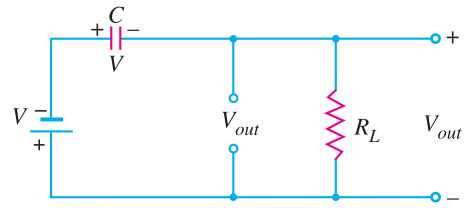
Fig. 18.52

Fig. 18.53

and behaves as an open as shown in Fig. 18.53. Since the discharging time constant ($= CR_L$) is much greater than the time period of the input signal, the capacitor almost remains fully charged to V volts during the off time of the diode. Referring to Fig. 18.53 and applying Kirchhoff 's voltage law to the input loop, we have,

$$-V - V - V_{out} = 0$$

or $$V_{out} = -2 \text{ V}$$

The resulting waveform is shown in Fig. 18.54. Note that total swing of the output signal is equal to the total swing of the input signal.

Example 18.18. *Sketch the output waveform for the circuit shown in Fig. 18.55. It is given that discharging time constant (CR_L) is much greater than the time period of input wave.*
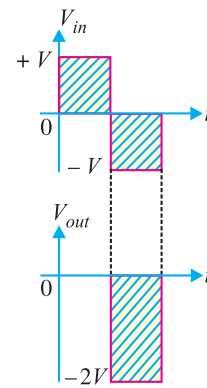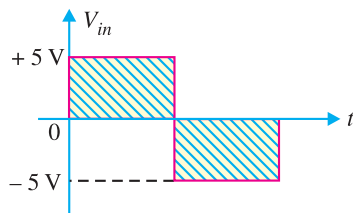

Fig. 18.54
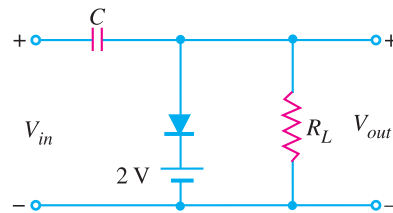
Fig. 18.55

Solution.

During positive half-cycle of the input signal, the diode is forward biased. The network will appear as shown in Fig. 18.56. It is clear that $V_{out} = +2 \text{ V}$. Further, applying Kirchhoff's voltage law to the input loop in Fig. 18.56, we have,

$$5 \text{ V} - V_C - 2 \text{ V} = 0$$

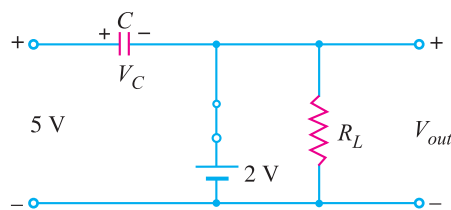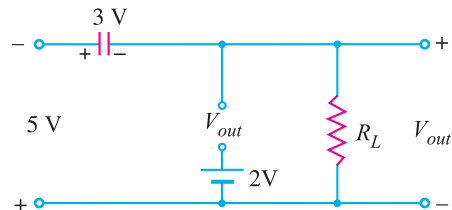∴ $$V_C = 3 \text{ V}$$

Fig. 18.56

Fig. 18.57

Therefore, the capacitor will charge up to 3 V.

During the negative half-cycle of the input signal, the diode is reverse biased and will behave as

an open [See Fig. 18.57]. Now battery of 2 V has no effect on V_{out}. Applying Kirchhoff's voltage law to the outside loop of Fig. 18.57, we have,

$$-5 - 3 - V_{out} = 0$$

or $$V_{out} = -8 \text{ V}$$

The negative sign results from the fact that the polarity of 8 V is opposite to the polarity defined for V_{out}. The clamped output is shown in Fig. 18.58. Note that the output swing of 10 V matches with the input swing.

Note. It is a biased clamper circuit. It allows a waveform to be shifted above or below (depending upon the polairty of 2 V battery) a *dc* reference other than 0 V.

Fig. 18.58

Example 18.19. *Sketch the output waveform for the circuit shown in Fig. 18.59. It is given that discharging time constant (= CR_L) is much greater than the time period of input wave.*
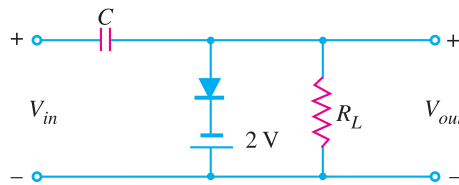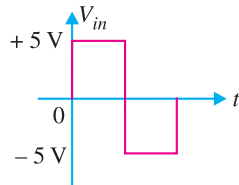

Fig. 18.59

Solution.

During the positive half-cycle of input signal, the diode is forward biased. Therefore, the diode behaves as a short [See Fig. 18.60]. It is easy to see that $V_{out} = -2$ V. Further, applying Kirchhoff's voltage law to the input loop [See Fig. 18.60], we have,

$$5 \text{ V} - V_C + 2 \text{ V} = 0$$

or $$V_C = 7 \text{ V}$$

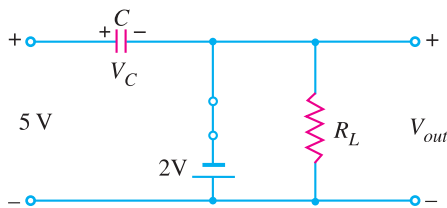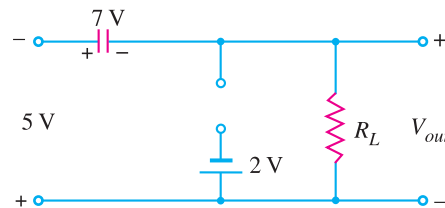Therefore, the capacitor will charge upto 7 V.

Fig. 18.60

Fig. 18.61

During the negative half-cycle of the input signal, the diode is reverse biased and behaves as an open as shown in Fig. 18.61. Now battery of 2 V has no effect on V_{out}. Applying Kirchhoff's voltage law to the outside loop of Fig. 18.61, we have,

$$-5 \text{ V} - 7 \text{ V} - V_{out} = 0$$

or $$V_{out} = -12 \text{ V}$$

The negative sign results from the fact that the polarity of 12 V is opposite to the polarity defined for V_{out}. The clamped output is shown in Fig. 18.62. Note that output and input swings are the same.
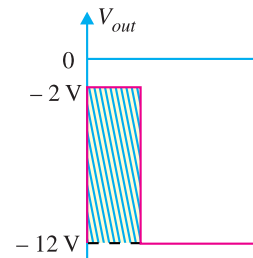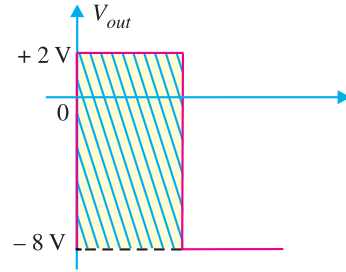

Fig. 18.62

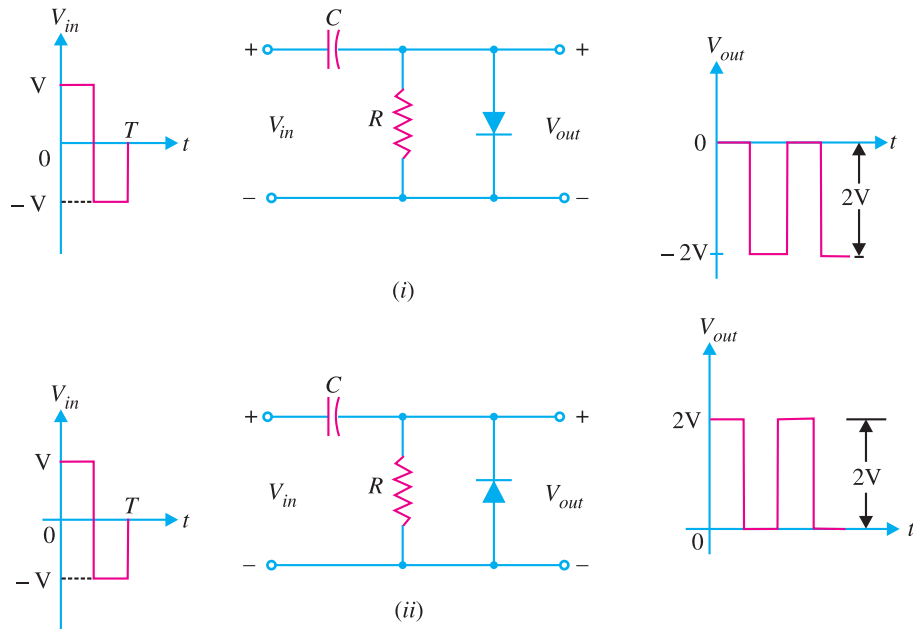**Examle 18.20.** *Draw the output voltage waveform for the input shown in Fig. 18.63.*

(i)

(ii)

Fig. 18.63

Solution. Fig. 18.63 (*i*) shows the output voltage waveform for the input wave to the clamping circuit. Note that it is a negative clamper and pushes the input wave downwards so that positive peaks fall on the zero level. Fig. 18.63 (*ii*) shows the output voltage waveform for the input wave to a positive clamper. The clamper pushes the input wave upwards so that the negative peaks fall on the zero level.

Example 18.21. *Draw the output voltage waveform for the input wave shown in Fig. 18.64.*
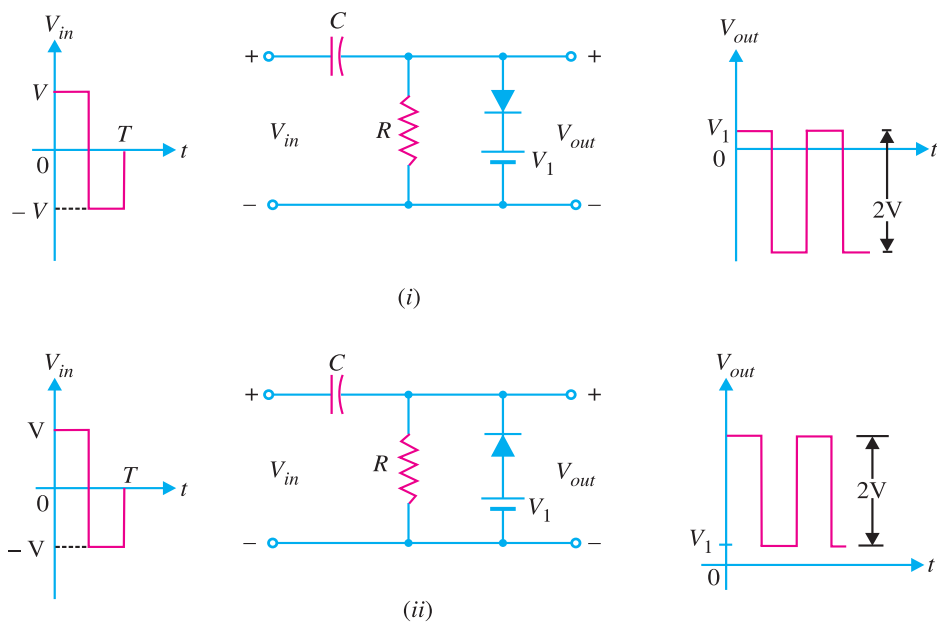

(i)

(ii)

Fig. 18.64

Solution. Fig. 18.64 (*i*) shows the output voltage waveform for the input wave to the clamping circuit. This is a negative clamper and pushes the input wave downward so that positive peak voltage is now V_1. Fig. 18.64 (*ii*) shows the output voltage waveform from a positive clamper. Note that the input wave is pushed upwards so that negative peaks are V_1 volts above the zero level.

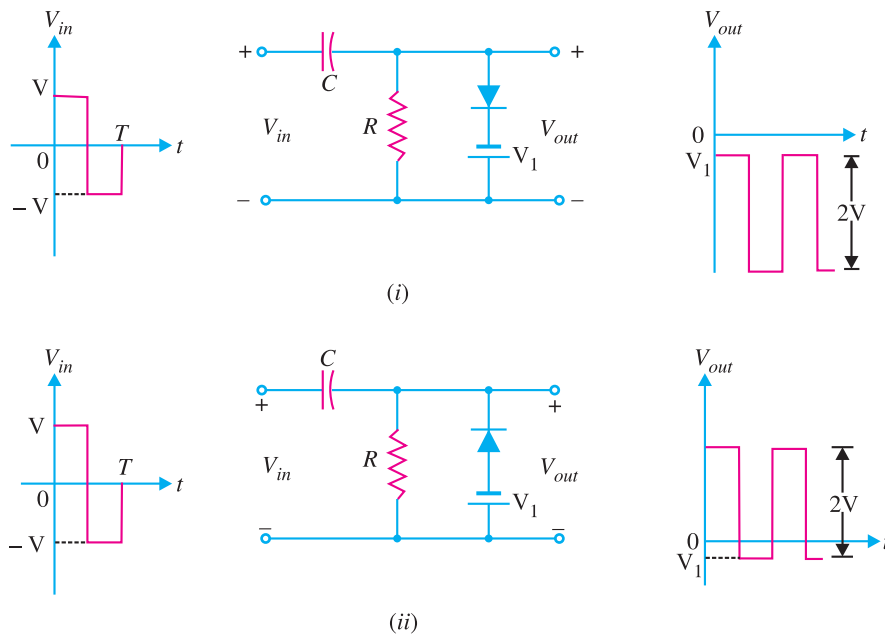**Example 18.22.** *Draw the output voltage waveform for the input wave shown in Fig. 18.65.*

(*i*)

(*ii*)

Fig. 18.65

Solution. Fig. 18.65 (*i*) shows the output voltage waveform for the input wave to the clamping circuit. This is a negative clamper and pushes the input wave downward so that positive peaks lie V_1 volts below the zero level. Fig. 18.65 (*ii*) shows the output voltage waveform from a positive clamper. Note that the input waveform is pushed upwards so that negative peaks lie V_1 volts below zero level.

MULTIPLE-CHOICE QUESTIONS

1. A switch has ....
   (*i*) one state
   (*ii*) two states
   (*iii*) three states
   (*iv*) none of the above

2. A relay is .... switch.
   (*i*) a mechanical
   (*ii*) an electronic
   (*iii*) an electromechanical
   (*iv*) none of the above

3. The switch that has the fastest speed of operation is .... switch.
   (*i*) electronic
   (*ii*) mechanical
   (*iii*) electromechanical
   (*iv*) none of the above

4. The most inexpensive switch is .... switch.
   (*i*) electronic
   (*ii*) mechanical
   (*iii*) electromechanical
   (*iv*) none of the above

5. The main disadvantage of a mechanical switch is that it ....
   (*i*) is operated mechanically
   (*ii*) is costly
   (*iii*) has high inertia
   (*iv*) none of the above

6. When a transistor is driven to saturation, ideally the output is ....
   (*i*) V_{CC}
   (*ii*) 0
   (*iii*) $V_{CC}/2$
   (*iv*) $2V_{CC}$

7. The maximum speed of electronic switch can be .... operations per second.
   (*i*) 10^4
   (*ii*) 10
   (*iii*) 1000
   (*iv*) 10^9

8. A relay is superior to a mechanical switch because it ....
   (*i*) is relatively inexpensive
   (*ii*) does not require moving contacts
   (*iii*) combines control with power amplification
   (*iv*) none of the above

9. When a transistor is driven to cut off, ideally the output is ....
   (*i*) V_{CC}
   (*ii*) 0
   (*iii*) $V_{CC}/2$
   (*iv*) $V_{CC}/3$

10. .... multivibrator is a square wave oscillator.
   (*i*) monostable
   (*ii*) astable
   (*iii*) bistable
   (*iv*) none of the above

11. An astable multivibrator has ....
   (*i*) one stable state
   (*ii*) two stable states
   (*iii*) no stable state
   (*iv*) none of the above

12. If d.c. supply of 10 V is fed to a differentiating circuit, then output will be ....
   (*i*) 20 V
   (*ii*) 10 V
   (*iii*) 0 V
   (*iv*) none of the above

13. If the input to a differentiating circuit is a saw-tooth wave, then output will be .... wave.
   (*i*) square
   (*ii*) triangular
   (*iii*) sine
   (*iv*) rectangular

14. A bistable multivibrator has ....
   (*i*) two stable states
   (*ii*) one stable state
   (*iii*) no stable state
   (*iv*) none of the above

15. If a square wave is fed to a differentiating circuit, the output will be ....
   (*i*) sine wave
   (*ii*) sharp narrow pulses
   (*iii*) rectangular wave
   (*iv*) triangular wave

16. An integrating circuit is a simple *RC* series circuit with output taken across ....
   (*i*) both *R* and *C*
   (*ii*) *R*
   (*iii*) *C*
   (*iv*) none of the above

17. For an integrating circuit to be effective, the *RC* product should be .... the time period of the input wave.
   (*i*) 5 times greater than
   (*ii*) 5 times smaller than
   (*iii*) equal to
   (*iv*) atleast 10 times greater than

18. A differentiating circuit is a simple RC circuit with output taken across ....
   (*i*) R
   (*ii*) C
   (*iii*) both R and C
   (*iv*) none of the above

19. A monostable multivibrator has ....
   (*i*) no stable state
   (*ii*) one stable state
   (*iii*) two stable states
   (*iv*) none of the above

20. The multivibrator which generates square wave of its own is the .... multivibrator.
   (*i*) monostable
   (*ii*) bistable
   (*iii*) astable
   (*iv*) none of the above

21. For a differentiating circuit to be effective, the RC product should be .... the time period of the input wave.
   (*i*) equal to
   (*ii*) 5 times greater than
   (*iii*) 5 times smaller than
   (*iv*) atleast 10 times greater than

22. When a rectangular voltage waveform is applied to a capacitor, then the current waveform is ....
   (*i*) rectangular
   (*ii*) sinusoidal
   (*iii*) sawtooth
   (*iv*) square

23. The positive clipper is that which removes the .... half-cycles of the input voltage.
   (*i*) negative
   (*ii*) positive
   (*iii*) both positive and negative
   (*iv*) none of the above

24. A clamping circuit adds .... component to the signal.

(*i*) d.c.

(*ii*) a.c.

(*iii*) both d.c. and a.c.

(*iv*) none of the above

25. One would find a clamping circuit in ....

(*i*) receiving antenna

(*ii*) radio transmitter

(*iii*) radio receiver (*iv*) television receiver

26. When transistor is used as an amplifier, it is operated in the .... region.

(*i*) off (*ii*) saturation

(*iii*) active (*iv*) none of the above

27. When the transistor (CE arrangement) is in the cut off region, the collector current is ....

(*i*) I_{CBO} (*ii*) I_{CEO}

(*iii*) $(\beta + 1) I_{CEO}$ (*iv*) $I_{C\,(sat)}$

28. A negative clipper removes the .... half-cycles of the input voltage.

(*i*) negative

(*ii*) positive

(*iii*) both positive and negative

(*iv*) none of the above

29. If the input to an integrating circuit is a succession of alternating positive and negative pulses of very short duration, the output will be .... wave.

(*i*) rectangular (*ii*) triangular

(*iii*) sine (*iv*) square

30. In a multivibrator, we have .... feedback.

(*i*) negative

(*ii*) 100 % positive

(*iii*) both positive and negative

(*iv*) none of the above

Answers to Multiple-Choice Questions

1. (*ii*)	2. (*iii*)	3. (*i*)	4. (*i*)	5. (*iii*)
6. (*ii*)	7. (*iv*)	8. (*iii*)	9. (*i*)	10. (*ii*)
11. (*iii*)	12. (*iii*)	13. (*iv*)	14. (*i*)	15. (*ii*)
16. (*iii*)	17. (*iv*)	18. (*i*)	19. (*ii*)	20. (*iii*)
21. (*iv*)	22. (*i*)	23. (*ii*)	24. (*i*)	25. (*iv*)
26. (*iii*)	27. (*ii*)	28. (*i*)	29. (*iv*)	30. (*ii*)

Chapter Review Topics

1. What is a switching circuit ?

2. Discuss the advantages of an electronic switch over a mechanical or electro-mechanical switch.

3. Explain the terms collector leakage current and saturation collector current.

4. Explain the switching action of a transistor with the help of output characteristics.

5. What is a multivibrator ? Explain the principle on which it works.

6. With a neat sketch, explain the working of (*i*) astable multivibrator (*ii*) monostable multivibrator (*iii*) bistable multivibrator.

7. What is the basic difference among the three types of multivibrators ?

8. Show that the output from a differentiating circuit is derivative of the input. What assumptions are made in the derivation ?

9. Sketch the output waveforms from a differentiating circuit when input is (*i*) a square wave (*ii*) saw-tooth wave.

10. Show that the output from an integrating circuit is the integral of the input.

11. What is a clipper ? Describe (*i*) positive clipper (*ii*) biased clipper and (*iii*) combination clipper.

12. What do you understand by a clamping circuit ? With neat diagrams explain the action of a (*i*) positive clamper (*ii*) negative clamper.

Problems

1. The negative shunt clipper shown in Fig. 18.66 has peak input voltage of +15 V. What is the output peak voltage ? **[12.54 V]**
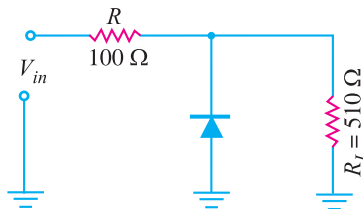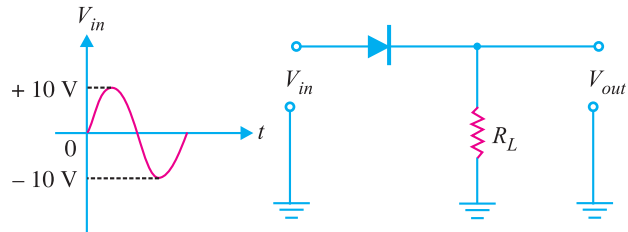

Fig. 18.66

Fig. 18.67

2. In the negative series clipper shown in Fig. 18.67, what is the peak output voltage ? **[9.3 V]**
3. In the circuit shown in Fig. 18.68, what are the minimum and peak values of the clamped output ? **[0 V ; –20 V]**
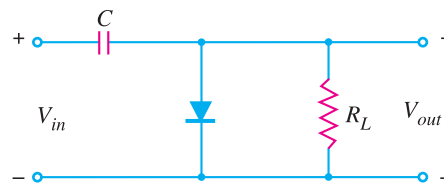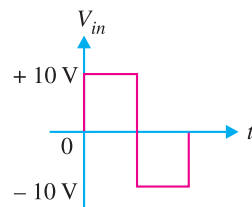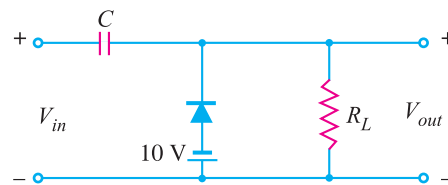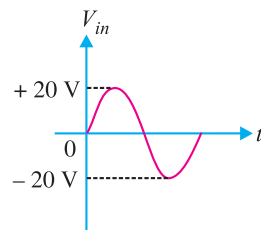

Fig. 18.68

Fig. 18.69

4. Sketch the wave shape of clamped output in Fig. 18.69.
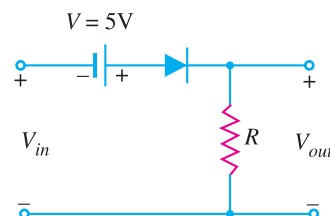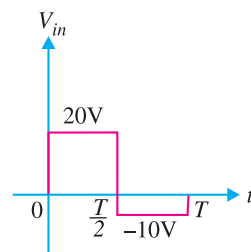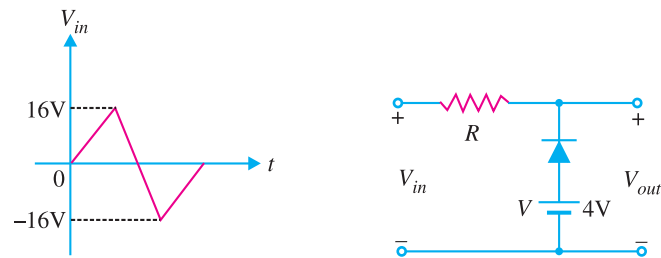5. Determine the output waveform for the clipper network shown in Fig. 18.70.

Fig. 18.70

Fig. 18.71

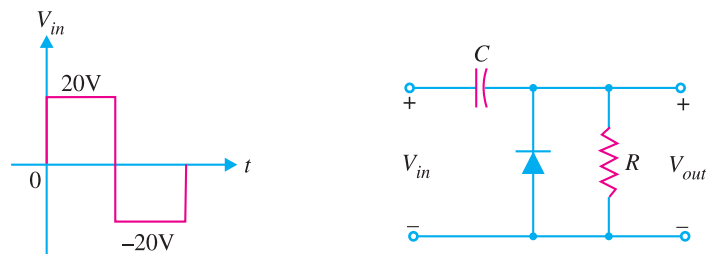6. Determine the output waveform for the clipper network shown in Fig. 18.71.

Fig. 18.72

7. Determine the output waveform for the clamper network shown in Fig. 18.72.

Discussion Questions

1. What is the effect of RC product on the output waveform in a differentiating circuit ?
2. A differentiating circuit is essentially an RC circuit. Why the output from RC coupling is not a differentiated wave ?
3. What is the difference between a switching transistor and an ordinary transistor ?
4. What effect does a clamper have on the average value of a given input wave ?
5. What effect does a clamper have on the r.m.s. voltage of a sine-wave input ?
6. What determines the d.c. reference voltage of a clamper ?
7. Discuss the differences between shunt and series clippers.

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