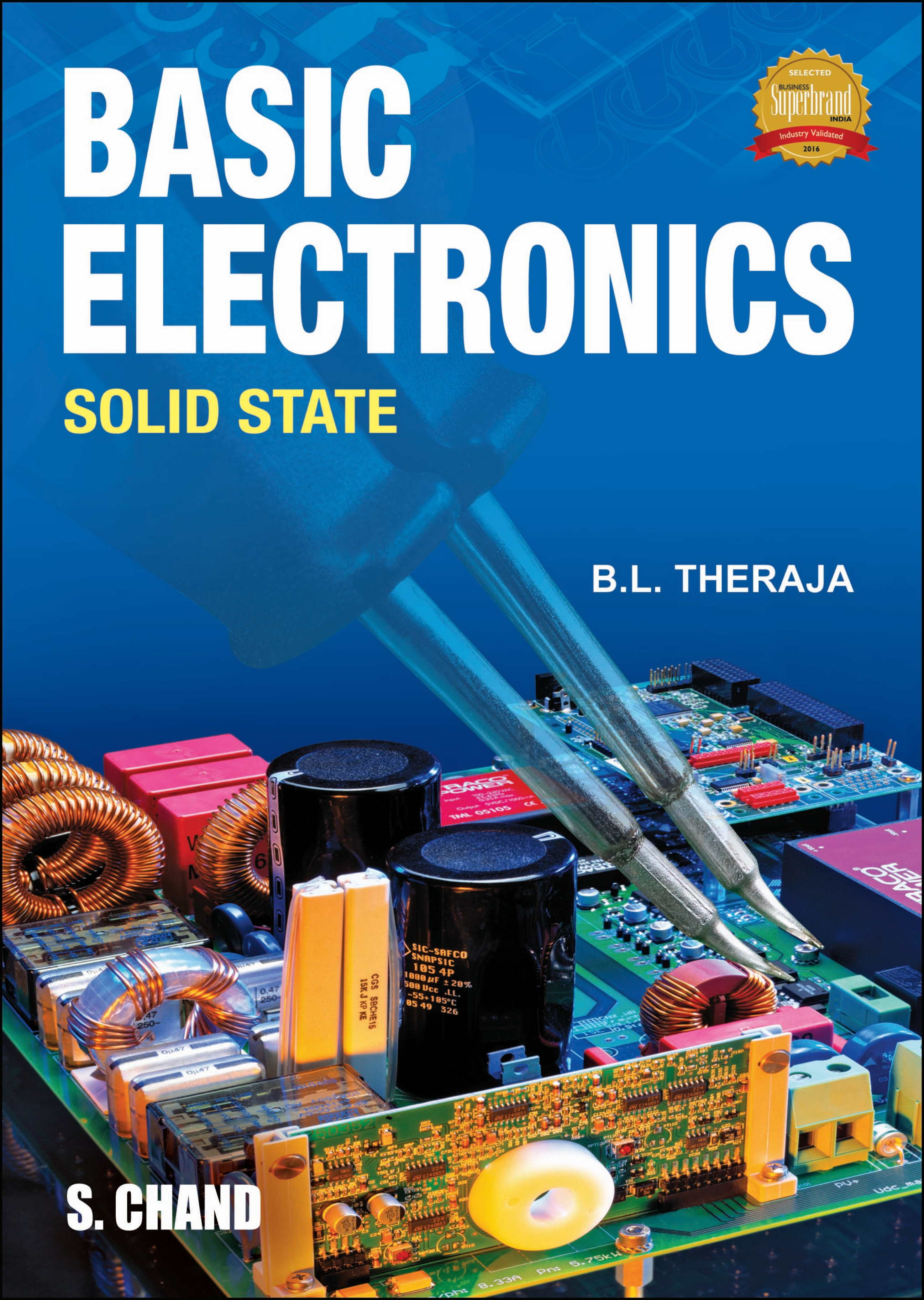
BASIC ELECTRONICS

SOLID STATE



B.L. THERAJA

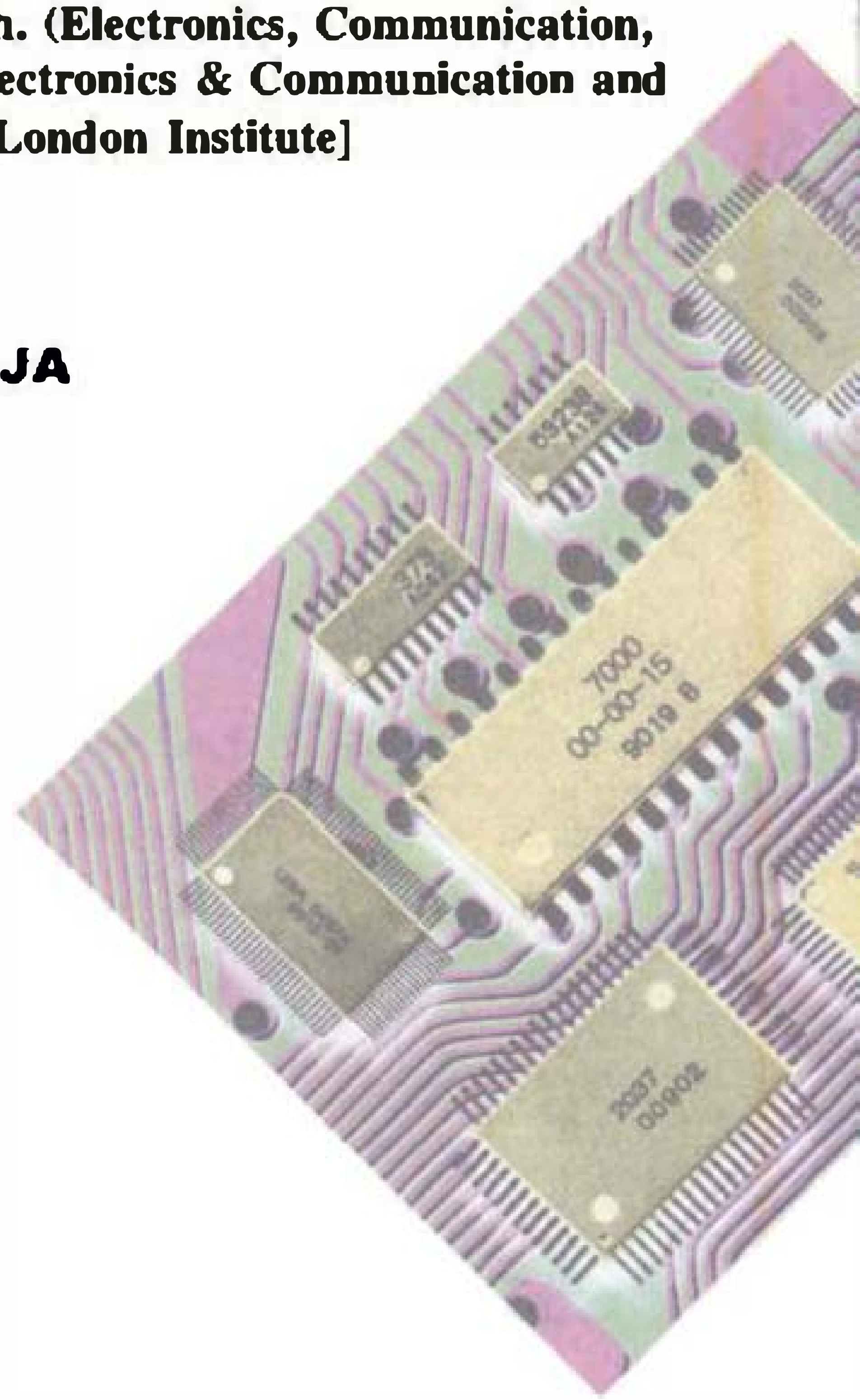
S. CHAND

MULTICOLOUR ILLUSTRATIVE EDITION

BASIC ELECTRONICS

SOLID STATE

[A Textbook for the Students of B.E./B. Tech. (Electronics, Communication, Electrical), B.Sc. (Electronics) Diploma in Electronics & Communication and also useful for City & Guilds London Institute]



B.L. THERAJA

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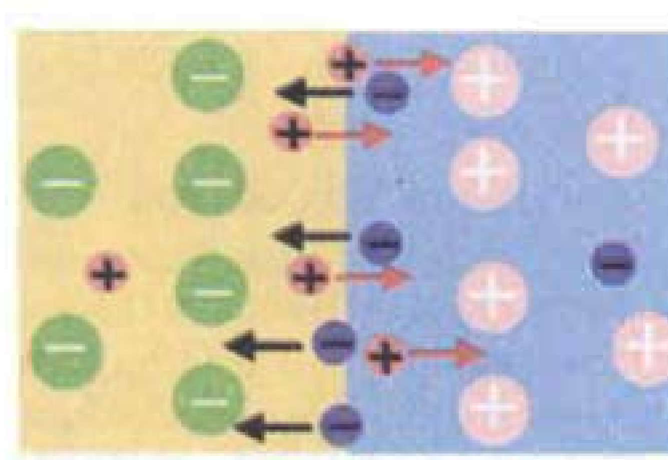

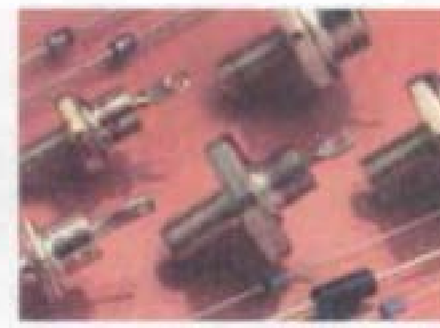

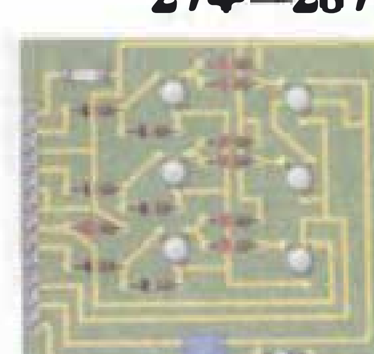

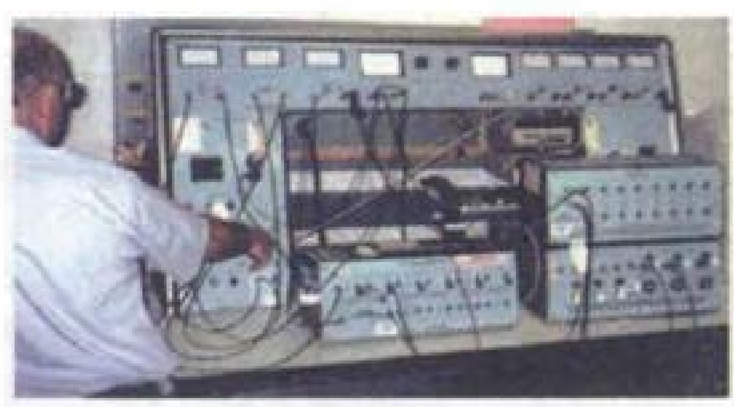

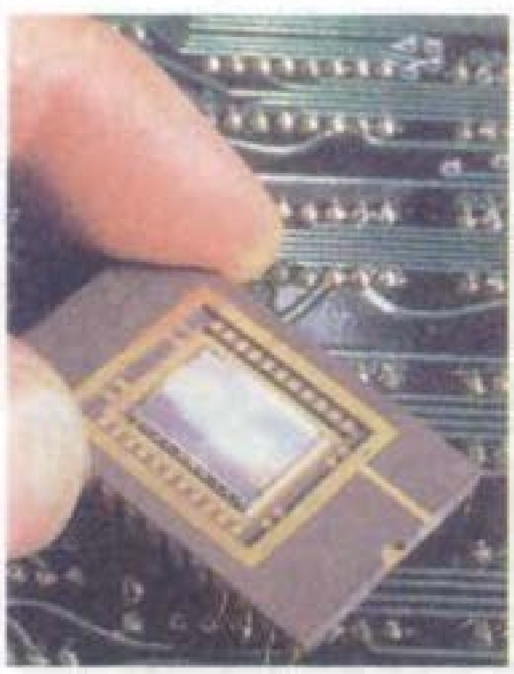

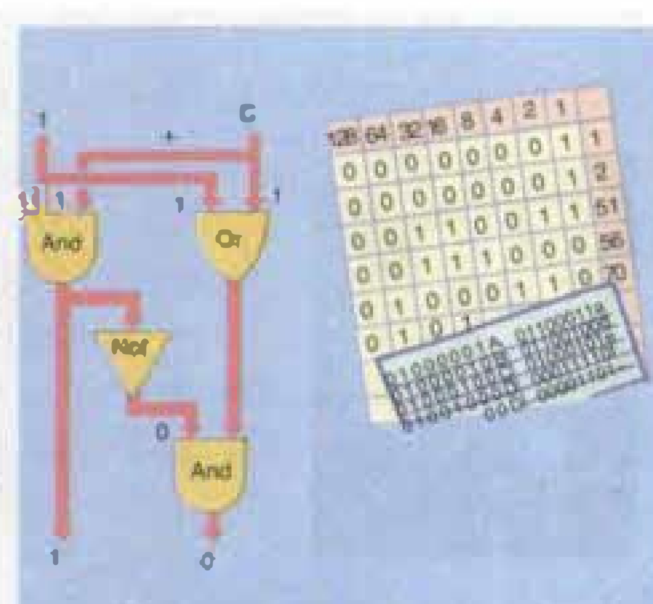
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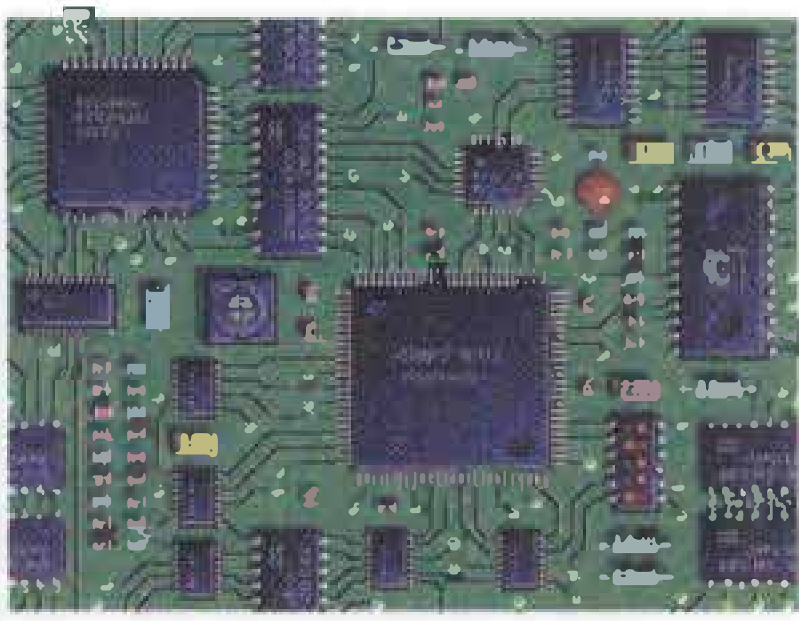
CHAPTER 1



Circuit Fundamentals

1.1. Zero Reference Level

In order to avoid errors in the measurement of various voltages in an electronic circuit, it is essential to select some common point which is *considered* to be at zero potential. All circuit voltages whether positive or negative, are measured with respect to this point. It can be any point in the circuit and need not be necessarily at 0 V. In Fig. 1.1 (*a*), negative battery terminal *i.e.*, point *D* is taken as reference point and voltages of other points in the circuit are stated with reference to this point.

For example, voltage of point *A* with respect to negative battery terminal (zero reference level) is +12 V, that of point *B* is +6 V and that of point *C* is 0 V since it is directly connected to point *D*. In fact, negative battery terminal can be grounded as shown by 3 short lines in Fig. 1.1 (*b*).

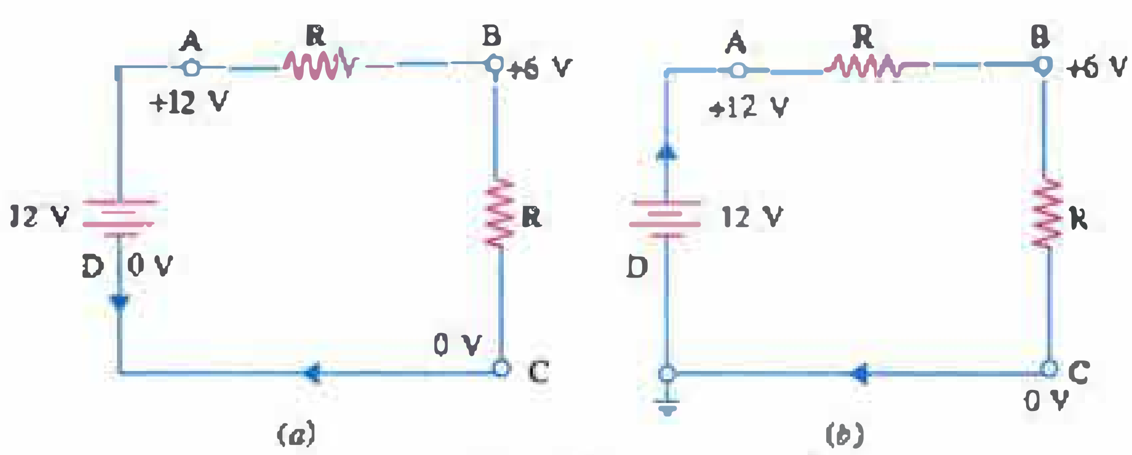


Fig. 1.1

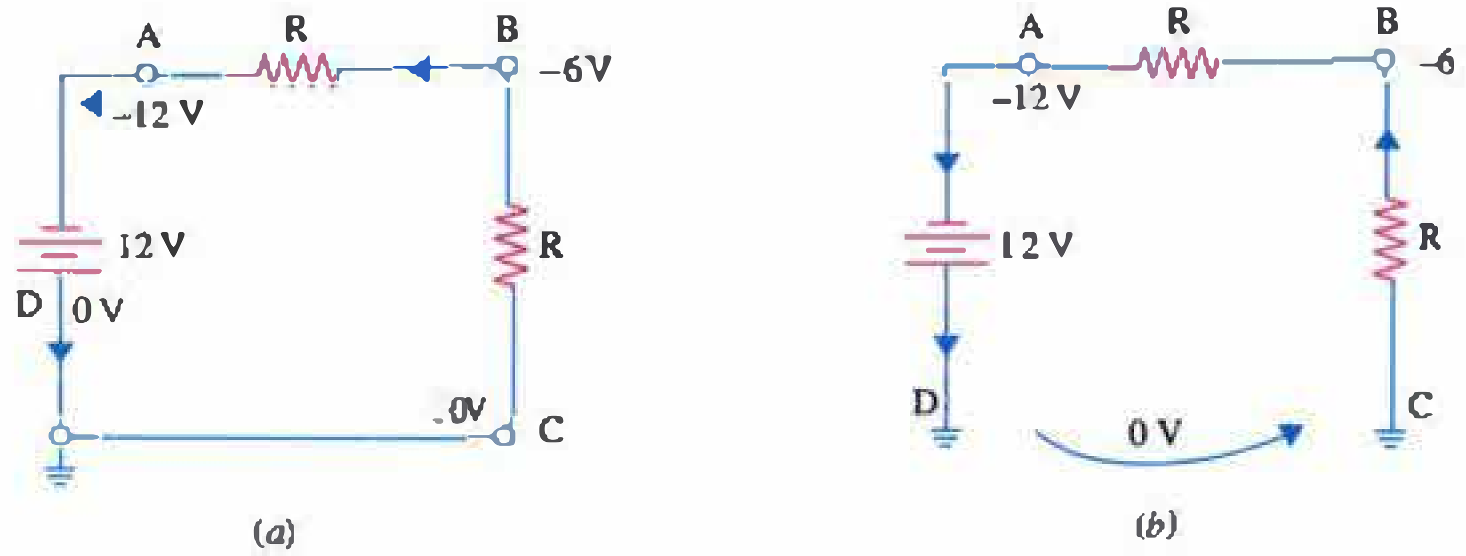


Fig. 1.2

It would make no difference to voltage measurements even if positive battery terminal is grounded as shown in Fig. 1.2 (*a*). The only difference is that now all circuit voltages would be negative with respect to the ground as shown in the figure. But their magnitude (which is our primary concern) remains unchanged. Of course, direction of current flow is reversed. Fig. 1.2 (*b*) shows another way of showing ground in circuit schematic diagrams.

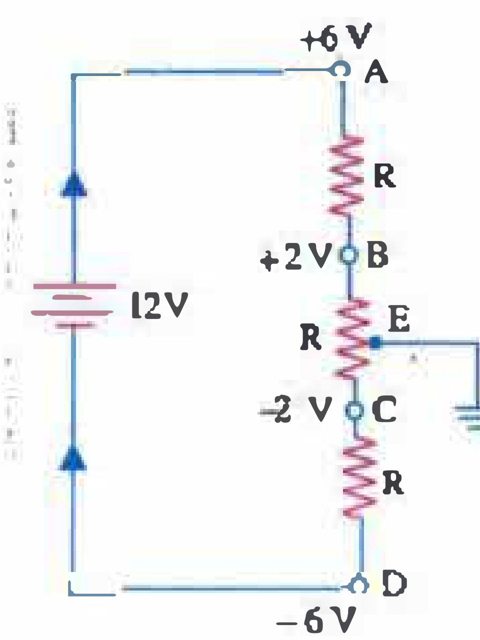
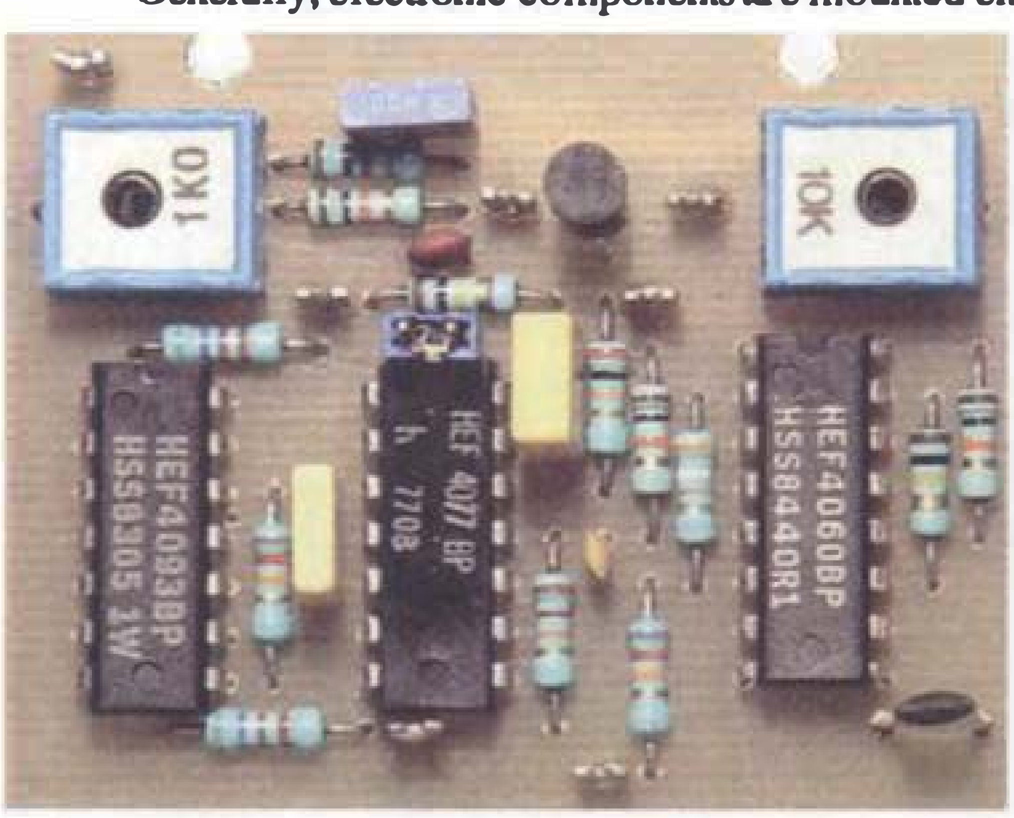


Fig. 1.3

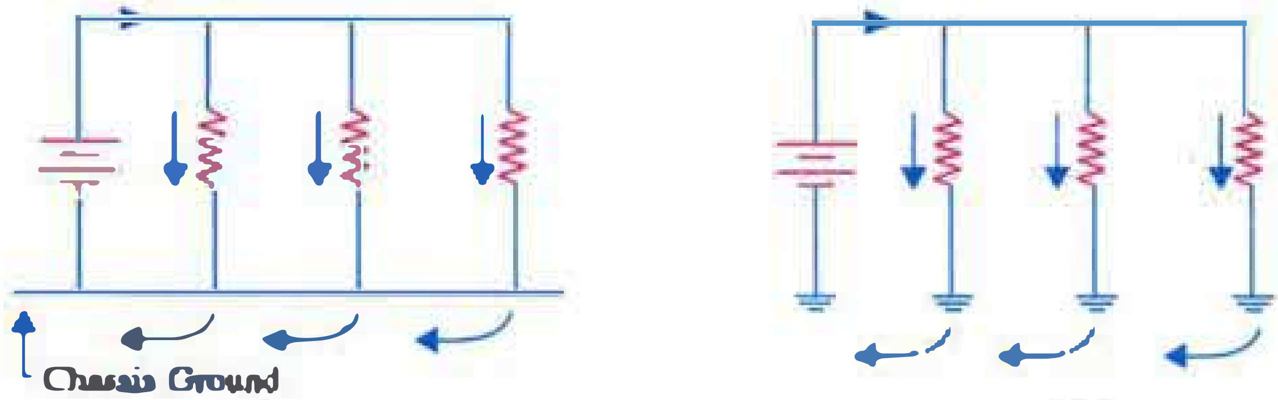
In Fig. 1.3, three equal resistors are connected in series across a 12 V battery. The centre point *E* of the middle resistor has been grounded *i.e.*, fixed as zero reference level for voltage measurements. It is seen that point *B* is 2 V *above* point *E i.e.*, it is positive with respect to *E* whereas point *C* is 2 V *below* point *E i.e.*, it is negative with respect to *E*. Similarly, point *A* is 6 V *above E* and point *D* is 6 V *below E*. Another point worth noting is that conventional current always flows from a point at higher potential to one at lower potential. Since *E* is at a higher potential as compared to point *D*, current flows from *E* to *D*. For similar reasons, current flow is from *A* to *E*.

1.2. Chassis Ground

Generally, electronic components are mounted either on a conducting metal sheet called *chassis* or on a non-conducting plastic board with printed wiring. When using chassis, it is common practice to treat the body of the chassis itself as the common ground. Being a good conductor, it provides a return path for different currents as shown in Fig. 1.4 (*a*). All circuit voltages are measured with respect to chassis ground which is supposed to be at zero potential. It would be appreciated that selection of chassis as a common ground greatly simplifies the circuit wiring. In drawing simple circuit diagrams, it is common practice to show various electronic components connected to chassis ground with the help of ground symbols depicted in Fig. 1.4 (*b*).



Electronic components including chips are usually linked together by fixing them to a printed circuit board, sometimes called a card.



(a) (b)

Fig. 1.4

In the case of printed-circuit boards (PCB) made of plastic, a rim of solder around the edge serves as the chassis ground as shown in Fig. 1.5. When a voltage source is connected between points A and B, its one end is grounded through B and the other is connected to the resistors R_1 and R_2.

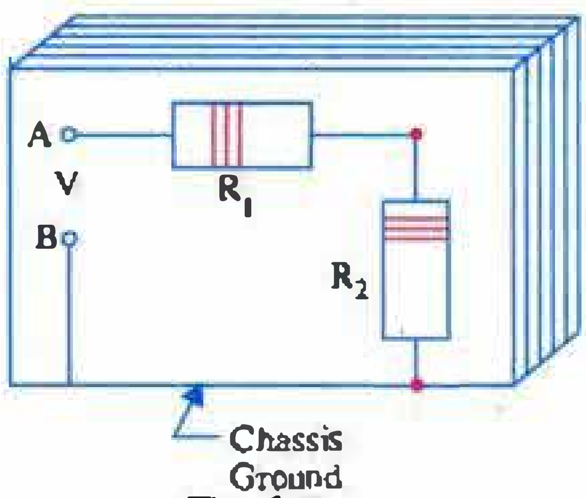


Fig. 1.5

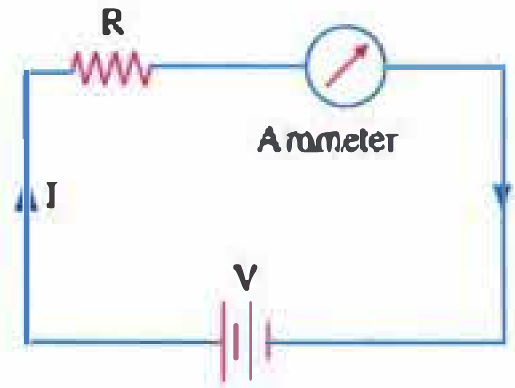


Fig. 1.6

1.3. Ohm's Law

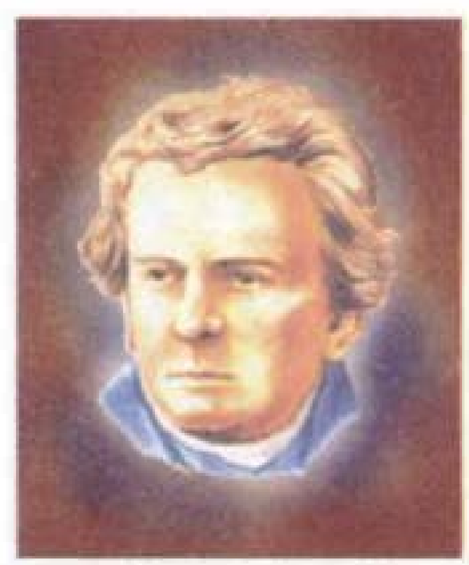
In circuits energised by dc voltage sources, there exists a definite relationship between the current (I) that flows through a resistance (R) and the voltage (V) applied across the resistance (Fig. 1.6). This relationship is called Ohm's law and may be expressed by the equation.

$$I = \frac{V}{R}$$

where I = current in amperes

V = applied voltage in volts

R = resistance in ohms

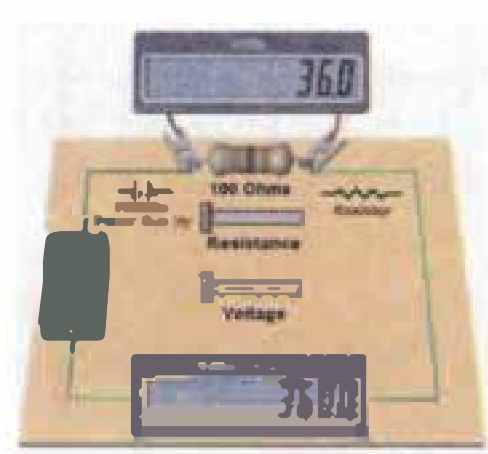


German physicist
George Ohm
(1789-1854)

It is seen from the above formula that current is

1. directly proportional to applied voltage and
2. inversely proportional to resistance.

1.4. Formula Variations of Ohm's Law



Ohm's law.

The three formula variations of Ohm's law are as under :

1. $I = V/R$ — for finding current
2. $R = V/I$ — for finding resistance
3. $V = I/R$ — for finding voltage

These formulae are an important aid to the understanding of circuit behaviour. They enable us to determine the value of any of the three quantities involved if the values of the other two are known. It makes it possible to design electronic circuits and to determine the values of various components mathematically thereby avoiding unnecessary measurements or experimentation and wastage of time.

The above formulae may be memorised by using the circle divided as in Fig. 1.7. To use the circle, all you need to do is to cover the factor you want and read the remaining formula. Remember that the above three quantities are given in the units of volt, ampere and ohm.

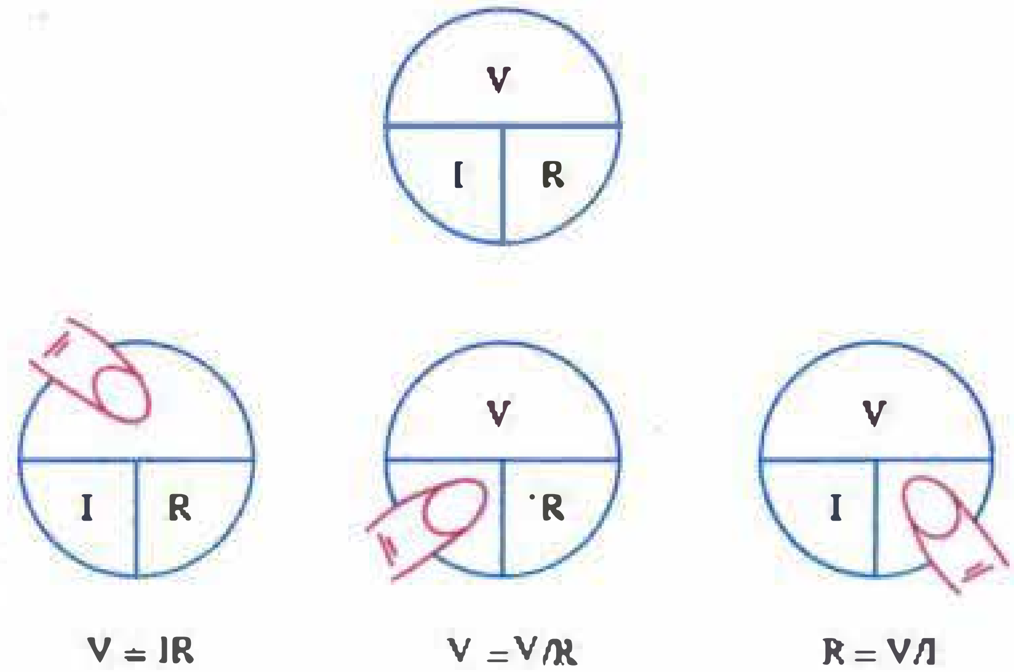


Fig. 1.7

For electronic circuit calculations, the resistances are often in kilohms (kΩ) and currents in milliamperes (though voltage is usually in volts). In that case, the above circle can be modified as shown in Fig. 1.8.

1.5. Graphical Representation of Ohm's Law

The Ohm's formula $I = V/R$ states that V and I are directly proportional for any given value of R. This relationship between V and I can be analysed with the help of the circuit shown in Fig. 1.9 (a) where a constant resistance of 2 Ω has been taken. When V is varied from 0 V to 12 V, the ammeter A shows I values directly proportional to V as tabulated in Fig. 1.9 (b). For example, with 12 V, I equals 6 A, for 10 V, $I = 5$ A and so on.

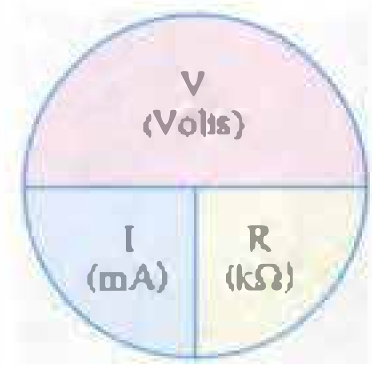
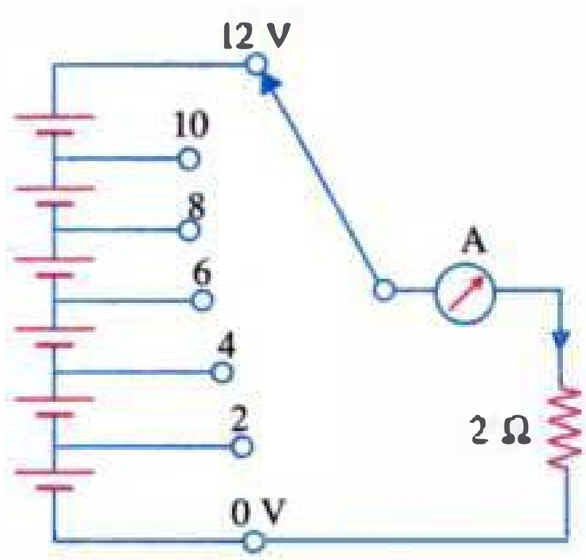


Fig. 1.8



(a)

VOLTS	OHMS	CURRENT
0	2	0
2	2	1
4	2	2
6	2	3
8	2	4
10	2	5
12	2	6

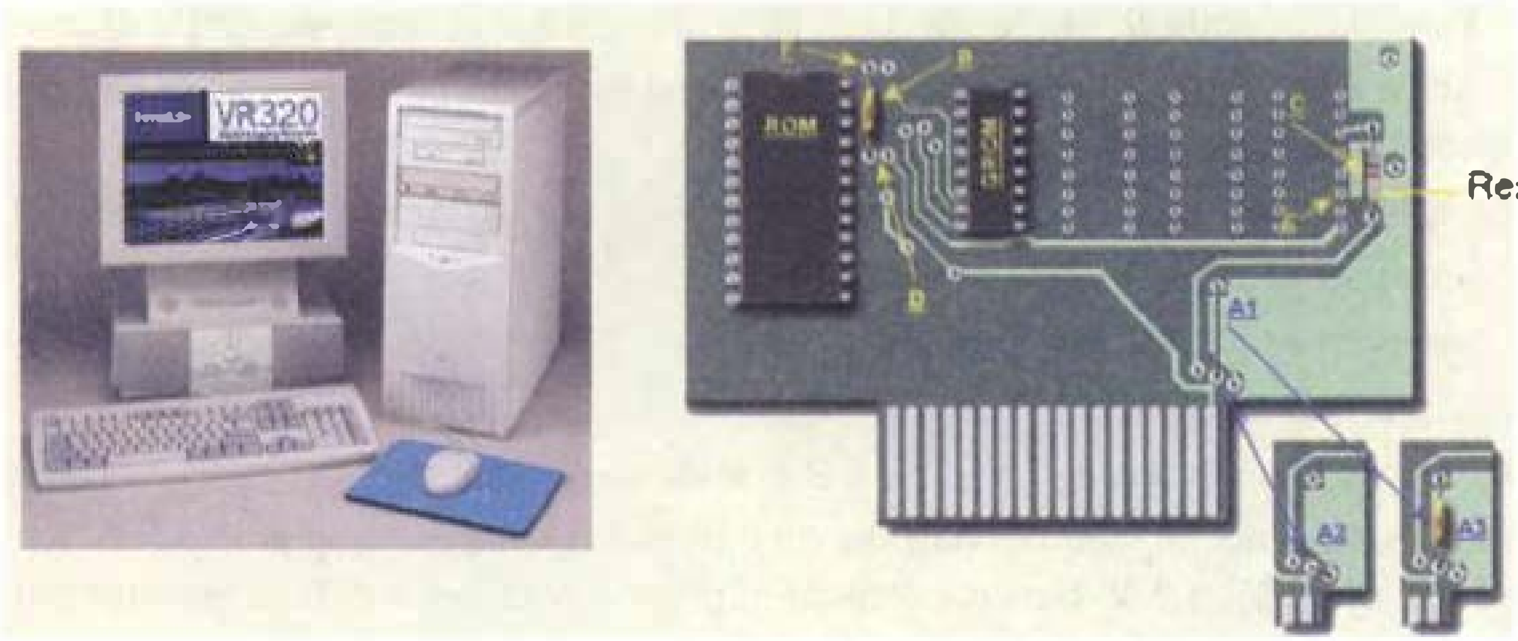
(b)

Fig. 1.9

The above relationship can be shown graphically. The voltage values are marked along the X-axis (also called horizontal axis or abscissa) and current values along Y-axis (also called vertical axis or ordinate). Since values of V and I depend on each other, they are called variable factors. Between the two, V is the independent variable because we assign different values to it and note the resulting current I.

Generally, independent variable is plotted along the X-axis and dependent variable along Y-axis. The two scales need not be the same.

The graph shown in Fig. 1.10 is also known as volt-ampere (V-I) characteristic of R because it shows how much current the resistor allows for different voltages.



Resistors are found on circuit-boards of computers.

1.6. Linear Resistor

A linear resistor is one whose value remains constant *i.e.*, it does not depend on applied voltage. The *V-I* characteristic of such a resistor is a straight line similar to the one shown in Fig. 1.10. Obviously, *V* and *I* are directly proportional.

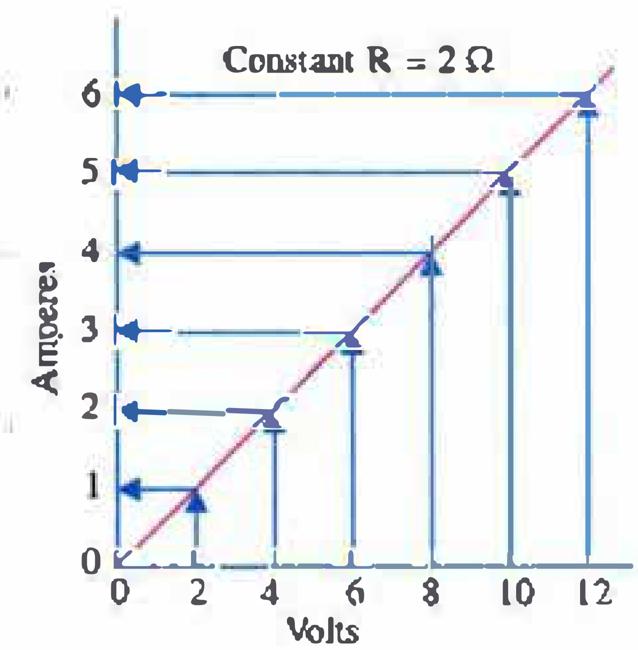
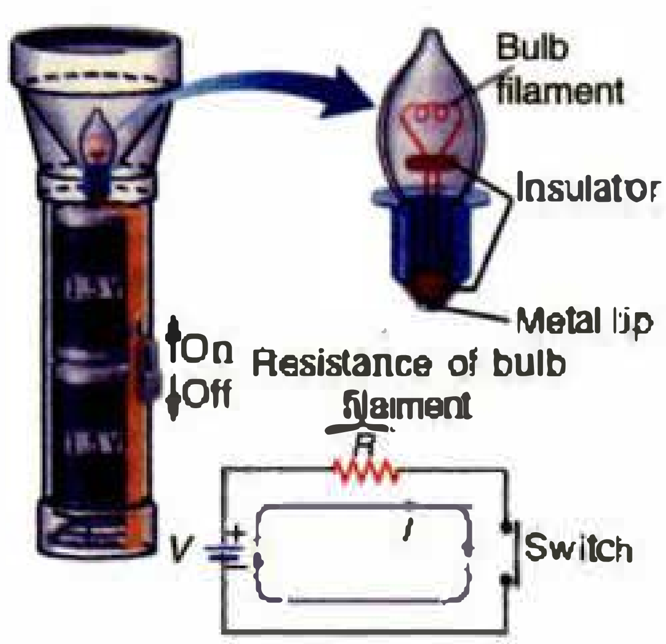


Fig. 1.10

1.7. Non-linear Resistor

It is that resistor in which *V* and *I* are not directly proportional to each other. If applied voltage is doubled, the resultant current is not exactly double of its previous value. Such a resistor has non-linear *V-I* characteristic. An example is tungsten filament in an electric bulb. Here, *R* increases with more current as the filament becomes hotter. Increasing the applied voltage does produce more current but it does not increase in the same proportion as *V*.



The circuit in this flashlight consists of a resistor (the filament of the light bulb) connected to a 3 V battery.

Example 1.1. *In the circuit of Fig. 1.11 (a), find*

(*i*) *circuit current, I*

(*ii*) *voltage of point A with respect to ground*

(*iii*) *voltage of point B with respect to A*

(*iv*) *voltage of point B with respect to ground.*

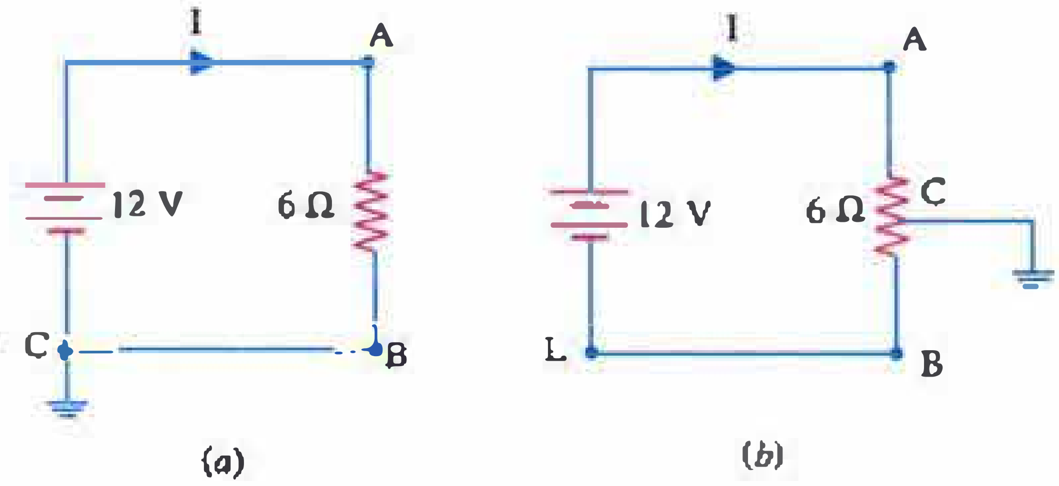


Fig. 1.11

Solution. (*i*) As per Ohm's law,

$I = V/R = 12/6 = 2$ A

(*ii*) Voltage drop across 6 Ω resistor

$= IR = 2 \times 6 = 12$ V

Since lower end of the resistor is grounded via point *B*, potential of point *A* w.r.t. ground is **+12 V.**

(*iii*) Potential of point B w.r.t. point A is -12 V (though it is at zero potential w.r.t. ground).

(*iv*) Since it is electrically connected to the ground by means of the conductor BC, point B is at ground potential *i.e.*, it is at **0 V.**

Example 1.2. *In Fig. 1.11 (b), mid-point C of the 6 Ω resistor has been grounded. Calculate*

(*i*) *potential of point A w.r.t. ground*

(*ii*) *potential of point B w.r.t. ground*

(*iii*) *p.d. between A and B*

(*iv*) *current flowing through portion CB and its direction.*

Solution. (*i*) Since R_{AC} equals half the total circuit resistance, drop across it is also half the applied voltage *i.e.*, 12/2 = 6 V. Hence, potential of point A w.r.t. point C (*i.e.*, ground) is **+6 V**

(*ii*) For similar reasons, potential of point B w.r.t. point C (*i.e.*, ground) is **–6V**

(*iii*) P.D. between A and B = 6 V – (– 6 V) = **+12 V**

(*iv*) Since, $R_{CB} = 3\Omega$ and $V_{CB} = 6$ V, $I_{CB} = 6/3 = $ **2 A**

This current must flow from higher to lower potential. Since point C is at 0 V and B is at -6 V, current flows along CB.

1.8. Work and Power

Work and energy are the same thing but power is different because it is defined as the rate of doing work. Suppose, a battery of V volts drives a current of I amperes through a resistance of R ohms for t seconds. Then, total work done by the battery to maintain this current is

$$\begin{aligned} \text{W.D.} &= VI\,t \text{ joules} \\ &= I^2 R\, t \text{ joules} && \text{—eliminating } V \\ &= V^2\, t / R \text{ joules} && \text{—eliminating } I \\ &= Wt \text{ joules} && \text{—putting } W = VI \end{aligned}$$

Unit of Work

1. The commonly-used unit of work is joule (J) which may be defined in the following two ways :

(*a*) It is equal to the work done when a force of 1 newton (N) moves a body through a distance of 1 metre (m) in its direction of application.

or

(*b*) It is equal to the work done when a charge of 1 coulomb (C) is moved between two points having a potential difference of 1 V.

$$\begin{aligned} 1 \text{ joule} &= 1 \text{ metre-newton} \\ &= 1 \text{ volt-coulomb} \end{aligned}$$

2. Another unit often employed in Semiconductor Physics is electron-volt (eV).

It is equal to the amount of work needed to move an electron between two points having a potential difference of one volt.

Since, there are 6.24×10^{18} electrons in one coulomb

$$\therefore \quad 1\text{ J} = 6.24 \times 10^{10} \text{ eV}$$

$$1 \text{ eV} = 1/6.24 \times 10^{18} = 1.6 \times 10^{-19} \text{ J}$$

Power. The electric power required to maintain this current is

$$P = \frac{\text{W.D.}}{t} \text{ watts} = \frac{VI\,t}{t} = VI \text{ watts}$$

$$= \frac{V^2 t}{Rt} = \frac{V^2}{R} \text{ watts} = \frac{I^2 Rt}{t} = I^2 R \text{ watts}$$

The bigger units are :

1 kilowatt (kW) = 1000 W = 10^3 W

1 megawatt (MW) = 1,000,000 W = 10^6 W

Example 1.3. *A 100 Ω resistor is required to be used in a circuit carrying a current of 0.15 A. What should be the power rating of the resistor?*

Solution. $P = I^2R = 0.15^2 \times 100 = 2.25$ W

In order to prevent overheating of such a resistor, its power or wattage rating should be nearly twice of that calculated above. Hence, a resistor of **5 W** power rating would be most suitable.

1.9. Cells in Series and Parallel

Electric cells may be connected either in series or in parallel to form *batteries*. Each of these combinations has a different value of the total voltage and current-delivering capacity.

1. Series Connection

In Fig. 1.12, four dry cells each of **1.5 V** have been connected in series *i.e.*, from end-to-end.

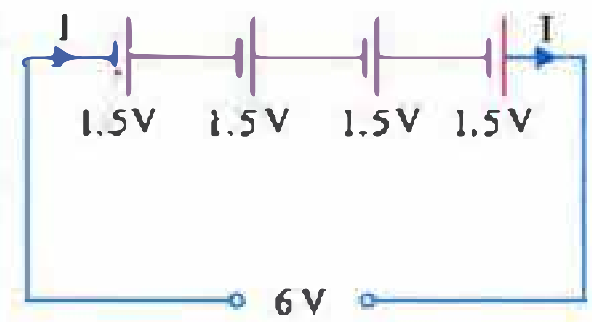
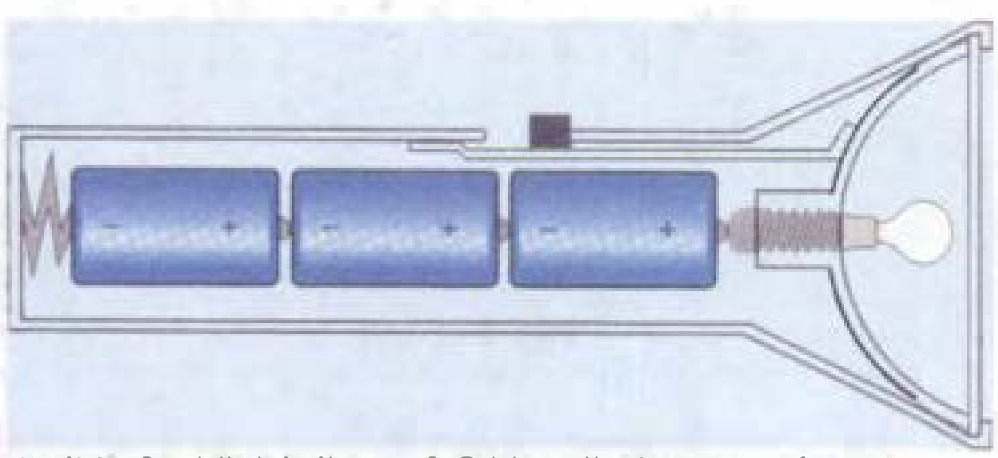


Fig. 1.12

The total voltage is 4 times the voltage of a single cell *i.e.*, 4 × 1.5 = 6 V. However, the current-delivering capacity of the series combination *does not exceed that of the single cell*. In case, cells of different emf's are connected in series, the current delivering capacity of such a combination is equal to that of the single cell which has the lowest current-delivering capacity.



In this flashlight, three 1.5 V batteries are placed in series to produce a larger voltage.

Hence, series combination of cells is employed when higher *voltages* (non-currents) are required.

2. Parallel Connection

Such a combination is used when the purpose is to obtain more current than is available from a single unit. As shown in Fig. 1.13, total voltage available across output terminals *A* and *B* is equal to the voltage of a single cell. However, output current *I* is equal to the sum of four cell currents *i.e.*, $I = i_1 + i_2 + i_3 + i_4$. Normally, only those cells having identical emf's are connected in parallel.

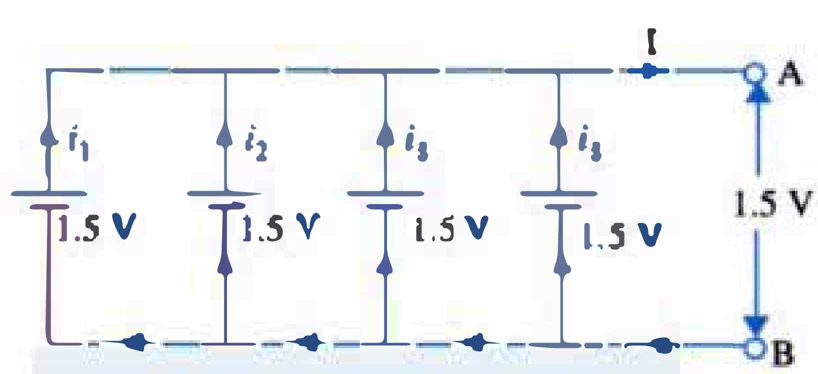


Fig. 1.13

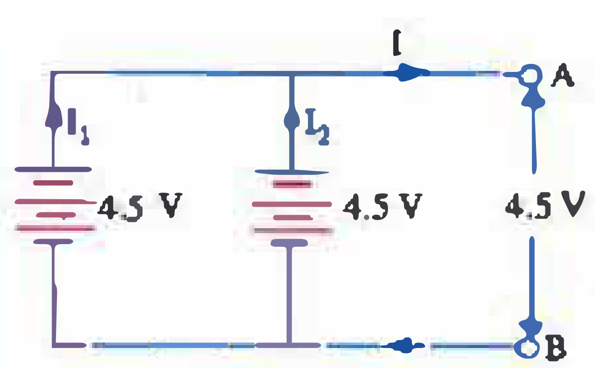


Fig. 1.14

Hence, parallel combination of cells is employed, where increased *current* (rather than voltage) is the main requirement.

However, series-parallel combination (Fig. 1.14) is employed where both higher voltage and increased current are required *i.e.*, greater power is required. Such connections are frequently found in many circuits including those in radio and television receivers.

CONVENTIONAL PROBLEMS

1. Find the potential of points (*i*) *C* and (*ii*) *D* in Fig. 1.15 if *C* is located at mid-point of the resistor *R*. What is the direction of current flow through *CD* ? **[–8 V; – 16 V; C to D]**

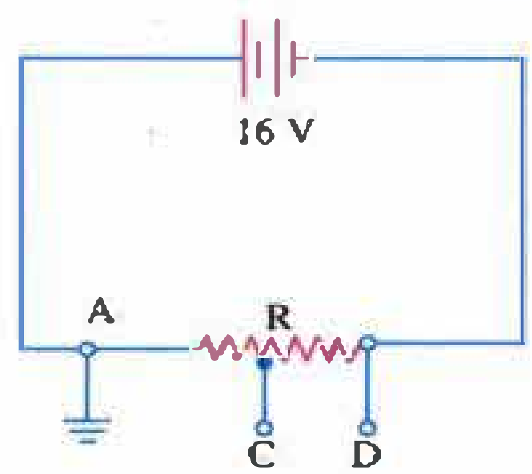


Fig. 1.15

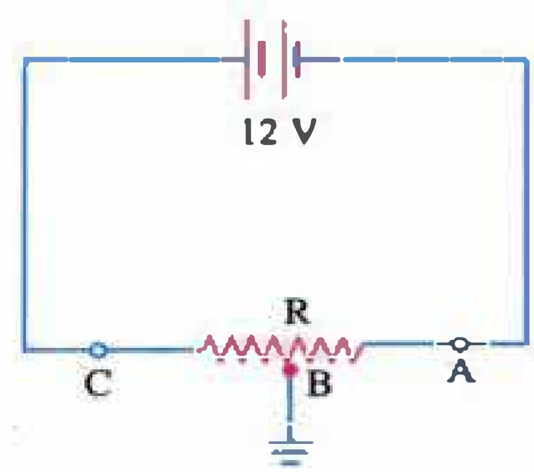


Fig. 1.16

2. In Fig. 1.16, the grounding point *B* is located at one-third of resistance *R* from *A*. Compute the potential of point (*i*) *A* and (*ii*) *C*. What is the p.d. between *A* and *C* ? What is the direction of flow of conventional current between points *A* and *C* ? **[(*i*) – 4 V (*ii*) +8 V; 12 V; C to A]**

3. Find the reading of the milliammeter connected in the circuit of Fig. 1.17. **[0.6 mA]**

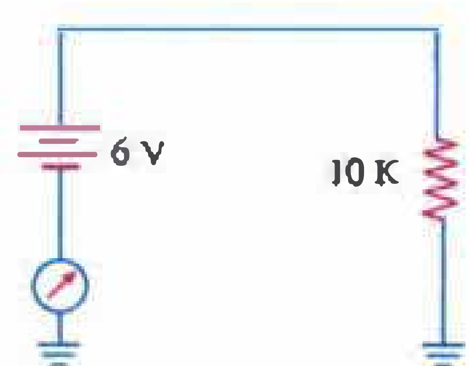


Fig. 1.17

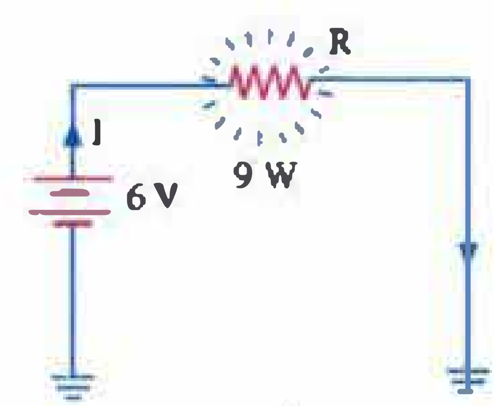


Fig. 1.18

4. Compute the value of resistor *R* in Fig. 1.18 if power dissipated by it is 9 W. **[4 Ω]**

5. What would be the voltage across points *A* and *B* in seriesparallel combination of Fig. 1. 19 if each cell has a voltage of 1.5V? **[3V]**

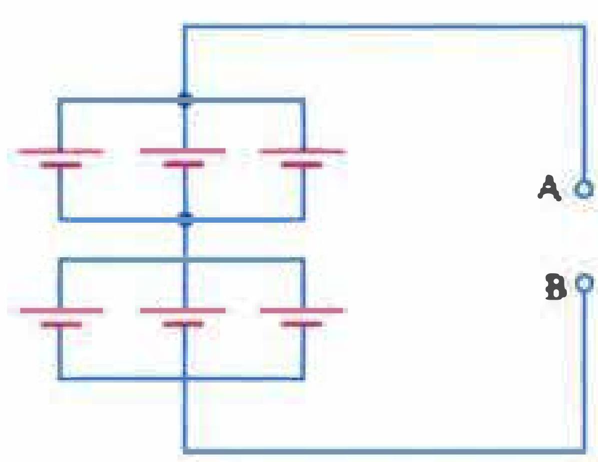


Fig. 1.19

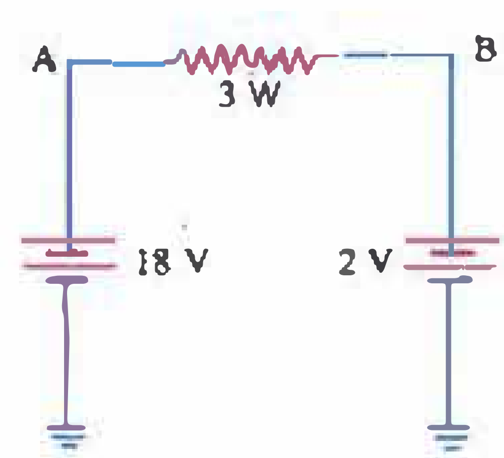


Fig. 1.20

6. Find the magnitude and direction of current in Fig. 1.20. **[2A; from A to B]**

7. In the series circuit of Fig. 1.21, compute the voltage to chassis ground of points *A*, *C* and *D*. What is the p.d. between *A* and *C* ? **[+10 V; –10 V; – 20 V; 20 V]**

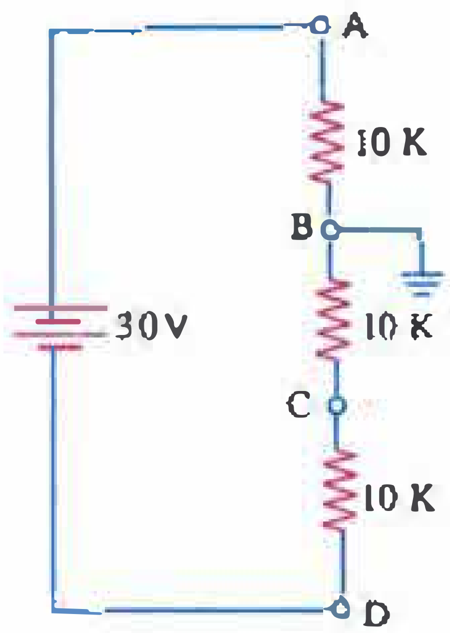


Fig. 1.21

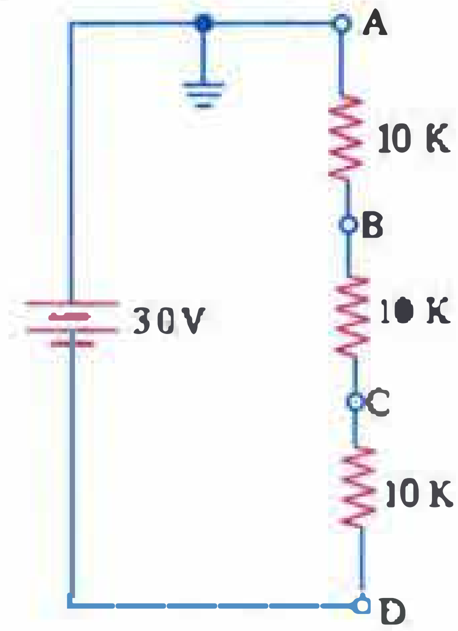


Fig. 1.22

8. In the network of Fig. 1.22, compute the potential of points *A*, *B*, *C* and *D*. Which point is at a higher potential : *B* or *C* ? **[0 V; – 0 V; – 20 V; – 30 V; B]**

SELF EXAMINATION QUESTIONS

A. Fill in the blanks by most appropriate word (s) or numerical values(s).

1. Chassis ground is assumed to have .... potential.
2. Ohm's law gives relationship between applied voltage, current and ....
3. The resistance of a circuit is equal to voltage divided by ....
4. Linear resistor is one whose .... remains constant.
5. Tungsten filament of an electric bulb represents an examples of .... resistance.
6. Basic unit of work is .... and that of power is ....
7. Wattage of a device is given by the product of .... and ....
8. Electron-volt is the unit of ....
9. For getting more current, cells should be connected in ....

B. Answer True or False

1. In an electronic circuit, it is immaterial whether positive or negative battery terminal is grounded.
2. The ends of a mid-earthed resistor have opposite polarity.
3. Ground is always at 0 V.
4. In electronic circuits, generally, chassis is treated as the common ground.
5. A long and straight wire is called a linear resistor.
6. A non-linear resistor is one whose current does not very linearly with its voltage.
7. If voltage across a resistor is doubled, its power dissipation is quadrupled.
8. Electron-volt is the unit of potential.
9. When a few similar cells are connected in series, current is increased proportionately.
10. Parallel combination of cells is used when more current is needed.
11. Series-Parallel grouping of cells provided more power.

C. Multiple Choice Items

1. In an electronic circuit, common reference point
   (*a*) is always the negative battery terminal
   (*b*) is always the most positive point
   (*c*) is always the most negative point
   (*d*) may be any point
2. The term 'ground' spoken in connection with an electronic circuit means
   (*a*) a direct connection to earth through a wire
   (*b*) a common connection for all components
   (*c*) a short circuit
   (*d*) negative battery terminal
3. For doubling the current in a circuit of constant resistance, the applied voltage must be
   (*a*) kept the same (*b*) doubled
   (*c*) halved (*d*) quadrupled
4. Total current drawn from four 1.5 V cells connected in series is 1 ampere. Each cell supplies.........ampere(s).
   (*a*) 1 (*b*) 0.25
   (*c*) 1.5 (*d*) 4

5. Electron-volt is the unit of
   (a) voltage (b) energy
   (c) current (d) power

6. The current flowing through the PNP transistor of Fig. 1.23 is

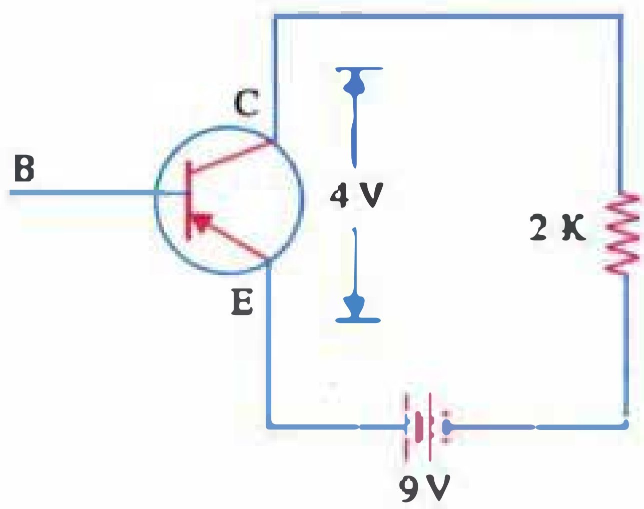


Fig. 1.23

   (a) 2.5 mA (b) 2 mA
   (c) 4.5 A (d) 6.5 mA.

7. A 100 Ω resistor is to be used in a circuit carrying a current of 0.5 A. Its power rating should be....watt.
   (a) 50 (b) 25
   (c) 200 (d) 500

8. A linear resistor is defined as a resistor
   (a) whose value is independent of applied voltage
   (b) whose *V-I* characteristic is a straight line
   (c) whose current varies inversely with the applied voltage
   (d) both (a) and (b)

ANSWERS

A. Fill in the blanks

1. zero 2. resistance 3. voltage, resistance 4. resistance 5. non-linear
6. joule, watt 7. voltage, current 8. energy 9. parallel

B. True or False

1. T 2. T 3. F 4. T 5. F 6. T 7. T 8. F 9. F 10. T 11. T

C. Multiple Choice Items

1. *d* 2. *b* 3. *b* 4. *a* 5. *b* 6. *a* 7. *b* 8. *d*

CHAPTER 2

Resistive Circuits

2.1. Series Circuit

When components in a circuit are connected end-to-end (Fig. 2.1) so that all the circuit current passes through each component, they form a series circuit. The three resistors R_1, R_2 and R_3 are in series with each other and the battery. The result is only one path for current flow. Hence, current I is the *same in all the three resistors*. Due to this current flow, voltage drops V_1, V_2, and V_3 occur across R_1, R_2 and R_3 respectively. Obviously,

$$V_1 = I R_1,\ V_2 = I R_2 \text{ and } V_3 = I R_3$$

The sum of these three voltage drops must equal the applied voltage.

$$\therefore\ V = V_1 + V_2 + V_3$$

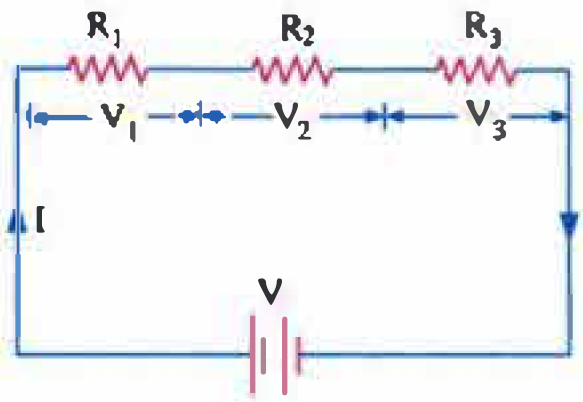


Fig. 2.1

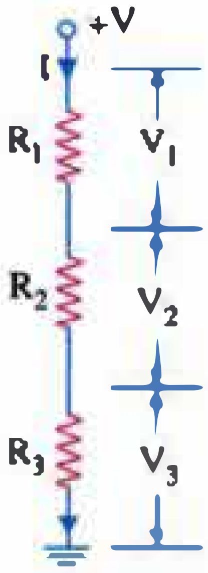


Fig. 2.2

Incidentally, circuit of Fig. 2.1 may be redrawn as shown in Fig. 2.2. In this diagram, the negative battery terminal has been grounded (even though we could ground the positive terminal as well).

2.2. Characteristics of a Series Circuit

A series resistive network has the following characteristics :

1. *Total resistance equals the sum of all series resistances.*

In the Fig. 2.3 are shown a few resistors connected in series across a voltage source.

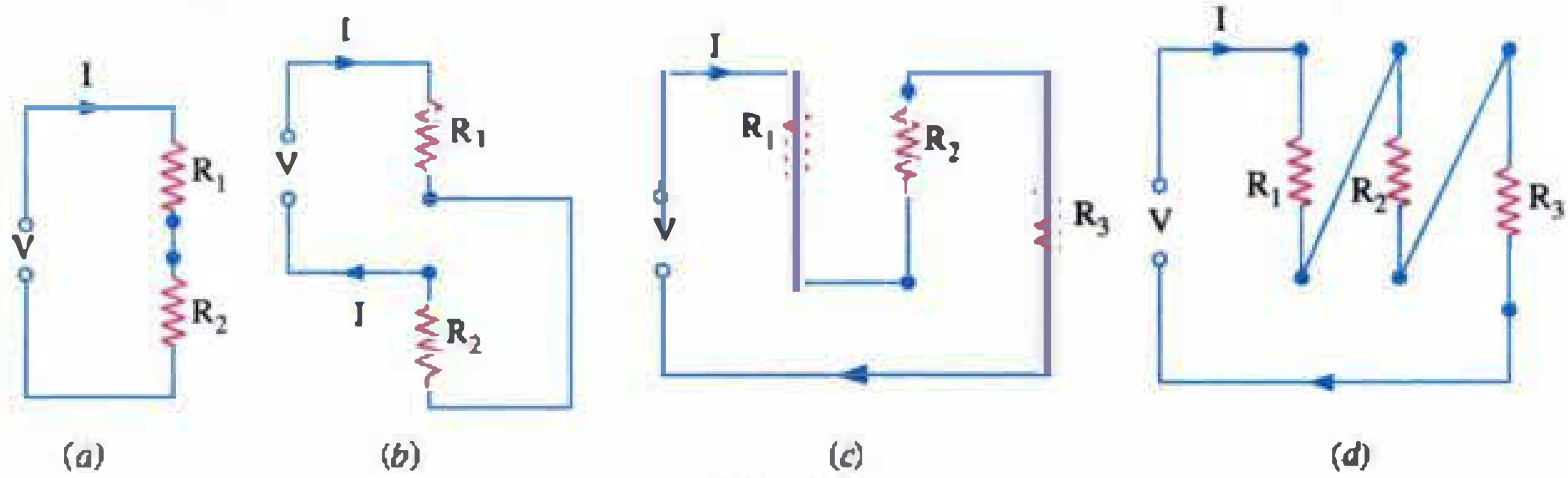


Fig. 2.3

In Fig. 2.3 (*a*)	$R = R_1 + R_2$
In Fig. 2.3 (*b*)	$R = R_1 + R_2$
In Fig. 2.3 (*c*)	$R = R_1 + R_2 + R_3$
In Fig. 2.3 (*d*)	$R = R_1 + R_2 + R_3$

Talking in terms of conductances, we have in Fig. 2.3 (*c*)

$$\frac{1}{G} = \frac{1}{G_1} + \frac{1}{G_2} + \frac{1}{G_3}$$

2. *Current through all resistors is the same.*

The value of circuit current is given by

$$I = \frac{\text{applied voltage}}{\text{total resistance}} = \frac{V}{R}$$

3. *The sum of individual IR drops equals the applied voltage.*

As seen from Fig. 2.1,

$$V = V_1 + V_2 + V_3$$

4. There is a stepped fall in voltage as we go from one end the battery to the other as shown in Fig. 2.4.

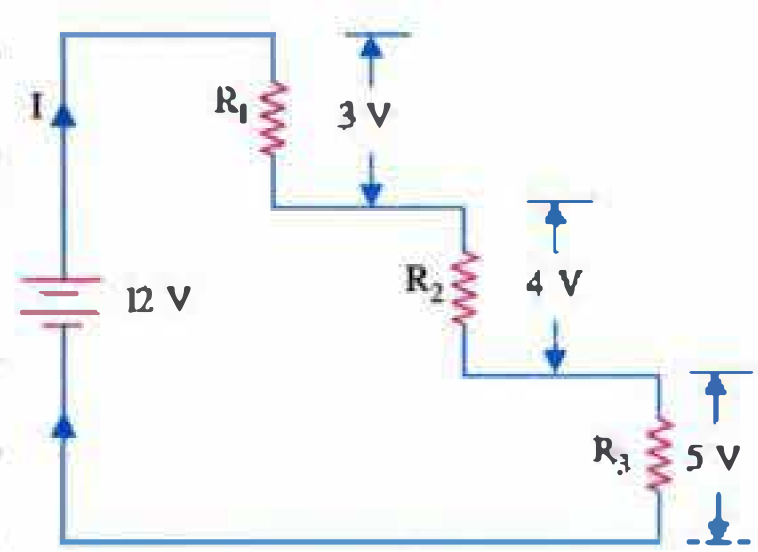


Fig. 2.4

2.3. The Case of Zero IR Drop

It is obvious that drop 'IR' will be zero when either I is zero or R is zero. Now, for copper connecting wires, R is practically zero. Hence, there is no voltage drop across such interconnecting wires even though they may carry their normal current.

Similarly, there is no IR drop when I is zero *i.e.*, when applied voltage has been disconnected or there is an open in the circuit.

2.4. Polarity of IR Drops

The study of voltage polarities, whether positive or negative, is of extreme importance in transistor and semiconductor circuits. When voltage drop exists across a resistor, its one end must be more positive than the other. Otherwise, without a potential difference, no current could flow through the resistance to produce the IR drop. The polarity of this drop can be associated with the direction of current flow. If current enters a resistor at point A and goes out from point B, then A must be at a higher potential than B. In other words, A must be positive with respect to B.

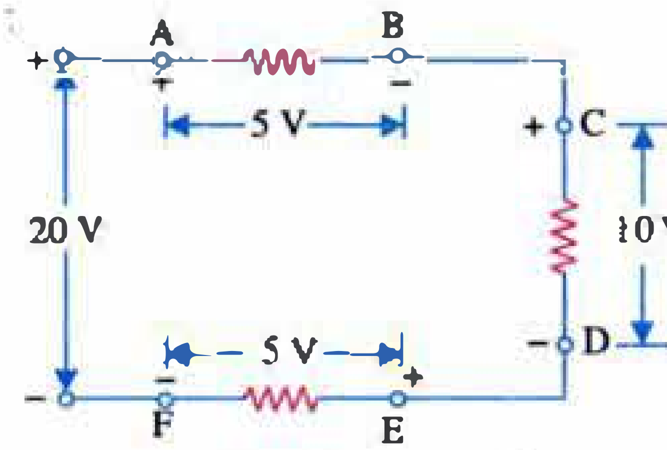


Fig. 2.5

It should be clearly understood that '+' and '–' polarities marked in Fig. 2.5 *relate to voltage drops across resistors only*. Otherwise, points B and C and, similarly, points D and E cannot be at different potentials because they are connected by a piece of conductor wire of zero resistance.

2.5. Total Power

The power needed to drive current through different resistors appears in the form of heat. Hence, total power supplied by the energy source must be equal to the sum of individual powers dissipated in different resistors.

$$\therefore \qquad P = P_1 + P_2 + P_3 \ldots\ldots \text{etc.}$$

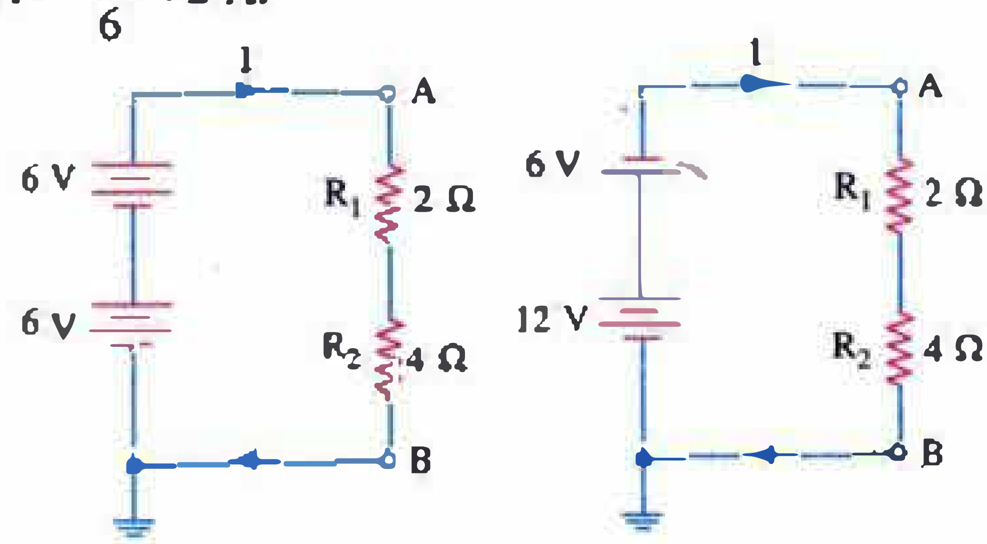
2.6. Series-Aiding and Series-Opposing Voltages

In series-aiding combination, the voltage sources (cells or batteries) are connected in series such that positive terminal of one is joined to the negative terminal of the next. In this case, the total voltage across the circuit is the sum of all voltages or battery emf's as shown in Fig. 2.6 (*a*). Here.

voltage applied across $AB = 6 + 6 = 12$ V and $I = \dfrac{12}{6} = 2$ A.

In series-opposing combination, positive terminal of one voltage source is connected to the positive terminal of the other source as shown in Fig. 2.6 (*b*). In this case, the net voltage is the difference of the two voltages and has the same polarity as the larger of the two voltages.

For example, in Fig. 2.6 (*b*), net voltage across AB is $12 - 6 = -6$ V. Hence, $I = 6/6 = 1$ A.



(*a*) Fig. 2.6 (*b*)

Example. 2.1. *In Fig. 2.7, compute*

1. *total circuit resistance*
2. *circuit current*
3. *p.d. between A and E*
4. *potential of point E*
5. *power supplied by the battery.*

Solution. 1. $R = R_1 + R_2 + R_3 = 2 + 3 + 1 = 6\ \Omega$

2. $I = V/R = 12/6 = 2$ A

3. $R_{AE} = 2 + 3 = 5\ \Omega$

$V_{AE} = IR_{AE} = 2 \times 5$

$= \mathbf{10\ V}$

4. $V_E = 1 \times 2 = \mathbf{+2\ V}$

— above ground

5. $P = VI = 12 \times 2 = \mathbf{24\ W}$

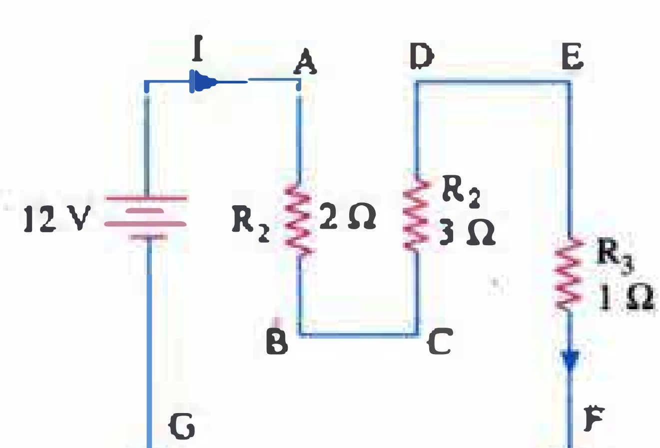


Fig. 2.7

Example. 2.2. *In the circuit of Fig. 2.8, calculate*

1. circuit current

2. potential of point C

3. potential of point B

4. point of lowest potential

5. value of lowest potential.

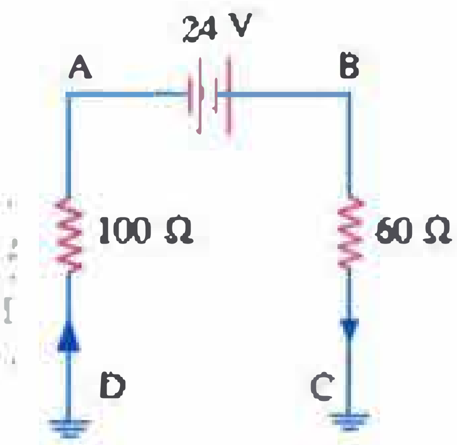


Fig. 2.8

Solution. 1. $I = 24/160 = \mathbf{0.15\ A}$

2. being grounded, point C is at **0 V**

3. potential of point $B = 0.15 \times 60 = \mathbf{+9\ V}$

4. point A has lowest potential *i.e.*, it has maximum negative potential.

5. potential of point $A = -0.15 \times 100 = \mathbf{-15\ V}$ *i.e.*, 15 V below ground potential.

Example 2.3. *With reference to the circuit of Fig. 2.9, compute*

1. circuit current — *2. power supplied by the two batteries*

3. power dissipated in the two resistors — *4. potential of point A and its polarity*

5. potential of point B and its polarity.

Solution. 1.

$$\text{Net driving voltage} = 12 - 6 = 6\ \text{V}$$

$$\text{Total resistance} = 4 + 8 = 12\ \Omega$$

$$I = 6/12 = \mathbf{0.5\ A} \qquad \text{— from } A \text{ to } B$$

2. Power is supplied by 12 V battery only and none by 6 V battery. In fact, 6 V battery consumes power as explained below.

Power supplied by 12 V battery is

$$= 12 \times 0.5 = \mathbf{6\ W}$$

3.

$$P_1 = I^2R_1 = 0.5^2 \times 4 = \mathbf{1\ W}$$

$$P_2 = I^2R_2 = 0.5^2 \times 8 = \mathbf{2\ W}$$

Note. It is seen that total power dissipated in the two resistors is 1 + 2 = 3 W. But power supplied by the 12V battery = 6 W. Question is : where has the balance of (6 – 3) = 3 W gone? It has been *consumed* by the 6V battery. Remember that power is needed to drive current against an opposing voltage. In the present case, opposing voltage is 6V and current driven is 0.5 A. Hence, power consumed by 6 V battery is $P_3 = 6 \times 0.5 =$ 3 W.

So, out of the 6 W input power, 3 W are dissipated by the two resistors and 3 W are consumed by the 6 V battery.

4. Potential of point A is $12 - 6 = +6$ V *i.e.*, positive with respect to the ground.

5. Potential of point $B = V_A - 4 \times 0.5 = 6 - 2 = 4$ V positive w.r.t. ground.

Alternatively, $V_B = 0.5 \times 8 = +4$ V w.r.t. point C *i.e.*, ground.

Example 2.4. *For the circuit of Fig. 2.10, find*

1. power delivered to element A — *2. power delivered to element B*

3. voltage drop across element B.

Solution. 1. $P_A = 4 \times 5 = \mathbf{20\ mW}$

2. Now, $P = 12 \times 5 = \mathbf{60\ mW}$

Also $\qquad P = P_A + P_B$

or $\quad 60 = 20 + P_B$

$\therefore \quad P_B = 40$ mW

3. Now, $\quad V = V_A + V_B$

$\therefore\ 12 = 4 + V_B \quad \therefore\ V_B = 8$ V

Alternatively, $P_B = V_B \times I$

or $\quad 40 = V_B \times 5$

$\therefore \quad V_B = 8$ V

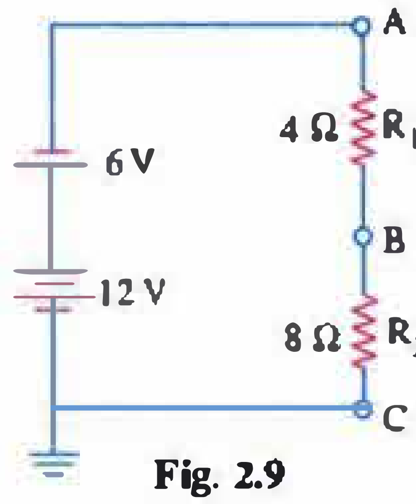


Fig. 2.9

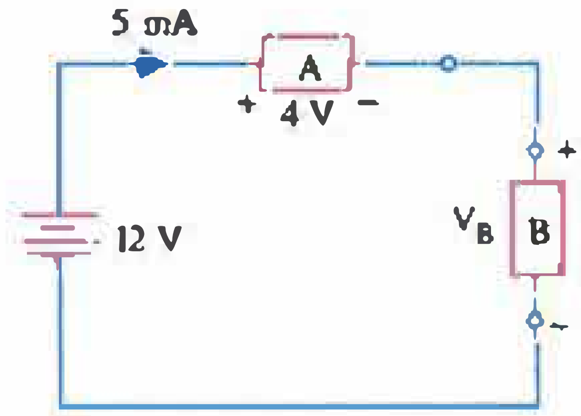


Fig. 2.10

2.7. Proportional Voltage Formula in a Series Circuit

In a series circuit, voltage drop varies directly with resistance. Hence, a simple relation can be found to calculate individual voltage drops without first finding the circuit current.

In Fig. 2.11 (*a*) is shown a 24 V battery connected across a series combination of three resistors, R_1, R_2 and R_3. Fig. 2.11 (*b*) shows a more popular way of drawing the same circuit.

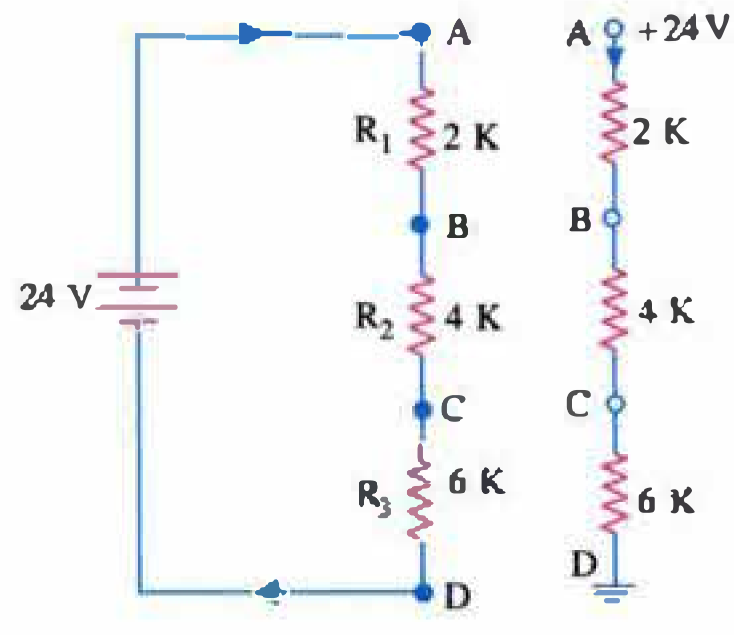
Now, total resistance $R = R_1 + R_2 + R_3 = 12$ K.

According to Proportional Voltage Formula, various drops are

$$V_1 = V \times \frac{R_1}{R} = 24 \times \frac{2}{12} = 4 \text{ V}$$

$$V_2 = V \times \frac{R_2}{R} = 24 \times \frac{4}{12} = 8 \text{ V}$$

$$V_3 = V \times \frac{R_3}{R} = 24 \times \frac{6}{12} = 12 \text{ V}$$



(*a*) (*b*)

Fig. 2.11

2.8. Series Voltage Dividers

A simple series voltage divider consists of two or more resistors connected in series across a voltage source, say, a battery, as shown in Fig. 2.12. Current flowing through the resistors gives rise to voltage drops proportional to their resistances. These voltages can be used for loads needing voltages less than the battery voltage. In fact, such voltage-divider circuits are used when it is necessary to obtain different values of voltage from a single energy source. A typical example is when we use a single power supply V_{CC} to provide collector voltage and bias voltage for transistor bias circuit as shown in Fig. 2.13.

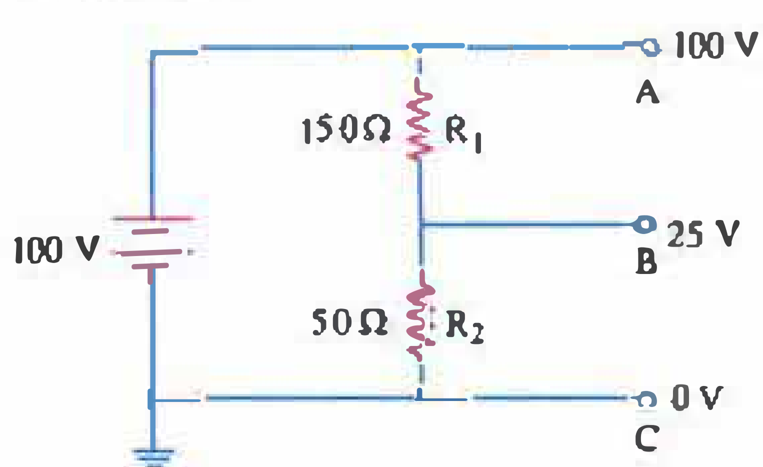


Fig. 2.12

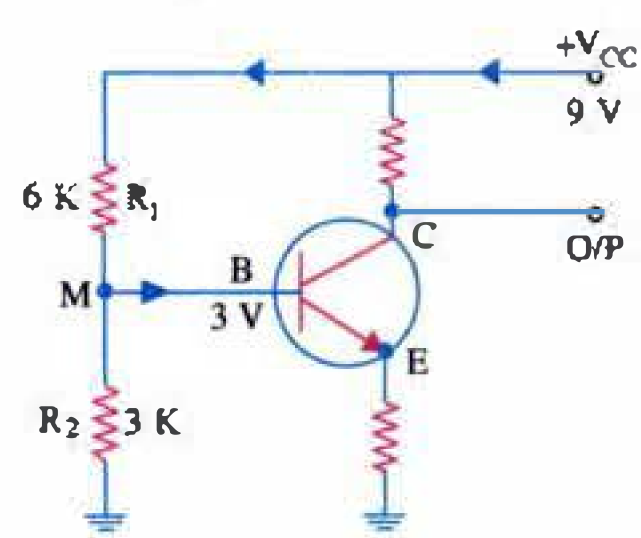
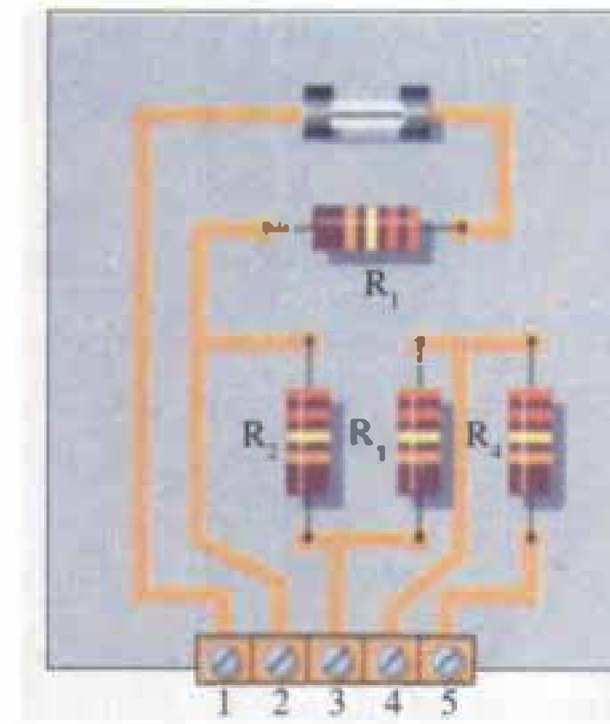


Fig. 2.13

In Fig. 2.12, two resistors of 150 Ω and 50 Ω are connected in series across a 100 V source. Voltage drop across $R_1 = 100 \times 150/200 = 75$ V. Similarly, drop across $R_2 = 100 \times 50/200 = 25$ V. As seen. point A is at 100 V whereas potential of point $B = 100 - 75 = 25$ V. Now, we have a choice of three voltages : 100 V, 75 V and 25 V. If we want 75 V, the pick off points are A and B. If we need 25 V, it is available between points B and C. Of course, 100 V is available between points A and C.



Voltage divider circuit board.

Now, take the transistor biasing circuit of Fig. 2.13. Here, collector voltage required is 9 V but base bias voltage required is 3 V. A simple series voltage divider network $R_1 - R_2$ is added to supply the two required voltages from a single source. As seen, total voltage across $R_1 - R_2$ is 9 V. Drop across $R_2 = 9 \times 3/9 = 3$ V. Hence, base B of the transistor is at + 3 V.

Example 2.5. *Find the values of different voltages that can be obtained from a 12 V battery with the help of voltage divider circuit of Fig. 2.14.*

Solution.

$$R = R_1 + R_2 + R_3 = 4 + 3 + 1 = 8\ \Omega$$

$$\text{drop across } R_1 = 12 \times 4/8 = 6 \text{ V}$$

$$\therefore \quad V_B = 12 - 6 = 6 \text{ V}$$

$$\text{drop across } R_2 = 12 \times 3/8 = 4.5 \text{ V}$$

$$\therefore \quad V_C = V_B - 4.5 = 6 - 4.5 = 1.5 \text{ V}$$

$$\text{drop across } R_3 = 12 \times 1/8 = 1.5 \text{ V}$$

Different load voltages available are :

(*i*) $V_{AB} = V_A - V_B = 6$ V

(*ii*) $V_{AC} = 12 - 1.5 =$ **10.5 V**

(*iii*) $V_{AD} = 12$ V

(*iv*) $V_{BC} = 6 - 1.5 =$ **4.5 V**

(*v*) $V_{CD} =$ **1.5 V**

Hence, there is a choice of five different voltages.

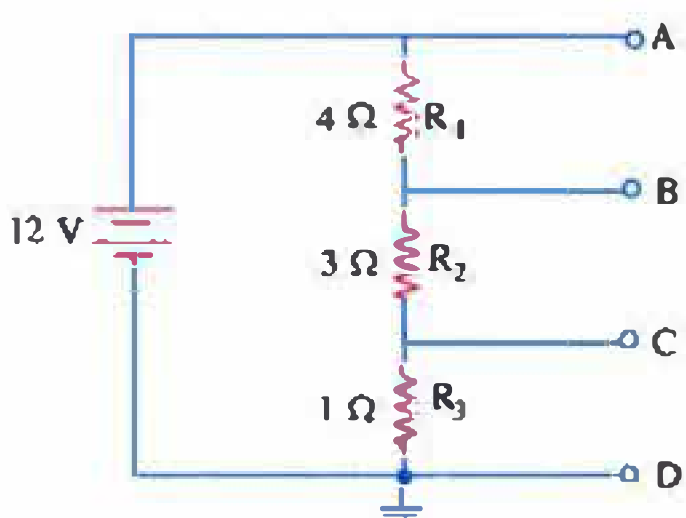


Fig. 2.14

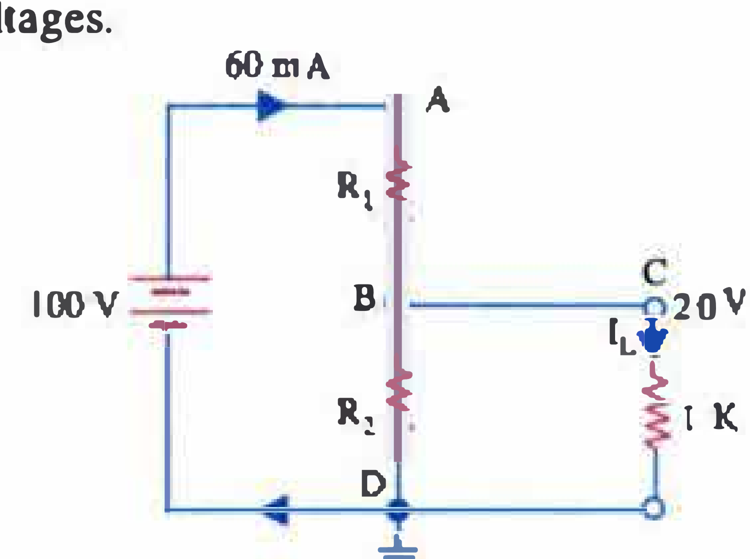


Fig. 2.15

Example 2.6. *In Fig. 2.15, find values of R_1 and R_2 if the voltage applied across load resistor of 1 K is to be 20 V. The maximum current which the battery can supply is 60 mA.*

Solution.

$$\text{Load current } I_L = 20/1 \text{ K} = 20 \text{ mA}$$

$$\text{Current through } R_2 = 60 - 20 = 40 \text{ mA}$$

$$\text{Voltage across } R_2 = 20 \text{ V} \quad \text{— same as across the load}$$

$$R_2 = 20/40 \text{ mA} = \mathbf{500\ \Omega}$$

$$\text{Drop through } R_1 = 100 - 20 = 80 \text{ V}$$

$$\text{Current through } R_1 = 60 \text{ mA}$$

$$R_1 = 80/60 \text{ mA} = \mathbf{1333.3\ \Omega}$$

2.9. 'Opens' In a Series Circuit

In a normal series circuit like the one shown in Fig. 2.16 (*a*), there is a current flow and voltage drops across different resistors are proportional to their resistances. If the circuit becomes open anywhere as shown in Fig. 2.16 (*b*), following two effects would be produced :

1. First, the 'open' will offer an infinite resistance. Hence, circuit current will become zero. Consequently, there would be no voltage drops across R_1 and R_2.

2. Second, *whole of the applied voltage would be felt across the 'open'*. The reason for this is that resistances R_1 and R_2 become negligible as compared to the infinite resistance of the 'open' which has practically whole of the applied voltage dropped across it (as per Proportional Voltage Formula).

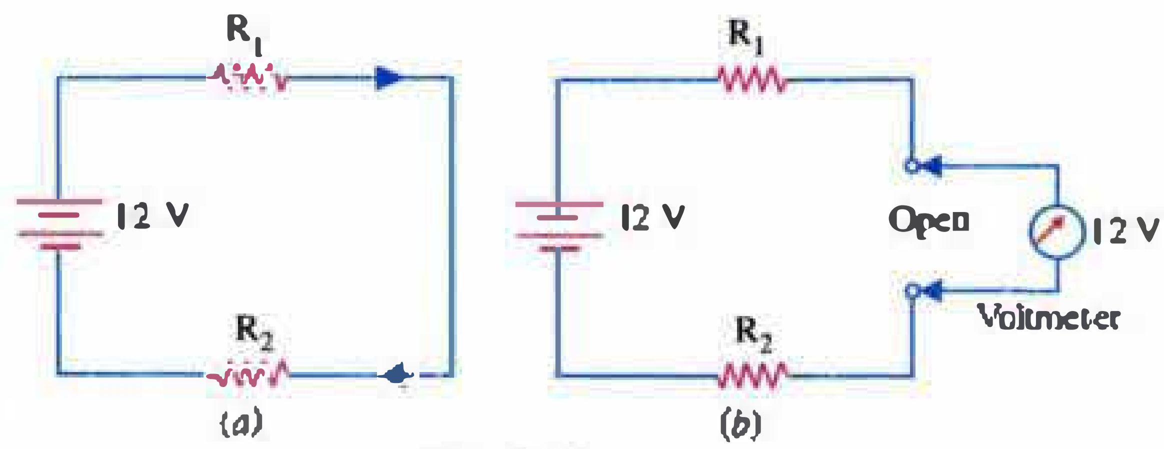
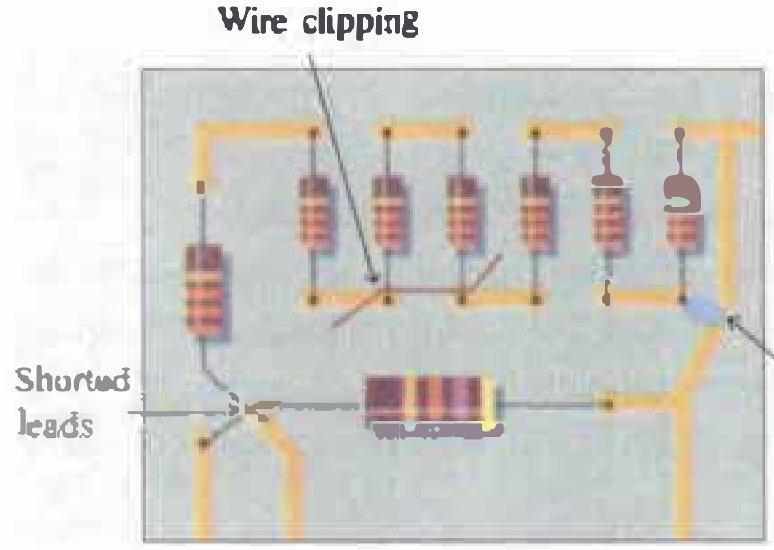


Fig. 2.16

2.10. 'Shorts' In a Series Circuit

A 'short' has practically zero resistance. Hence, it causes the problem of excessive current which, in turn, causes power to increase many times and circuit components to burn out.

In Fig. 2.17 (*a*) is presented the normal series circuit where $V = 12$ V, $R = 6\ \Omega$, $I = 12/6 = 2$ A, $P = I^2R = 2^2 \times 6 = 24$ W.



Examples of shorts on a PC board.

In Fig. 2.17 (*b*), the 3 Ω resistance has been shorted out by a resistanceless copper wire. Now, total circuit resistance is $R = 1 + 2 + 0 = 3\ \Omega$. Hence, $I = 12/3 = 4$ A and power increases to $4^2 \times 3 = 48$ W.

Fig. 2.17 (*c*) shows the situation where both 2 Ω and 3 Ω resistances have been shorted out of the circuit. In this case, $R = 1\ \Omega$, $I = 12/1 = 12$ A, $P = 12^2 \times 1 = 144$ W.

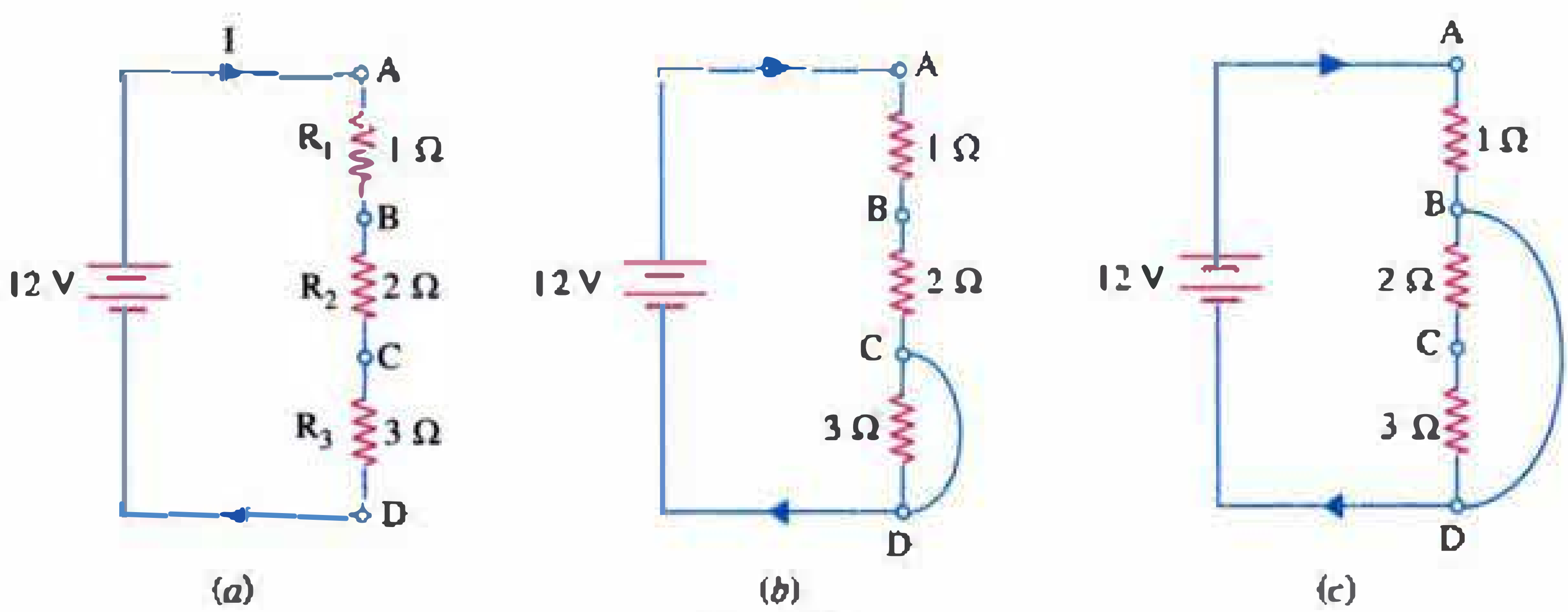


Fig. 2.17

Because of this excessive current (6 times the normal value) wires and other circuit components can become hot enough to ignite and burn. Hence, there should be a fuse which should open if there is too much current in the circuit.

2.11. Parallel Circuits

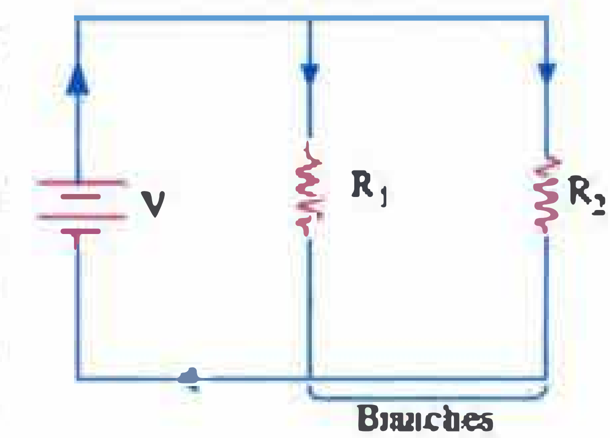


Fig. 2.18

A parallel circuit is a *branched* arrangement in which two or more resistors are connected side by side across a single voltage source as shown in Fig. 2.18. Here, two resistors R_1 and R_2 are in parallel with each other and the battery. It is a two-branched circuit. Parallel connections are also called *multiple connections or shunt connections.* A very important feature of parallel circuits, as compared to series circuits, is that in parallel circuits different branch loads operate independently of each other. Hence, if any load is disconnected or turned off, other branch loads continue to operate.

2.12. Laws of Parallel Circuits


A car's headlights are connected in parallel. Hence each headlight is exposed to the full potential difference supplied by the car's electrical system, giving maximum brightness. One headlight burns out, the other one will keep shining.

Some of the important features of a parallel circuit are as under :

1. Voltage across each branch is the same

For example, in Fig. 2.19 (*a*), voltage across all the three resistors R_1, R_2 and R_3 is the same *i.e.*, battery voltage of 12 V. Therefore, parallel circuit arrangement is used to connect components which require the same voltage.

2. Reciprocal resistance formula

According to this formula, the *reciprocal* of the net or equivalent resistance of the entire circuit equals the sum of the reciprocals of the individual resistances.

In Fig. 2.19 (*a*), if R is the equivalent resistance, then

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{4} + \frac{1}{6} + \frac{1}{12} = \frac{1}{2} \qquad \therefore \quad R = 2\,\Omega$$

It means that the three parallel-connected resistors of 4 Ω, 6 Ω and 12 Ω can be replaced by a single resistor of 2 Ω as shown in Fig. 2.19 (*b*). Talking in terms of conductances, it means that

$$G = G_1 + G_2 + G_3$$

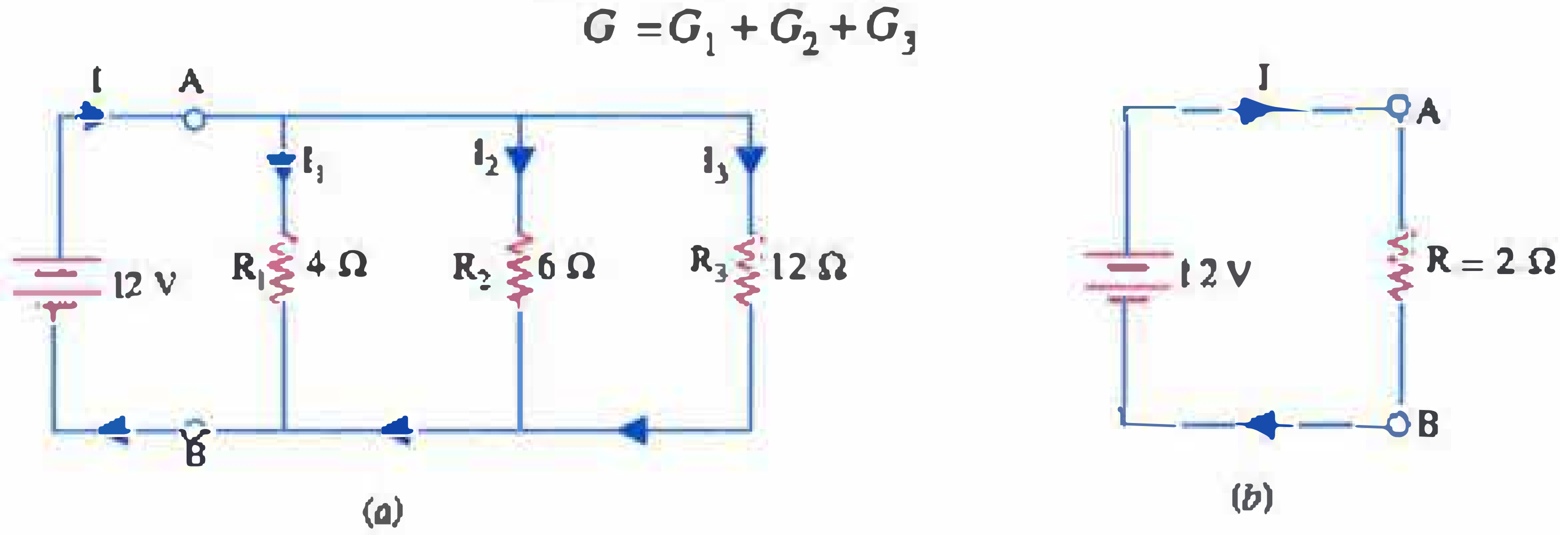


Fig. 2.19

3. Each branch current is given by V/R

In Fig. 2.19 (*a*) above, each branch current is given by

$$I_1 = \frac{V}{R_1} = \frac{12}{4} = 3\text{ A}$$

$$I_2 = \frac{V}{R_2} = \frac{12}{6} = 2\text{ A}$$

$$I_3 = \frac{V}{R_3} = \frac{12}{12} = 1\text{ A}$$

4. The sum of branch currents is equal to the total current supplied by the battery

As seen from Fig. 2.19 (*b*) on previous page,

Battery current = 12/2 = 6 A

Sum of branch currents = 3 + 2 + 1 = 6 A

2.13. Special Case of Equal Resistances in all Branches

If resistances in all branches of a parallel circuit are equal, then combined resistance equals the value of one branch resistance divided by the number of branches.

In Fig. 2.20 (*a*), three equal 60 Ω resistances are connected in parallel across terminals *A* and *B*. The equivalent resistance of the entire circuit = 60/3 = 20 Ω as shown in Fig. 2.20 (*b*). If there were four such resistances, then *R* would have been = 60/4 = 15 Ω. If five, then *R* = 60/5 = 12 Ω. In fact, as we keep adding more branch resistances, the total resistance keeps on decreasing.

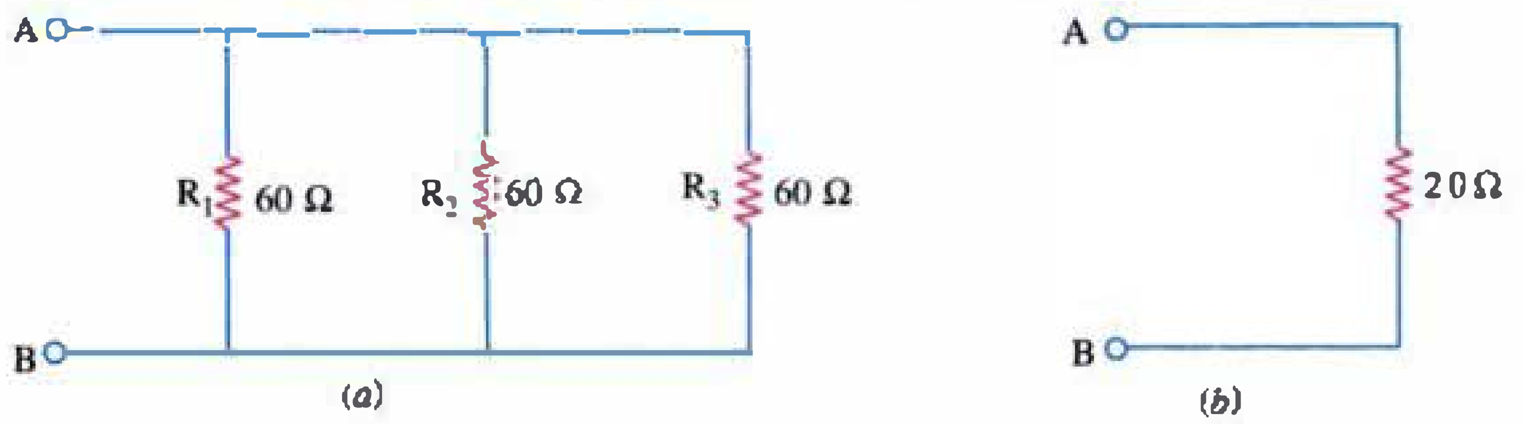


Fig. 2.20

It may seem somewhat unusual at first that putting more resistances into a parallel circuit lowers the total circuit resistance. However, it should become quite clear if one realizes that each resistor provides an additional current path and thus increases the total current. Now, with a *constant* voltage, an *increase* in current can only mean a *decrease* in circuit resistance.

2.14. Special Case of Only Two Branches

The combined resistance of two unequal resistances connected in parallel (Fig. 2.18) is given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_1 + R_2}{R_1 R_2}$$

or
$$R = \frac{R_1 R_2}{R_1 + R_2}$$

It is easier to find combined resistance by the above relation directly instead of using the reciprocal formula.

It is seen that combination of two parallel resistances is equal to their product divided by their sum. Often, the combined resistance is written in the form

$$R = R_1 \parallel R_2$$

2.15. Any Branch Resistance

It can be verified that combined or equivalent resistance of a parallel circuit is less than the least amongst them. From example, in Fig. 2.21, $R = 2 \parallel 500 \parallel 1000 \parallel 10{,}000 = 1.98\ \Omega$.

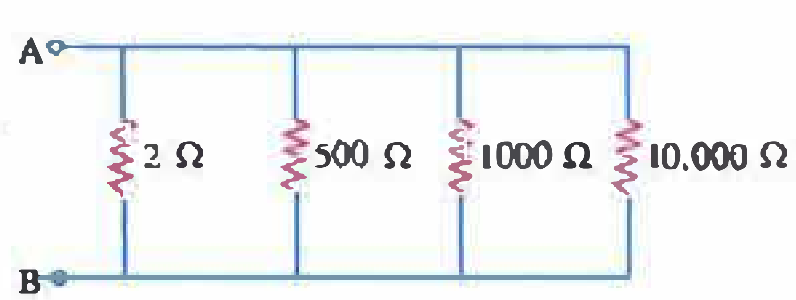


Fig. 2.21

It is less than the least of the three resistances *i.e.*, 2 Ω. In Fig. 2.21,

$$\frac{1}{R} = \frac{1}{2} = \frac{1}{500} + \frac{1}{1000} + \frac{1}{10{,}000}$$

or $\quad R = 1.98\ \Omega$

It is less than the least branch resistance of 2 Ω.

2.16. Proportional Current Formula

Current is inversely proportional to resistance. Hence, current through each branch of a parallel circuit [Fig. 2.22 (*a*)] can be found by setting up an inverse formula like the one given below :

$$I_1 = I \cdot \frac{R_2}{R_1 + R_2}$$

$$I_2 = I \cdot \frac{R_1}{R_1 + R_2}$$

where I is the total current entering the parallel circuit.

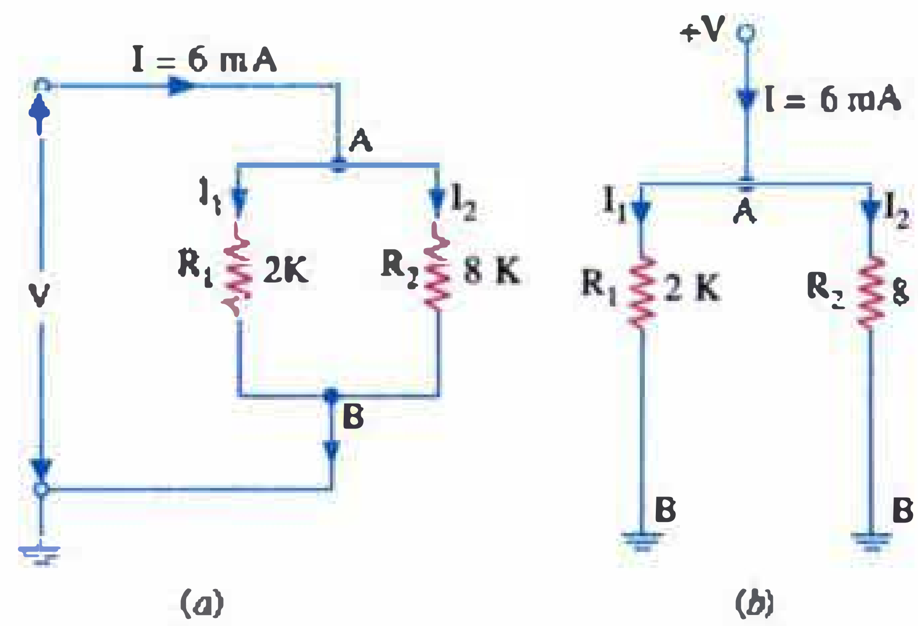


Fig. 2.22

Consider the parallel combination of two resistors shown connected in two different ways in Fig. 2.22.

$$I_1 = 6 \times \frac{8}{2+8} = 4.8\text{ mA}; \qquad I_2 = 6 \times \frac{2}{2+8} = 1.2\text{ mA}$$

Example 2.7. *A 12 V battery of negligible internal resistance is connected across a parallel combination of 4 K, 6 K and 12 K resistors as shown in Fig. 2.23. Compute*

1. *combined circuit resistance*
2. *current supplied by the battery*
3. *power supplied by the battery*
4. *power developed by each resistor*

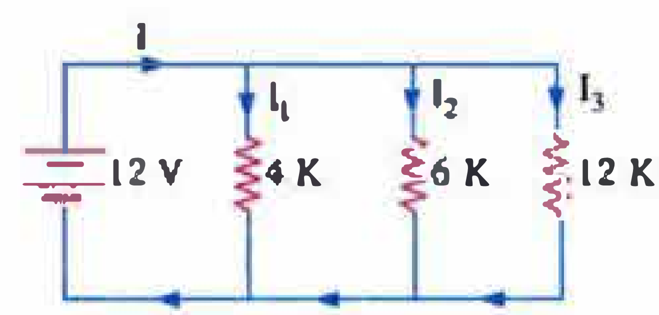


Fig. 2.23

Solution. 1. $\quad \dfrac{1}{R} = \dfrac{1}{4} + \dfrac{1}{6} + \dfrac{1}{12} = \dfrac{1}{2}$

$\quad R = \mathbf{2\ K}$

2. $\quad I_1 = 12/4\text{ K} = 3\text{ mA}$

$\quad I_2 = 12/6\text{ K} = 2\text{ mA} \qquad I_3 = 12/12\text{ K} = 1\text{ mA}$

$\quad I = I_1 + I_2 + I_3 = \mathbf{6\ mA} \quad$ or $\quad I = V/R = 12/2 = 6\text{ mA}$

3. Power supplied by the battery is

$\quad P = VI = 12 \times 6 = \mathbf{72\ mW}$

4. $\quad P_1 = I_1^2 R_1 = 3^2 \times 4 = \mathbf{36\ mW} \qquad P_2 = 2^2 \times 6 = \mathbf{24\ mW}$

$\quad P_3 = 1^2 \times 12 = \mathbf{12\ mW}$

2.17. 'Opens' in a Parallel Circuit

Since an 'open' is equivalent to an infinite resistance, there would be no current in the part of the circuit where it occurs. In a parallel circuit, an 'open' can occur either in the main line or in any parallel branch.

As shown in Fig. 2.24 (*a*), an 'open' in the main line prevents flow of current *to all branches.*

Hence, none of the three bulbs glows. But full *applied voltage is available across the 'open'*.

In Fig. 2.24 (*b*), 'open' has occurred in branch circuit of bulb B_1. Since, there is no current in this branch, B_1 would not glow. However, as the other two bulbs remain connected across the voltage supply, they would keep operating normally.

It may be noted that if a voltmeter is connected across the open bulb, it will read full supply voltage of 220 V.

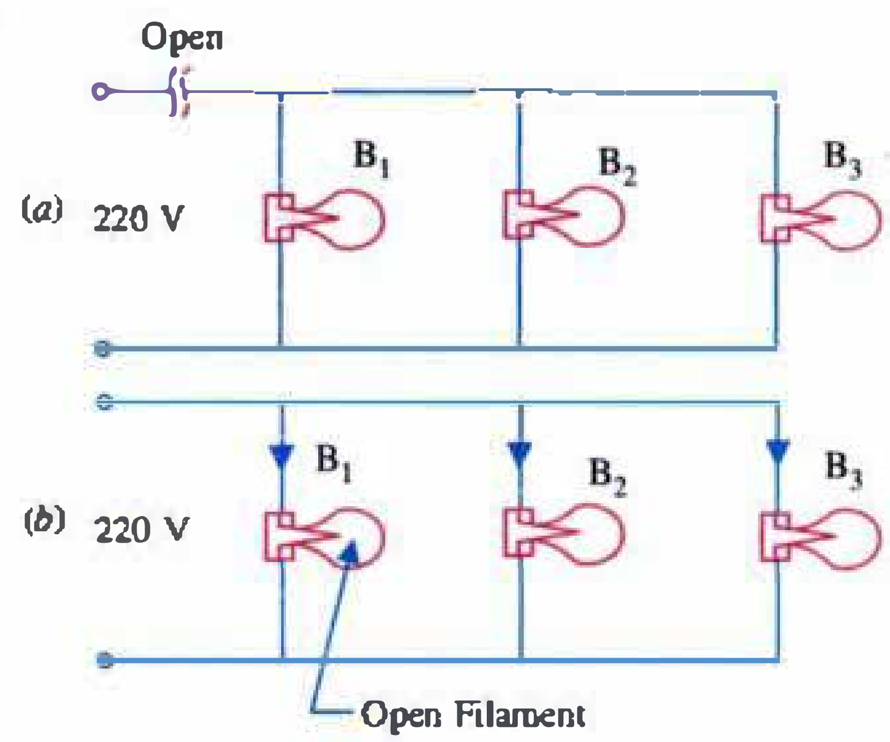


Fig. 2.24

2.18. 'Shorts' in a Parallel Circuit

Suppose a 'short' is placed across resistor R_3 as shown in Fig. 2.25. It becomes directly connected across the battery and draws almost infinite current because not only its own resistance but that of the connecting wires *AC* and *BD* is negligible. Due to this excessive current, the wires may get hot enough to burn out unless the circuit is protected by a fuse. Following points are worth noting :

1. not only is R_3 short-circuited but both R_1 and R_2 are also shorted out *i.e., short across one branch means short across all branches.*
2. there is no current in the shorted resistors. If there were three bulbs, they will not glow.
3. the shorted components are not damaged.

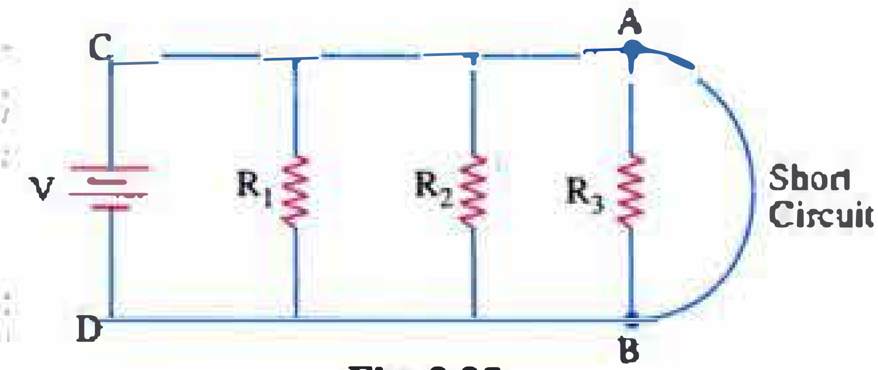


Fig. 2.25

For example, if we had three bulbs in Fig. 2.25, they would glow again when circuit is restored to normal condition by removing the short-circuit.

2.19. Series-Parallel Circuits

Series-parallel circuits are used where it is necessary to provide various amounts of current and voltages with single power supply. Electronic circuits are usually of this type because they generally use only one voltage source. In such circuits, some resistors are connected in parallel and then this parallel combination is connected in series with other resistors as shown in Fig. 2.26.

2.20. Analysing Series-Parallel Circuits

In most of the situations, it is helpful to reduce the given circuit to an equivalent series circuit. This can be done by first handling the parallel part of the circuit and then reducing it to an equivalent single resistance as shown in Fig. 2.26 (*c*).

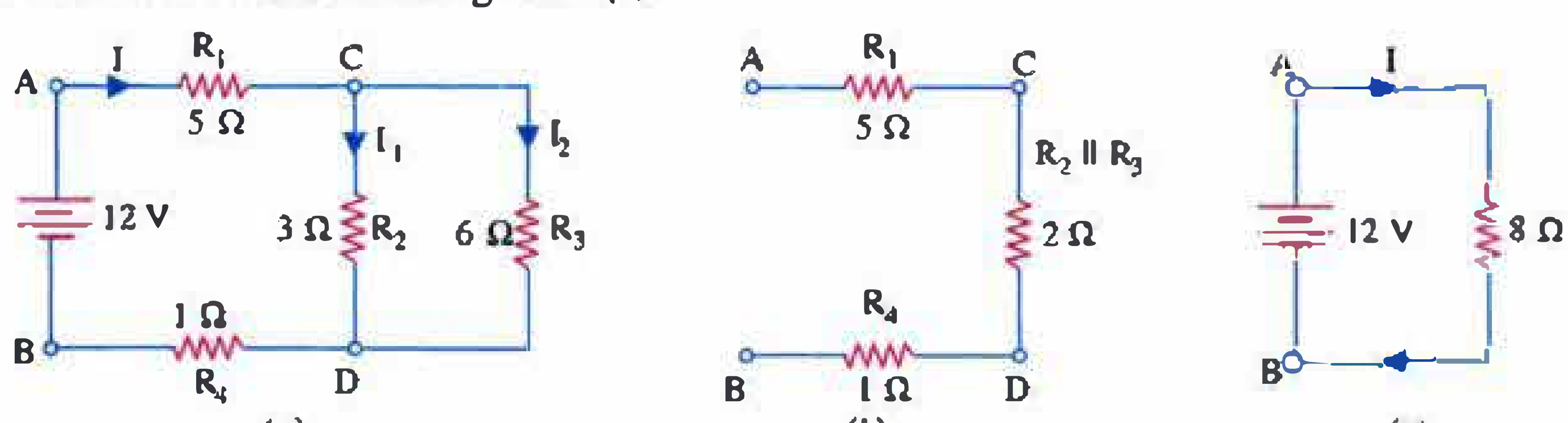


Fig. 2.26

First step is to find equivalent resistance of R_2 and R_3 which is

$$R_2 \parallel R_3 = \frac{R_2 \times R_3}{R_2 + R_3} = \frac{3 \times 6}{6 + 3} = 2\ \Omega$$

The circuit becomes as shown in Fig. 2.26 (*b*).

Second step is to find total resistance by addition.

$$R = 5 + 2 + 1 = 8\ \Omega$$

Third step is to calculate total current supplied by the battery by using Ohm's law.

$$I = 12/8 = 1.5\ \text{A}$$

The branch current I_1 and I_2 and various voltage drops can be found as under :

$$I_1 = I\frac{R_3}{R_2 + R_3} = 1.5 \times \frac{6}{9} = 1\ \text{A}$$

$$I_2 = I\frac{R_2}{R_2 + R_3} = 1.5 \times \frac{3}{9} = 0.5\ \text{A}$$

(or $\quad I_2 = I - I_1 = 1.5 - 1.0 = 0.5$ A)

Drop across $5\ \Omega$ resistor $= 1.5 \times 5 = 7.5$ V

Drop across $R_2 = 3 \times 1 = 3$ V

Drop across $R_3 = 6 \times 0.5 = 3$ V

It should be noted that the above two 3 V drops are not two different voltages but actually the one and the same voltage of 3 V across points *C* and *D* is driving both currents I_1 and I_2.

Drop across $R_1 = 1.5 \times 1 = 1.5$ V

Sum of various drops $= 7.5 + 3 + 1.5 = 12$ V

This sum equals the battery voltage as it, in fact, should.

2.21. 'Opens' in Series-Parallel Circuits

As indicated earlier, an 'open' has the effect of introducing infinite resistance in the branch or leg of the circuit, where it occurs. The effect of an 'open' would be explained with the help of Fig. 2.27.

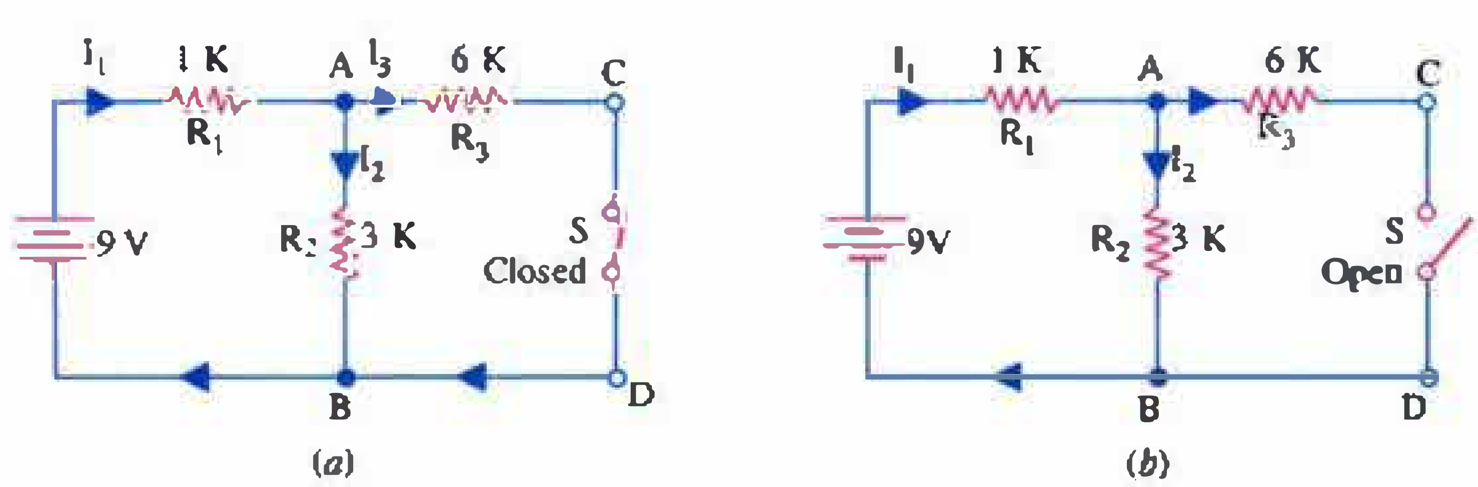


Fig. 2.27

Let us calculate the values of currents and voltages in the circuit of Fig. 2.27 (*a*) when it is working normally with switch *S* closed. Since R_2 and R_3 are in parallel, their combined resistance is $R_2 \parallel R_3 = 6 \times 3/(6 + 3) = 2$ K. This is in series with R_1. Hence, total resistance of the series-parallel circuit becomes $= 1 + 2 = 3$ K.

$$\therefore \quad I_1 = 9/3\ \text{K} = 3\ \text{mA}$$

Branch currents can be found by using the relation given in Art. 2.16.

$$I_2 = 3 \times \frac{6}{9} = 2\ \text{mA}$$

$$I_3 = 3 \times \frac{3}{9} = 1 \text{ mA}$$

Drop across $R_1 = 3 \times 1 = 3$ V

Dropacross $R_2 = 2 \times 3 = 6$ V

(same is the drop across R_3)

Of course, total voltage drop is equal to the battery voltage.

Now, let us consider the effect of opening the switch as in Fig. 2.27 (*b*). First thing to note is that because of 'open' in path *CD*, R_3 cannot be considered in parallel with R_2. In fact, now R_1 and R_2 become in series with the battery. Treated as a voltage divider,

$$\text{Drop across } R_1 = 9 \times \frac{R_1}{R_1 + R_2} = 9 \times \frac{1}{4} = 2.25 \text{ V}$$

$$\text{Drop across } R_2 = 9 \times \frac{3}{4} = 6.75 \text{ V}$$

Since there is no current through R_3, its voltage drop is zero. Moreover, point *C* in Fig. 2.27(*b*) is at the same potential as point *A*. Consequently, *p.d.* across the open terminals *C* and *D* is the same as across points *A* and *B* *i.e.*, 6.75 V.

Another point worth noting is that battery current has decreased from previous value of 3 mA to the present value of 9/4 K = 2.25 mA. Similarly, power supplied by the battery decreases from (9 × 3) = 27 mW to (9 × 2.25) = 20.25 mW.

2.22. 'Shorts' in Series-Parallel Circuits

As explained earlier, a short-circuit has practically zero resistance. Depending on where it occurs, it can change all the current and voltage values in the circuit. Let us calculate the normal current and voltage values etc., for the circuit shown in Fig. 2.28 (*a*).

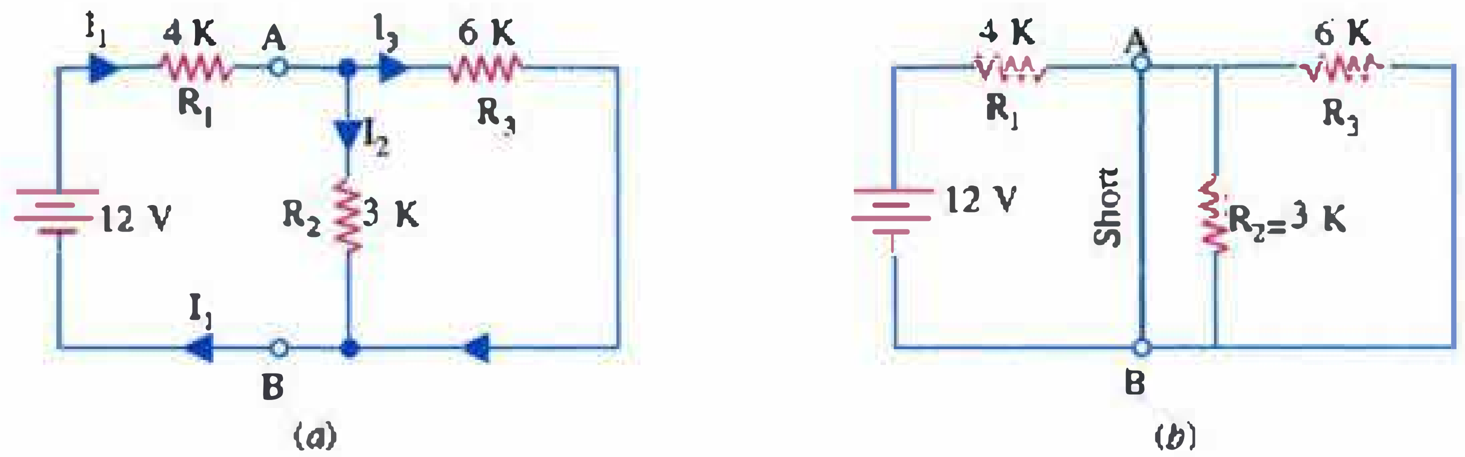


Fig. 2.28

Resistance to the right of points *A* and *B* is

$$R_2 \| R_3 = \frac{6 \times 3}{9} = 2 \text{ K}$$

∴ total circuit resistance = 4 + 2 = 6 K

∴ I_1 = 12/6 K = 2 mA I_2 = 2 × 6/9 = 1.33 mA

I_3 = 2 × 3/9 = 0.67 mA

Drop across R_1 = 4 × 2 = 8 V Drop across R_2 = 1.33 × 3 = 4 V

(same is the drop across R_3)

Power supplied by the battery = 12 × 2 = 24 mW.

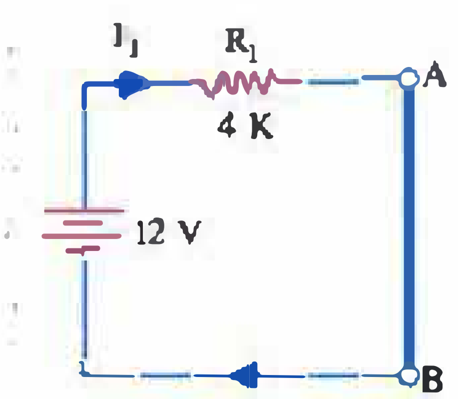


Fig. 2.29

Suppose, now, a short occurs across terminals *A* and *B* as shown in Fig. 2.28 (*b*). It not only shorts out R_2 but R_3 as well thereby reducing the given circuit to the series circuit shown in Fig. 2.29.

Battery current I_1 = 12/4 K = 3 mA

Power supplied by battery = 12 × 3 = 36 mW

As seen, the effect of 'short' is to increase the value of both these quantities.

2.23. Voltage Division in a Complex Series-Parallel Circuit

In Fig. 2.30 is shown a circuit which has many parallel paths. One can analyse it from any point by looking at the path or paths to the ground.

It is seen that

1. $V_6 = V_7$
2. $V_4 = V_5 + V_6 = V_5 + V_7$
3. $V_2 = V_3 + V_4 = V_3 + (V_5 + V_6) = V_3 + (V_5 + V_7)$
4. $V = V_1 + V_2 = V_1 + (V_3 + V_4)$
   $= V_1 + (V_3 + V_5 + V_6) = V_1 + (V_3 + V_5 + V_7)$

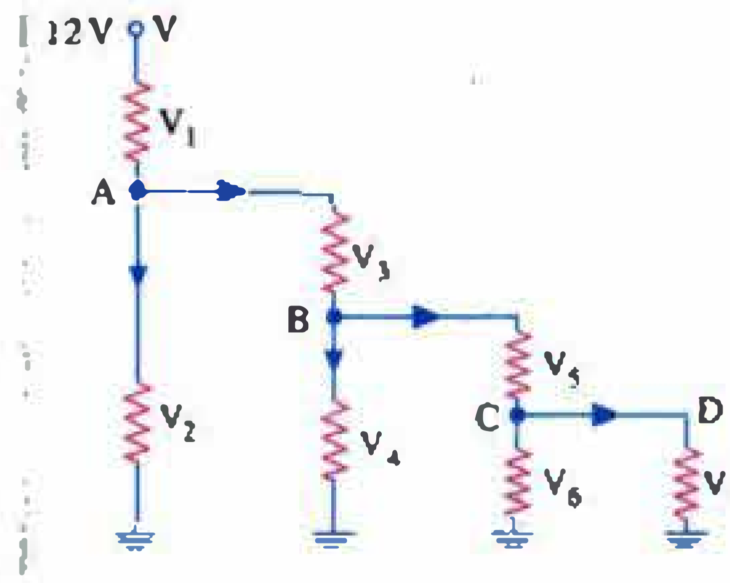


Fig. 2.30

Example 2.8. *For the circuit shown in Fig. 2.31, compute*

1. resistance of the entire circuit

2. current in each resistor

3. voltage drop across each resistor

All resistances are in kilohm.

Solution. 1. First, let us simplify parallel circuit *CD*.

R_{CD} = 8/2 = 4 K

R_{BCD} = 6 + 4 = 10 K

∴ R_{BE} = 10/2 = 5 K

$R = R_{AB} + R_{BE} + R_{EG}$

= 20 + 5 + 5 = 30 K

2. I = 15/30 K = 0.5 mA

Since $R_{BCE} = R_{BFE}$

∴ $I_1 = I_2$ = 0.5/2 = **0.25 mA**

Similarly, $I_3 = I_4$ = 0.25/2

= **0.125 mA**

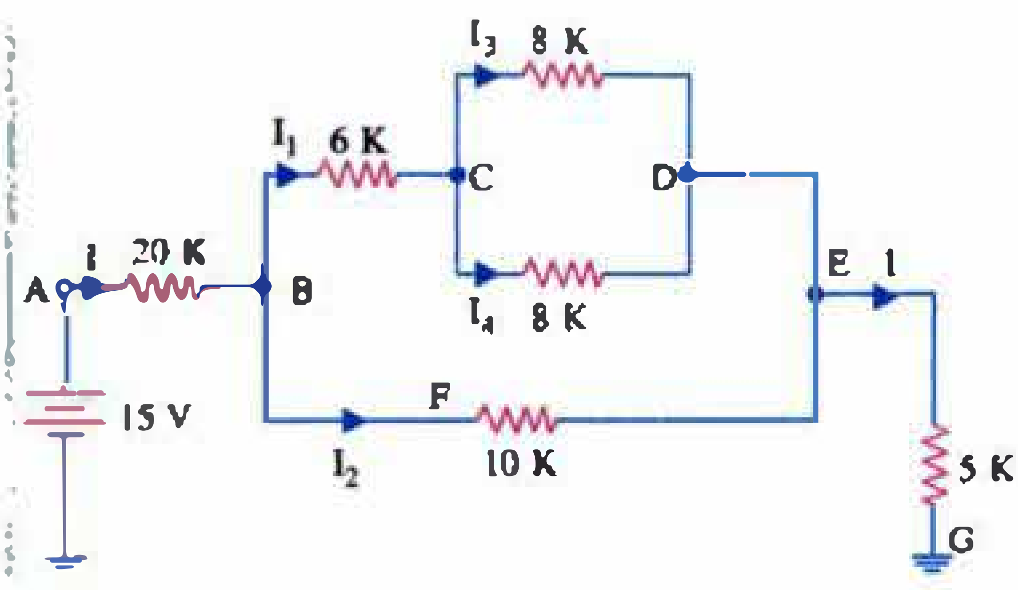


Fig. 2.31

Current through 5 K resistor

= I = **0.5 mA**

3. V_{AB} = 20 × 0.5 = **10 V**

V_{BC} = 6 × 0.25 = **1.5 V**

V_{CD} = 8 × 0.125 = **1V** (or = 4 × 0.25 = 1 V)

V_{BFE} = 10 × 0.25 = **2.5 V** (same as V_{BCE})

V_{EG} = 5 × 0.5 = **2.5 V**

Example 2.9. (*a*). *Find the current and voltage drop across each resistor in Fig. 2.32.*

(*b*) *How will these value change if point D is shorted to ground accidentally ?*

Solution. (*a*) We will first find the combined resistance of the circuit shown in Fig. 2.32. We will use laws of series and parallel combination and start from point *D* upwards to point *A*. As seen, there are two 4 K resistors in parallel across point *C* (or *D*) and ground *G*.

R_{CG} = 4 / 2 = 2 K

resistance of *leg EG* $= 6 + 2 = 8$ K

Again, there are two 8 K resistors in parallel between points B (or E) and ground G.

$\therefore \quad R_{BG} = 8/2 = 4$ K

$\therefore$ resistance of *leg FG* $= 4 + 2 = 6$ K

Now, there are two 6 K resistors in parallel across point A (or F) and G.

$\therefore \quad R_{AC} = 6/2 = 3$ K

This 3 K resistor is in series with the topmost 3 K resistor. Hence, combined or equivalent resistance of the whole circuit is

$$R = 3 + 3 = 6 \text{ K}$$

battery current, $I = 12/6 \text{ K} = 2$ mA

This current gets divided into two equal parts at points A because $R_{FG} = R_{FG} = 6$ K.

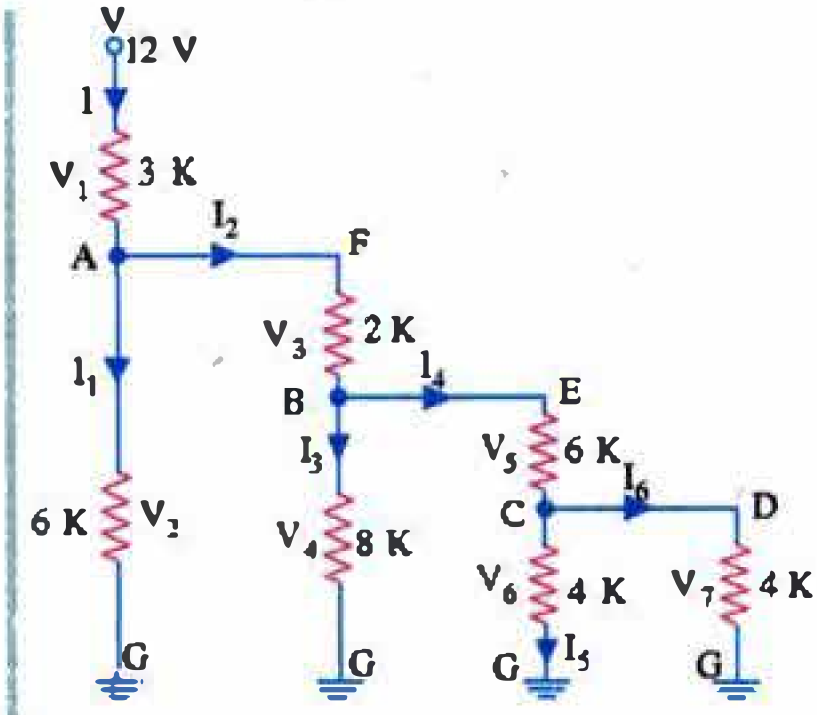


Fig. 2.32

$I_1 = 2/2 \text{ K} = \mathbf{1\ mA}$; $I_2 = \mathbf{1\ mA}$

Next, I_2 gets divided into two equal parts at point B for similar reasons as above.

$I_3 = 1/2 = \mathbf{0.5\ mA}$; $I_4 = \mathbf{0.5\ mA}$

Finally, I_4 lets divided into two equal parts at point C.

$I_5 = 0.5/2 = \mathbf{0.25\ mA}$

$I_6 = 0.25$ mA

$V_1 = 3 \times 2 = \mathbf{6\ V}$; $\quad V_2 = 6 \times 1 = \mathbf{6\ V}$

$V_3 = 2 \times 1 = \mathbf{2\ V}$

$V_4 = 8 \times 0.5 = \mathbf{4\ V}$

$V_5 = 6 \times 0.5 = \mathbf{3\ V}$, $\quad V_6 = 4 \times 0.25 = \mathbf{1\ V}$, $\quad V_7 = \mathbf{1\ V}$

(*b*) When D is shorted to ground (Fig. 2.33), C also gets shorted. Hence, R_{CG} becomes zero as shown in Fig. 2.33. Now, $R_{BG} = 8 \times 6/14 = 24/7$ K.

Resistance of *leg FG* $= 2 + (24/7) = 38/7$ K

$$\therefore \quad R_{AG} = \frac{6 \times 38/7}{6 + (38/7)} = 2.85 \text{ K}$$

$\therefore \quad$ total $R = 3 + 2.85 = 5.85$ K

$I = 12 \div 5.85 = 2$ mA (approximately)

Currents I_1 and I_2 can be found by using Proportional Current Formula (Art. 2.16)

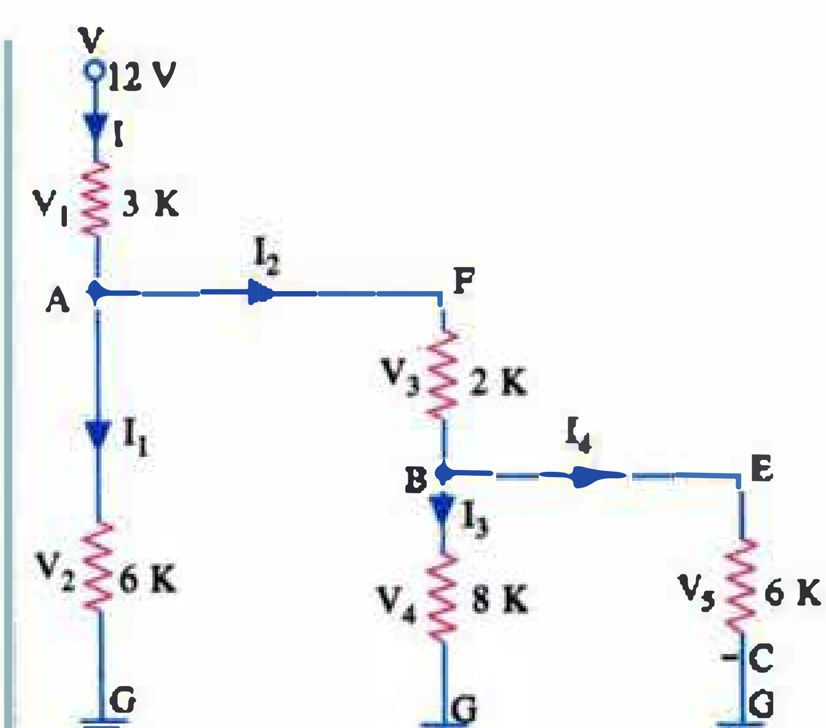


Fig. 2.33

$$I_1 = 2 \times \frac{38/7}{6 + 38/7} = \mathbf{0.95\ mA};$$

$I_2 = 2 - 0.95 = \mathbf{1.05\ mA}$

Again, there is division of current at point B

$$\therefore \quad I_3 = 1.05 \times \frac{6}{6+8} = \mathbf{0.45\ mA}$$

$I_4 = 1.05 - 0.45 = \mathbf{0.6\ mA}$

$V_5 = 6 \times 0.6 = \mathbf{3.6\ V}$; $V_4 = 8 \times 0.45 = \mathbf{3.6\ V}$

$V_3 = 1.05 \times 2 = \mathbf{2.1\ V}$; $V_2 = 6 \times 0.95 = \mathbf{5.7\ V}$

$V_1 = 3 \times 2 = \mathbf{6\ V}$

Example 2.10. *A tapped voltage divider is to be connected across a 220 V dc supply to provide outputs of (a) 15 mA at 100 V and (b) 20 mA at 160 V. Find the resistance of each section of the divider, its power dissipation and total resistance if the bleeder current passed by the divider is to be 60 mA.*

Solution. The divider circuit is shown in Fig. 2.34.

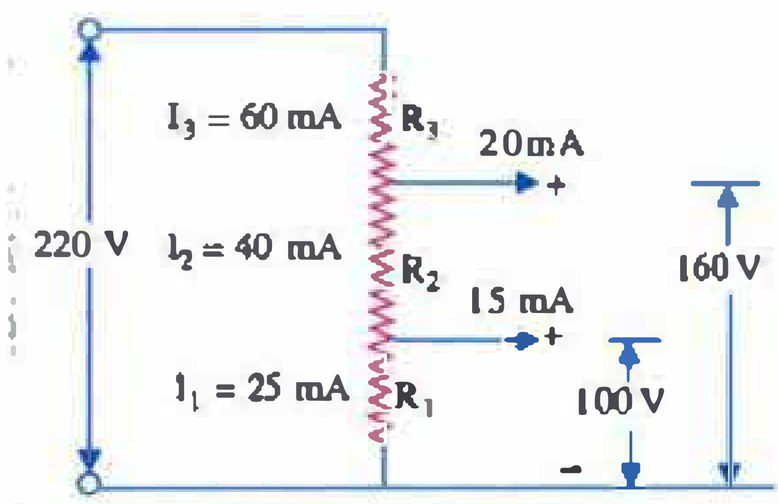


Fig. 2.34

Section R$_1$

$I_2 = 25$ mA. $V_1 = 100$ V.

$R_1 = 100/25 \times 10^{-3} = \mathbf{4000\ \Omega}$

$P_1 = I^2_1\ R_1 = (25 \times 10^{-3})^2 \times 4{,}000 = \mathbf{2.5\ W}$

or $P = V_1 I_1 = 100 \times 25 \times 10^{-3} = \mathbf{2.5\ W}$

Section R$_2$

$I_2 = 25 + 15 = 40$ mA; $V_2 = 160 - 100 = \mathbf{60\ V}$

$\therefore$ $R_2 = V_2 / I_2 = 60/40 \times 10^{-3} = \mathbf{1500\ \Omega}$

$P_2 = V_2\ I_2 = 60 \times 40 \times 10^{-3} = \mathbf{2.4\ W}$

Section R$_3$

$I_3 = 40 + 20 = 60$ mA, $V_3 = 220 - 160 = \mathbf{60\ V}$

$R_3 = V_3 / I_3 = 60 / 60 \times 10^{-3} = \mathbf{1000\ \ \Omega}$

$P_3 = V_3 I_3 = 60 \times (60 \times 10^{-3}) = \mathbf{3.6\ W}$

Total resistance of the divider

$= 4{,}000 + 1{,}500 + 1{,}000 = \mathbf{6{,}500\ \Omega}$

CONVENTIONAL PROBLEMS

1. In the circuit of Fig. 2.35, compute
(*i*) circuit current (*ii*) value of V_1
All resistances are in kilohm. **[(*i*) 0.5 mA; (*ii*) 3.5 V]**

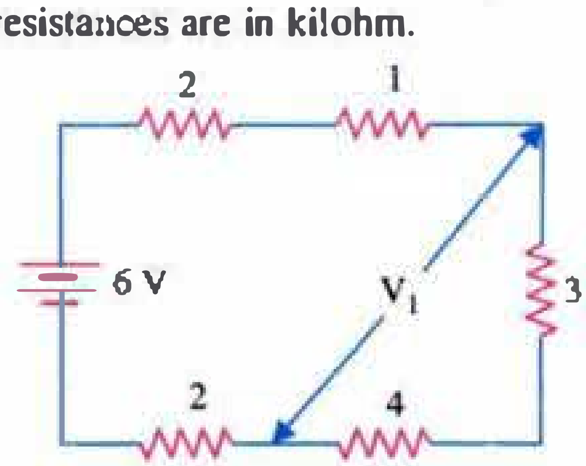


Fig. 2.35

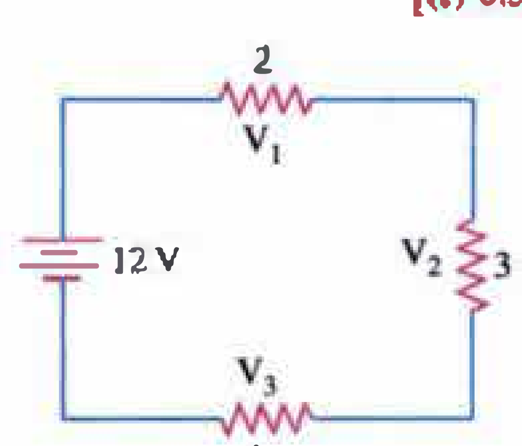


Fig. 2.36

2. Calculate voltage drops across the three series-connected resistors in Fig. 2.36. All values are in kilohm. **[4 V; 6 V; 2V]**

3. In the series network of Fig. 2.37, compute
(*i*) circuit current and (*ii*) power supplied by the battery.
How will these values change if a short is placed, between points *A* and *B* ? All resistances are in kilohm. **[(*i*) 2 mA; (*ii*) 60 mW; 5 mA; 150 mW]**

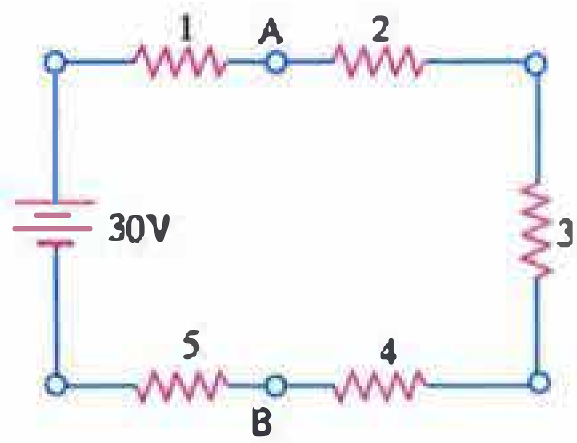


Fig. 2.37

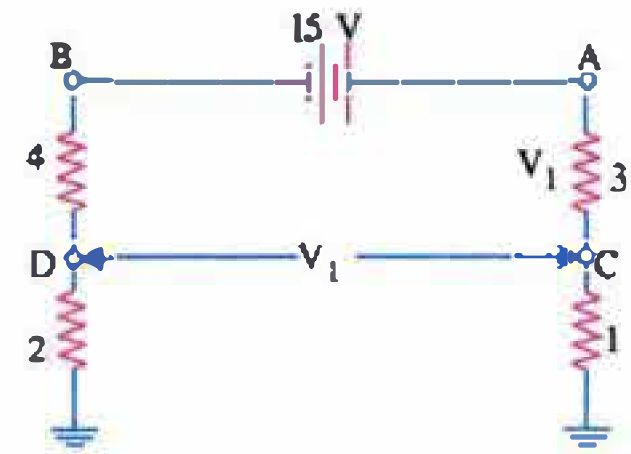


Fig. 2.38

4. In the circuit of Fig. 2.28, find
   (*i*) potentials of points *A* and *B* and (*ii*) value of V_1 and its polarity.
   All resistance values are in kilohm. [(*i*) V_A = +6 V; V_B = – 9 V; (*ii*) 4.5 V with point C positive]
5. In the series voltage-divider circuit of Fig. 2.39, rated load current is 2 mA and maximum current the battery can supply is 10 mA. Calculate the values of resistances R_1 and R_2 and their power ratings. [500 Ω; 800 Ω ; 3 mW; 80 mW]

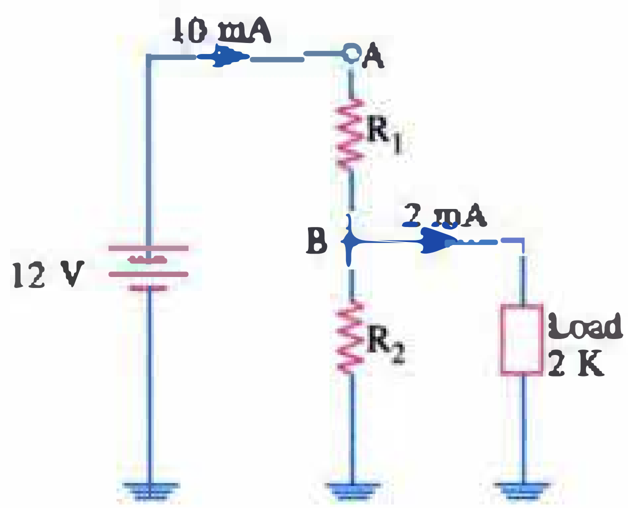


Fig. 2.39

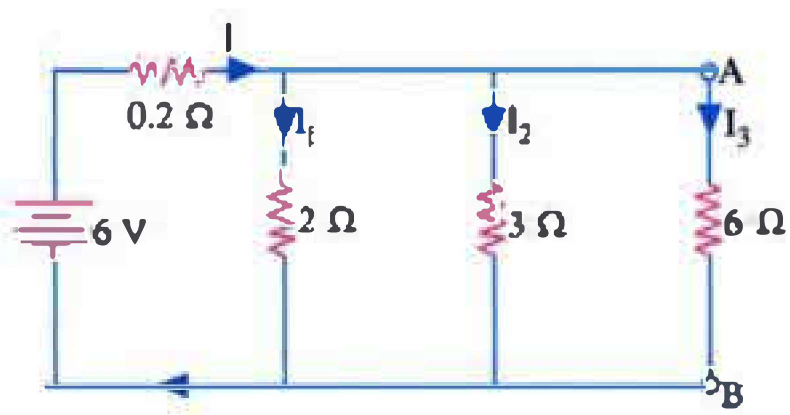


Fig. 2.40

6. In the network of Fig. 2.40, compute
   (*i*) equivalent resistance of the network
   (*ii*) values of branch currents
   (*iii*) current and power supplied by the battery
   (*iv*) current and power supplied by the battery if an accidental short occurs across points *A* and *B*.
   [(*i*) 1.2 Ω ; (*ii*) I_1 = 2.5 A, I_2 = 5/3 A, I_3 = 5/6 A ; (*iii*) 5 A ; 30 W; (*iv*) 30 A, 180 W]
7. In the circuit of Fig. 3.41, compute the value of circuit current. What is the value of the potential of point A with respect to the negative battery terminal ? How do you account for the fact that power supplied by 12 V battery is more than the sum of powers dissipated by the three resistors. [1 mA, 8 V]

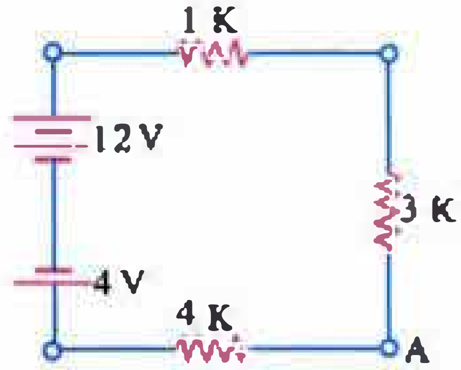


Fig. 2.41

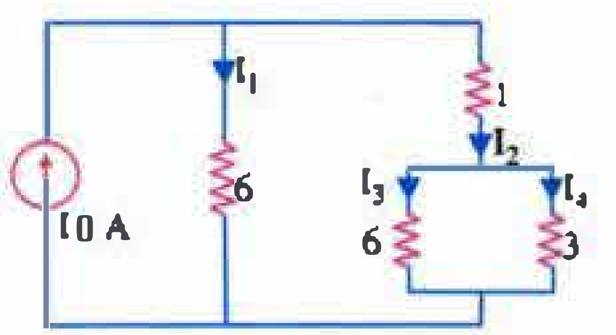


Fig. 2.42

8. Calculate the various branch currents of the circuit shown in Fig. 2.42. All resistance values are in ohms. [I_1 = 10/3 A, I_2 = 20/3 A; I_3 = 20/9 A; I_4 = 40/9 A]

SELF EXAMINATION QUESTIONS

A. Fill in the blanks by most appropriate word (s) or numerical value(s).

1. Resistors are said to be connected in series when .... current passes through each resistor.
2. A series network of resistors used for providing different voltages from a single voltage source is called ....
3. The same .... is present across all branches of a parallel circuit.
4. The total resistance of a parallel circuit is always .... than the lowest resistance connected in any of its branches.
5. Cells are connected in series when higher .... is required.
6. If more current is required, then cells may be joined in ....
7. When both higher voltage and higher current are required. cells may be joined in ....

B. Answer True or False

1. If same amount of current passes through each resistor of a combination, they must be connected in series.
2. In a series circuit, the sum of voltage drops across different components is equal to the applied battery voltage.
3. A 'short' in a series circuit always results in grounding of the voltage source.
4. 'Open' in a series circuit always results in damage to the connected apparatus.
5. A 'short' anywhere in parallel circuit leads to excessive power demand on the source of energy supply.
6. The combined resistance of a parallel circuit is sometimes less than the least resistance connected in the circuit.
7. An 'open' in a parallel circuit may or may not disable all the connected components.
8. A branch 'open' in a parallel circuit does not disrupt the working of other branches.

C. Multiple Choice Items

1. Two resistors are said to be connected in series when
   (*a*) both carry the same amount of current
   (*b*) total current equals the sum of branch currents
   (*c*) sum of IR drops equals battery emf
   (*d*) they provide only one path for the current flow
2. The combined resistance of two equal resistors connected in parallel is equal to
   (*a*) 1/2 the resistance of one resistor
   (*b*) twice the resistance of one resistor
   (*c*) the resistance of one resistor divided by the other
   (*d*) 1/4 the resistance of one resistor
3. When two resistances are connected in series, they have
   (*a*) same resistance value
   (*b*) same voltage across them
   (*c*) same current passing through them
   (*d*) different resistance values
4. If, in Fig. 2.43. voltmeter V measures 20 V, then value of circuit voltage V is about .... volt.
   (*a*) 40 (*b*) 70
   (*c*) 60 (*d*) 20

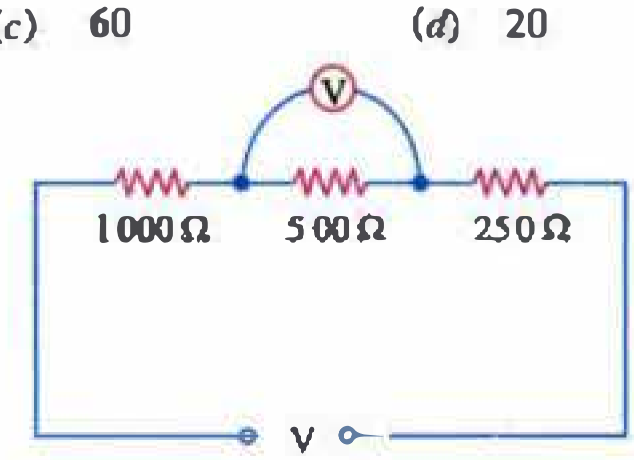


Fig. 2.43

5. If, in Fig. 2.44, R_2 becomes open-circuited, the reading of the voltmeter will
   (*a*) fall to zero (*b*) increase slightly
   (*c*) decrease slightly (*d*) become 200 V

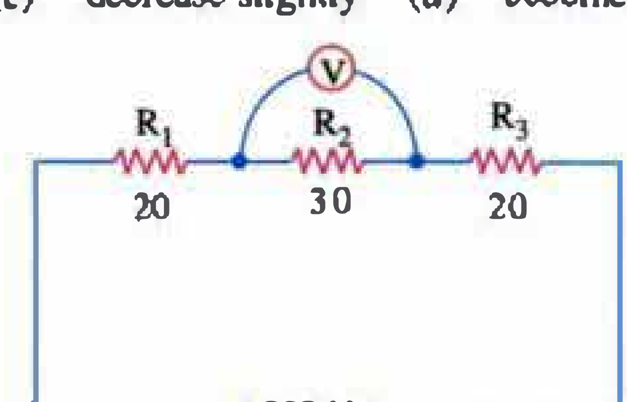


Fig. 2.44

6. In Fig. 2.45, V is an ideal voltmeter having infinite resistance. It will read .... volt.
   (*a*) 40 (*b*) 60
   (*c*) 0 (*d*) 100

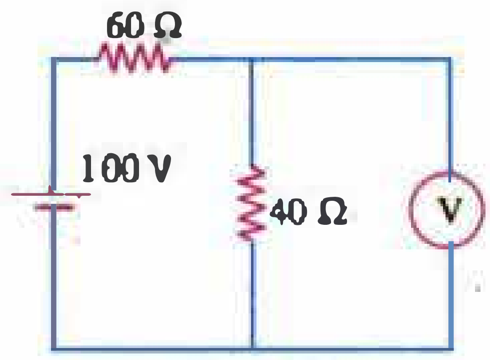


Fig. 2.45

7. The ideal voltmeter V of Fig. 2.46 will read.............volt.

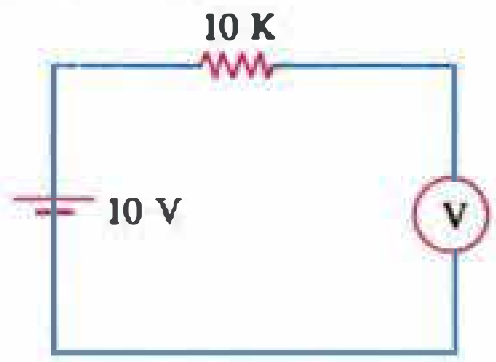


Fig. 2.46

(a) 0 (b) 10

(c) 5 (d) 100

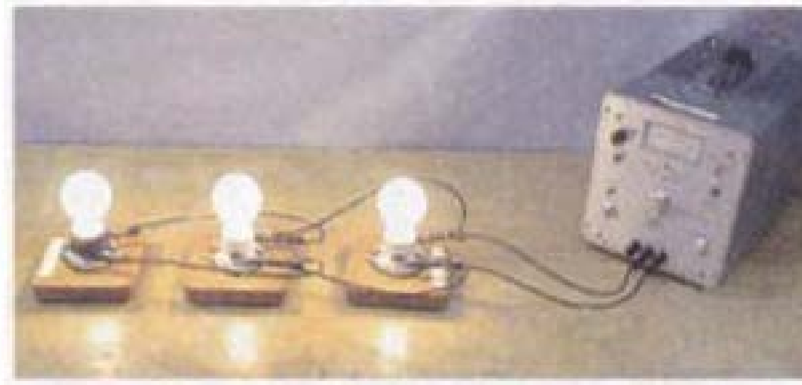
8. In a parallel circuit, all components must

(a) have same p.d. across them

(b) have the same value

(c) carry the same current

(d) be switched ON or OFF simultaneously



A parallel circuit of light bulbs is shown in above Fig.

ANSWERS

A. Fill in the blanks

1. same 2. voltage divider 3. voltage 4. less 5. voltage

6. parallel 7. series, parallel

B. True or False

1. F 2. T 3. F 4. F 5. T 6. F 7. T 8. T

C. Multiple Choice Items

1. *d* 2. *a* 3. *c* 4. *b* 5. *d* 6. *a* 7. *b* 8. *a*

CHAPTER 3

Kirchhoff's Laws

3.1. General

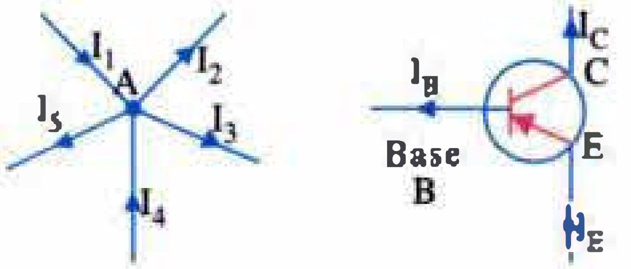
We come across many circuits in which various components are neither in series nor in parallel nor in series-parallel. One example is a circuit with two or more batteries connected in its different branches. Another is an unbalanced bridge circuit. Here, rules of series and parallel circuits are inapplicable. Such circuits can be easily solved with the help of Kirchhoff's laws which are two in number :

1. Kirchhoff's Current Law (KCL)
2. Kirchhoff's Voltage Law (KVL)

3.2. Kirchhoff's Current Law

It states that **in any network of conductors, the algebraic sum of currents meeting at a point (or junction) is zero.**

Put in another way, it simply means that the total current **leaving** a junction is equal to the total current **entering** that junction.



(a) (b)

Fig. 3.1

Explanation

Consider the case of five currents meeting at junction A of the network shown in Fig. 3.1(a). Let us adopt the following sign convention for determining the algebraic sign of different currents.

All currents *entering* the junction would be taken as positive whereas those *leaving* it would be taken as **negative.**

According to the above convention, I_1 and I_4 would be taken as positive whereas I_2, I_3 and I_5 would be taken as negative. Using KCL, we have

$$I_1 + (-I_2) + (-I_3) + I_4 + (-I_5) = 0 \quad \text{or} \quad I_1 - I_2 - I_3 + I_4 - I_5 = 0$$

$$\therefore \qquad \Sigma I = 0 \qquad \text{— at a junction}$$

Also, transposing the negative terms to the right-hand side, we get

$$I_1 + I_4 = I_2 + I_3 + I_5$$

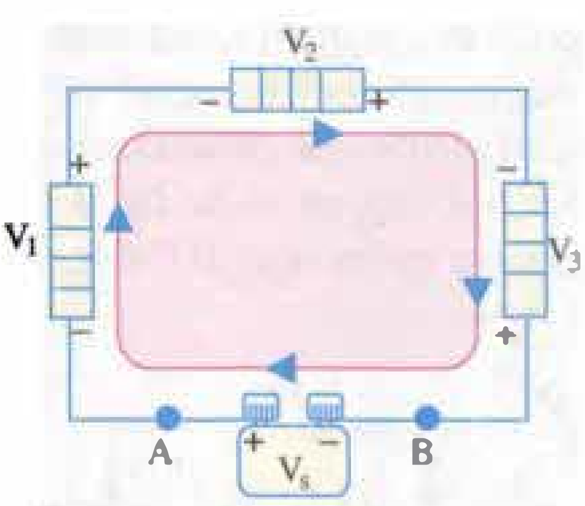
incoming currents = outgoing currents

$$\text{or} \qquad I_{in} = I_{out} \qquad \text{— at a junction}$$

Similarly, in Fig. 3.1 (b), I_E is the emitter current directed *towards* the base. The two currents *i.e.*, base current I_B and collector current I_C are directed *away* from the base. Hence, according to KCL

$$I_E + (-I_B) + (-I_C) = 0 \quad \text{or} \quad I_E - I_B - I_C = 0 \quad \text{or} \quad I_E = I_B + I_C$$

3.3. Kirchhoff's Voltage Law



The sum of the voltage drops equals the source voltage.

It states that **the algebraic sum of all IR drops and EMFs in any closed loop (or mesh) of a network is zero.**

$$\text{or} \qquad \Sigma\, IR = \Sigma\, \text{EMF} = 0 \qquad \text{— round a loop}$$

While applying the above two laws for circuit calculations, plenty of errors can occur unless proper algebraic signs are given both to IR drops and battery EMFs.

3.4. Determination of Algebraic Sign

We will follow a very simple sign convention which would apply equally to IR drops and battery EMFs.

A *rise* (or increase) in voltage would be considered *positive* and given a +ve sign and a *fall* (or decrease) in voltage would be considered negative and hence given a –ve sign. Let us see how we will apply this convention (*i*) firstly, to battery EMFs or voltage sources and (*ii*) secondly, to IR drops across various branch resistors.


Gustav R. Kirchhoff (1824-1887)

(*i*) Battery EMF

While going round a loop (in a direction of our own choice) if we go from the –ve terminal of a battery to its +ve terminal, there is a *rise* in potential, hence this EMF should be given +ve sign. If, on the other hand, we go from its +ve terminal to its –ve terminal, there is fall in potential, hence this battery EMF should be given –ve sign.

It is important to note that algebraic sign of battery EMF is independent of the direction of current flow (whether clockwise or anticlockwise) through the branch in which the battery is connected.

(*ii*) IR drops on resistors

If we go through a resistor in the *same* direction as its current, then there is a *fall* or *decrease* in potential for the simple reason that current always flows from a higher to a lower potential. Hence, this IR drop should be taken −ve. However, if we go around the loop in a direction *opposite* to that of the current, *i.e.,* if we go upstream, there is a rise in voltage. Hence, this IR drop should be a taken as positive.

It is clear from above that algebraic sign of IR drop across a resistor depends on the direction of current that resistor.

Consider the closed loop $ABCDA$ of Fig. 3.2. Starting from point A if we go around this mesh in clockwise direction,* then different EMFs and IR drops will have following values and signs :

I_1R_1 is −ve (fall in potential)
I_2R_2 is +ve (rise ,,)
E_2 is −ve (fall ,,)
I_3R_3 is −ve (fall ,,)
E_1 is +ve (rise ,,)
I_4R_4 is −ve (fall ,,)

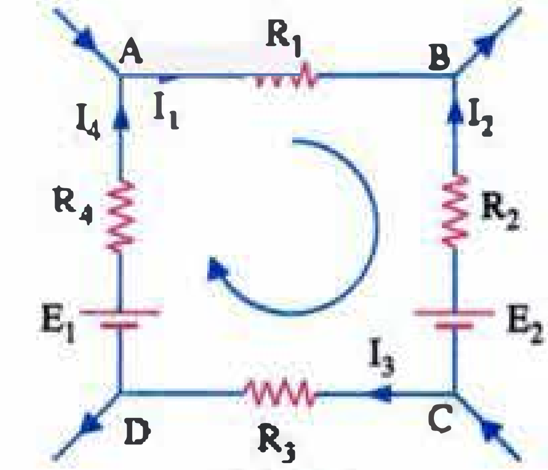


Fig. 3.2

Hence, according to KVL,

$$-I_1R_1 + I_2R_2 - E_2 - I_3R_3 + E_1 - I_4R_4 = 0$$

or $$-I_1R_1 + I_2R_2 - I_3R_3 - I_4R_4 = E_2 - E_1 \quad \text{or} \quad I_1R_1 - I_2R_2 + I_3R_3 + I_4R_4 = E_1 - E_2$$

3.5. Assumed Direction of Current Flow

In applying Kirchhoff's laws to electrical or electronic networks, one is often faced with the tricky question of assuming proper direction of current flow through different branches of the network. However, the matter is quite simple because one is at full liberty to choose either clockwise or anticlockwise direction. If the assumed direction of current does not happen to be the actual direction, then on solving the question, this current would be found to have minus sign. If the answer is positive, then assumed direction is the correct direction of current flow.

Example 3.1. *Using Kirchhoff's laws, calculate the branch currents in the network of Fig. 3.3.*

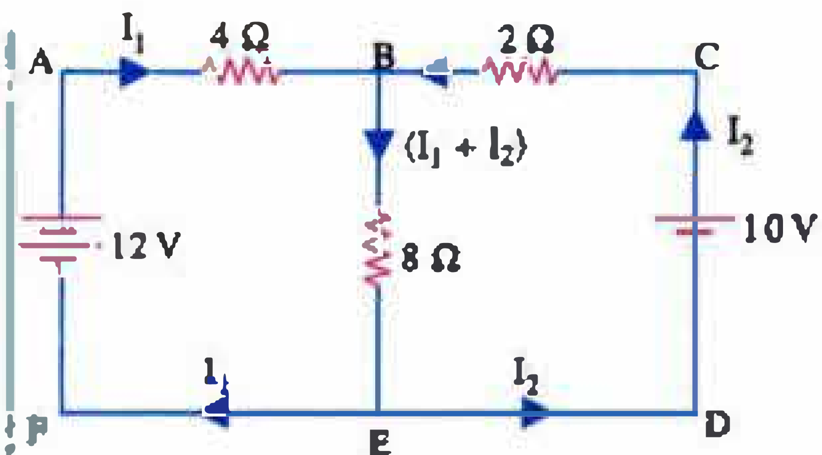


Fig. 3.3

Solution. As shown in the figure, we have taken currents I_1 and I_2 as *originating* from the *positive* terminals of the batteries. However, it is not always essential to do so because a stronger battery can drive current *into* one with lower emf *i.e.,* it can charge it. We will consider the following two closed loops :

(i) Loop ABEFA

Starting from point A and going clockwise round the loop, we have

$$-4I_1 - 8(I_1 + I_2) + 12 = 0 \quad \text{or} \quad 3I_1 + 2I_2 = 3 \quad \text{...(i)}$$

(ii) Loop BCDEB

Starting from point B and again going clockwise round the loop, we get

$$+2I_2 - 10 + 8(I_1 + I_2) = 0 \quad \text{or} \quad 4I_1 + 5I_2 = 5 \quad \text{...(ii)}$$

Multiplying Eq. (*i*) by 5 and Eq. (*ii*) by 2 and substracting one from the other, we get

$$15I_1 - 8I_1 = 15 - 10 \quad \text{or} \quad 7I_1 = 5 \quad \therefore I_1 = 5/7 \text{ A}$$

Substituting this value either in Eq. (*i*) or (*ii*), say, Eq. (*i*), we have

$$3 \times (5/7) + 2I_2 = 3 \quad \text{or} \quad I_2 = 3/7 \text{ A}$$

* We could as well choose to go along anticlockwise direction.

Since these have come out to be positive, it means that their assumed directions are the actual directions.

$$\text{Current through branch } BE = I_1 + I_2 = \frac{5}{7} + \frac{3}{7} = 1\frac{1}{7} \text{ A}$$

Example 3.2. *In the grounded-emitter transistor amplifier circuit of Fig. 3.4, calculate the base current I_B and collector current I_C.*

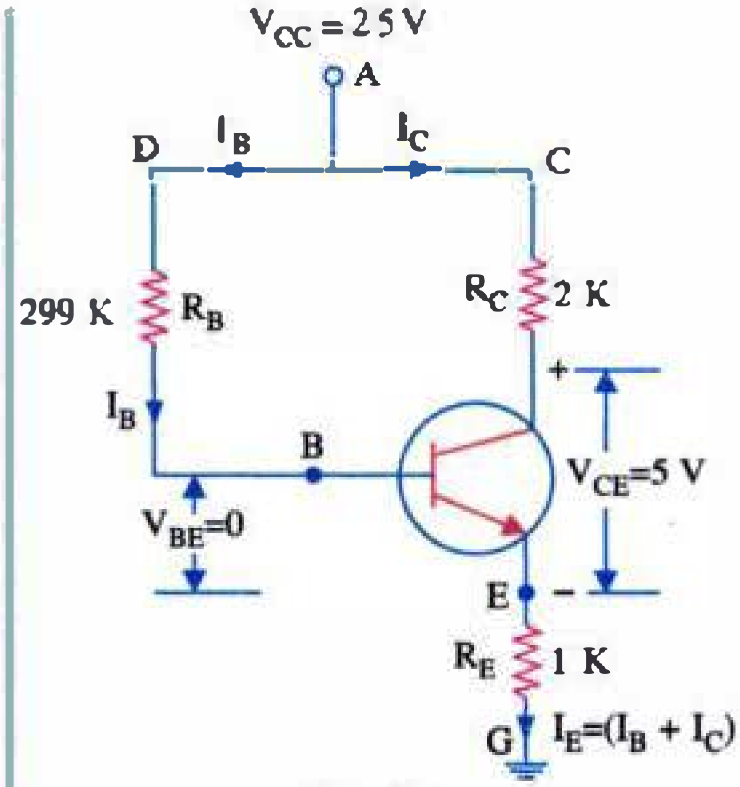


Fig. 3.4

Solution. We will consider two loops : base-current loop ADBEGA and collector-current loop ACBEGA.

Loop ADBEGA

As we move down from the positive terminal A of collector supply battery V_{CC}*,

(*i*) we first get $I_B R_B$. It would be taken negative because we are moving *alongwith* the curent *i.e.*, downstream.

(*ii*) then we meet V_{BE} which also would be taken –ve because we are going from its positive end to negative end.

(*iii*) next, we meet $I_E R_E = (I_B + I_C) R_E$ drop which will be taken as negative since we again are going downstream.

(*iv*) finally, we go from ground G (where –ve battery terminal is supposed to be connected) to positive battery terminal A. Hence, battery EMF of V_{CC} = 25 V would be taken positive.

Applying KVL to the loop, we get

$$-I_B R_B - V_{BE} - I_E R_E + V_{CC} = 0$$

or $$-299 I_B - 0 - 1(I_B + I_C) + 25 = 0$$

or $$300 I_B + I_C = 25 \qquad ...(i)$$

Since resistances are in kilohms, we are taking I_B and I_C to be in milliamperes so that their product gives volts (Art. 2.4).

Loop ACBEGA

$$-2 I_C - 5 - 1(I_B + I_C) + 25 = 0 \quad \text{or} \quad I_B + 3 I_C = 20 \qquad ...(ii)$$

Solving for I_B and I_C from Eq. (*i*) and (*ii*), we get,

$$I_C = 5975/899 = 6.64 \text{ mA}; \qquad I_B = 0.08 \text{ mA} = 80 \mu\text{A}$$

CONVENTIONAL PROBLEMS

1. Use Kirchhoff's laws to find the magnitude and direction of current flow through the 10 Ω resistor of Fig. 3.5. **[1/23 A from A to B]**

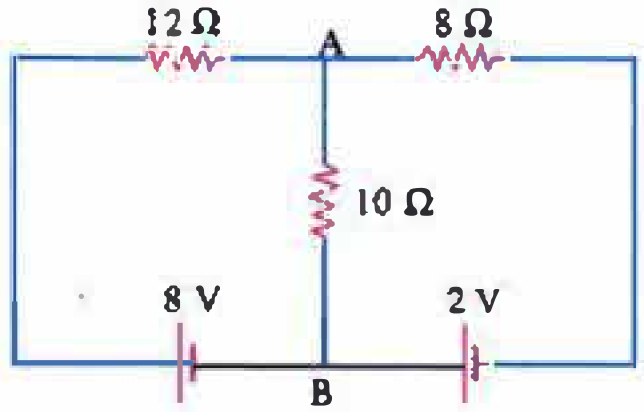


Fig. 3.5

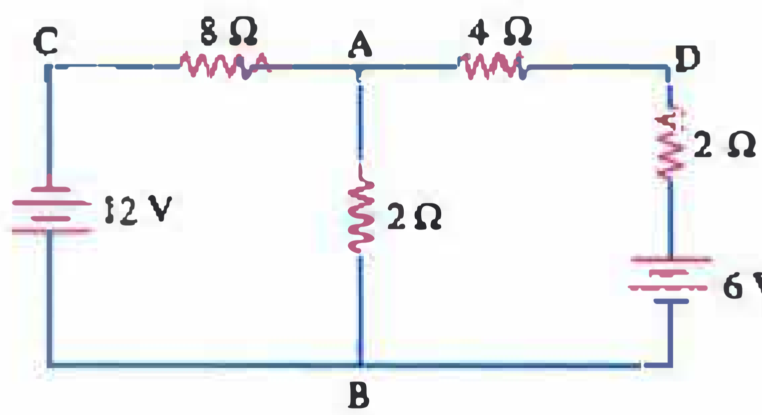


Fig. 3.6

* Please remember that in an NPN transistor, base is positive w.r.t. emitter (Art. 18.2).

2. With the help of Kirchhoff's laws, calculate the magnitude and direction of current flowing through branches *AC*, *AB* and *AD* of the circuit shown in Fig. 3.6.
What would be the potentials of points *A*, *C*, *D* and *E* if point *B* is grounded?

[$I_{AC} = 27/19$ A; $I_{BA} = 6/19$ A; $I_{DA} = 21/19$ A;
$V_A = -12/19$ V; $V_C = -12$ V; $V_E = +6$ V; $V_D = +72/19$ V]

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word (s) or numerical value (s).

1. The two Kirchhoff's laws are : current law and .... law.
2. According to KCL, in any network, the .... sum of currents meeting at a junction is zero.
3. Generally, currents entering a junction in a network are taken as .... a those leaving it as ....
4. According to KVL, algebraic sum of all *IR* drops and EMFs in any closed loop in a network is ....
5. Generally, rise in voltage is considered .... whereas fall is taken as ....
6. The algebraic sign of *IR* drop depends on the .... of current flow through the connected resistor.

B. Answer True or False

1. In a circuit, the sum of all EMFs around a mesh or a closed loop must always equal zero.
2. Kirchhoff's laws are true for all electronic circuits.
3. Input currents at a junction in a network of conductors equal the output currents at that junction.
4. While applying Kirchhoff's laws to networks, one is at full liberty to assume the directions of flow of various branch currents.

C. Multiple Choice Items

1. According to KCL as applied to a junction in a network of conductors
   (*a*) total sum of currents meeting at the junction is zero
   (*b*) no current can leave the junction without some current entering it
   (*c*) net current flow at the junction is positive
   (*d*) algebraic sum of the currents meeting at the junction is zero
2. Kirchhoff's voltage law is concerned with
   (*a*) *IR* drops
   (*b*) battery EMFs
   (*c*) junction voltages
   (*d*) both (*a*) and (*b*)
3. According to KVL, the algebraic sum of all *IR* drops and EMFs in any closed loop of a network is always
   (*a*) zero
   (*b*) positive
   (*c*) negative
   (*d*) greater than unity
4. According to the commonly-used sign convention for voltages
   (*a*) a fall in voltage is considered positive
   (*b*) a rise in voltage is considered positive
   (*c*) *IR* drop is taken as negative
   (*d*) battery EMFs are taken as positive
5. The algebraic sign of an *IR* drop is primarily dependent upon the
   (*a*) amount of current flowing through it
   (*b*) value of *R*
   (*c*) direction of current flowing through it
   (*d*) battery connection
6. While applying Kirchhoff's laws to electronic circuits, assumed direction of current flow must be
   (*a*) clockwise
   (*b*) from left to right
   (*c*) anticlockwise
   (*d*) either (*a*) or (*b*)

ANSWERS

A. Fill in the blanks

1. voltage 2. algebraic 3. positive, negative 4. zero 5. positive, negative 6. direction

B. True or False

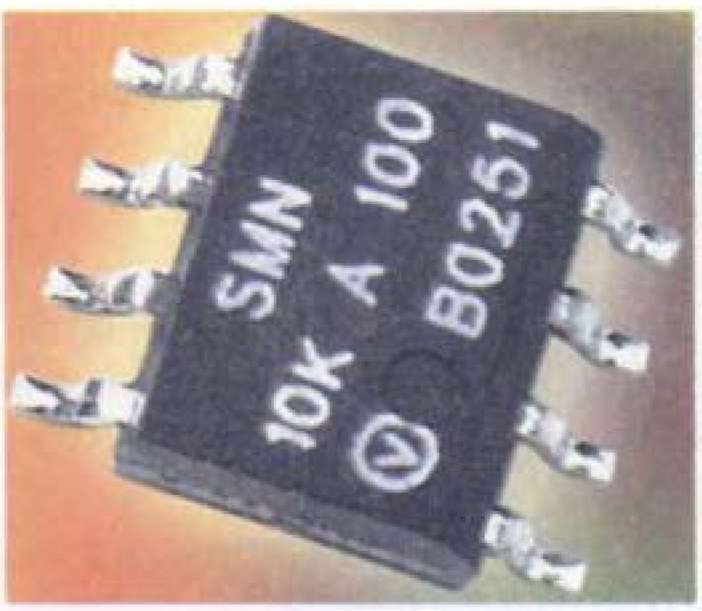
1. *F* 2. *T* 3. *T* 4. *T*

C. Multiple Choice Items

1. *d* 2. *d* 3. *a* 4. *b* 5. *c* 6. *d*

CHAPTER 4

Network Theorems



4.1. General

As we know, a network is just a combination of various components such as resistors etc., interconnected in all sorts of manner. Most of these networks cannot be solved merely by applying laws of series and parallel circuits. Of course, Kirchhoff's laws can always be used. But often it makes the solution quite long and laborious. Hence, various network theorems have been developed which provide very short and time-saving methods to solve these complicated circuits. The reason is that such theorems enable us to convert the given complicated network into a much simpler one which can then be easily solved by only applying the rules of series and parallel circuits. We will discuss the following network theorems which find wide application in electronic and transmission circuits :

1. Superposition Theorem
2. Thevenin's Theorem
3. Norton's Theorem
4. Maximum Power Transfer Theorem

Though we will consider only dc networks in this chapter, these theorems are applicable to ac networks as well.

4.2. Superposition Theorem

According to this theorem, if there are a number of voltage or current sources acting simultaneously in a network, then each source can be treated as if it acts independently of the others.

Hence, we can calculate the effect of one source at a time and then superimpose *i.e.*, algebraically add the results of all the other sources.

Following steps are taken while applying this theorem to the solution of networks which contain more than one voltage or current source :

1. First, all sources except the one under consideration are removed. While removing these voltage sources, their internal resistances (if any) are left behind. While removing current sources, they are replaced by an open circuit since their internal resistance (by definition) is infinite (Art. 4.4).

2. Next, currents in various resistors and their voltage drops due to this single source are calculated.

3. This process is repeated for other sources taken one at a time.

4. Finally, *algebraic* sum of currents and voltage drops over a resistor due to different sources is taken. It gives the actual value of current and voltage drop in that resistor or component.

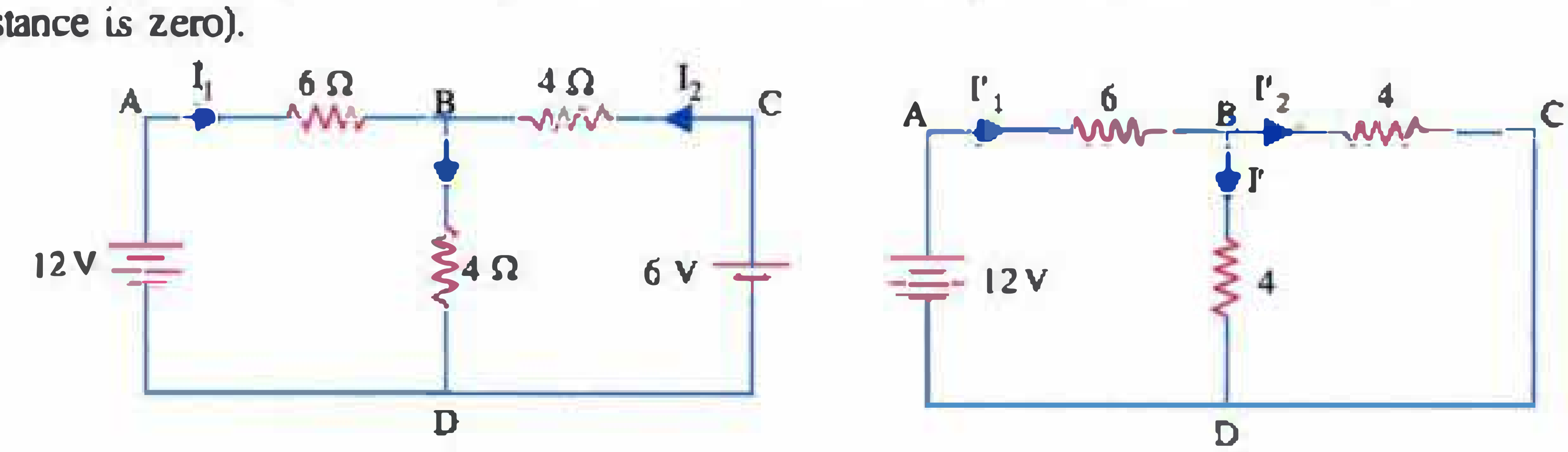
Example 4.1. *Using Superposition theorem, calculate current in each branch of the network shown in Fig. 4.1 (a).*

Solution. We will find two sets of branch currents : one when 6 V battery is not there and the other, when 12 V battery is not there. Let the different branch currents be I_1, I_2 and I as shown in Fig 4.1 (*a*). In Fig. 4.1 (*b*), 6 V battery has been removed and then replaced by short- circuit (since its internal resistance is zero). Various branch currents are as under :

R_{BD} = 4 1 4 = 2 Ω. Hence, total circuit resistance is = 6 + 2 = 8 Ω. Therefore, I_1' = 12/8 1.5A. At point *B*, this current divides equally into two parts.

$$I_1' = 0.75 \text{ A and } I_2' = 0.75 \text{ A}$$

In Fig. 4.2 (*a*) 12 V battery has been removed and replaced by short circuit (since its internal resistance is zero).

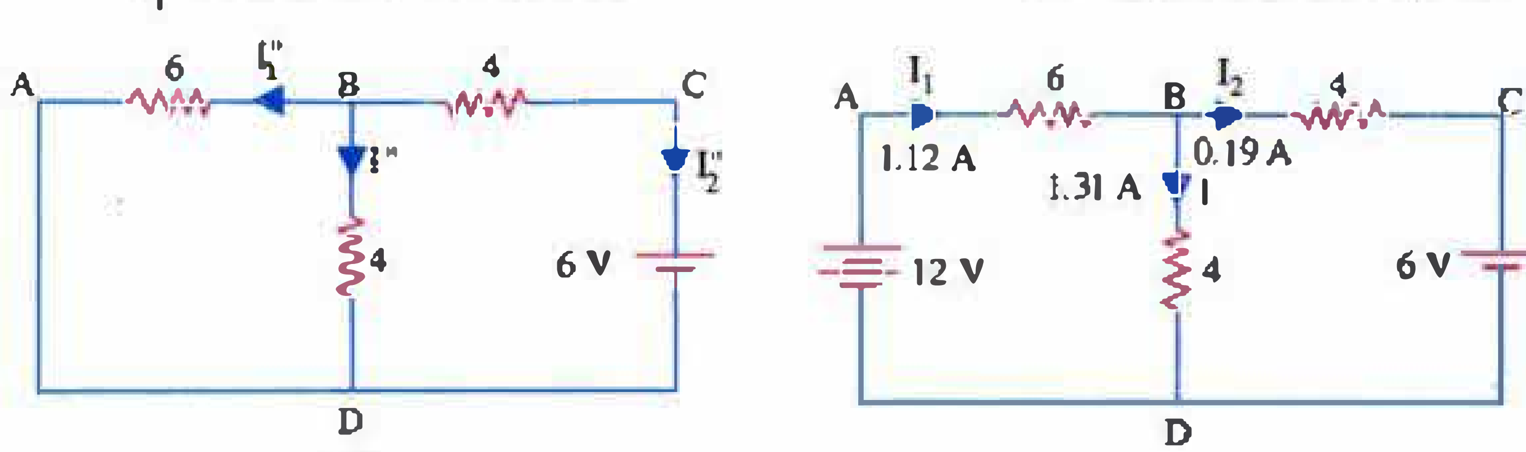


(*a*) (*b*)

Fig. 4.1

Here, R_{BD} = 6 1 4 = 2.4 Ω, total resistance, R = 4 + 2.4 = 6.4 Ω. Hence, I_2'' = 6/6.4 = 0.94 A. This current divides at point *B* in the inverse ratio of the resistances of the two parallel paths.

I_1'' = 0.94 × 4/10 = 0.38 A; I'' = 0.94 × 6/10 = 0.56 A



(*a*) (*b*)

Fig. 4.2

If we combine the results of Fig. 4.1 (*b*) and 4.2 (*a*), we get,

$$I_1 = I''_1 - I'_1 = 1.5 - 0.38 = \mathbf{1.12\ A}$$
$$I_2 = I''_2 - I'_2 = 0.94 - 0.75 = \mathbf{0.19\ A}$$
$$I = I' + I'' = 0.75 + 0.56 = \mathbf{1.31\ A}$$

Actual currents are shown in Fig. 4.2 (*b*).

Example 4.2. *The circuit of Fig. 4.3 (a) is excited by two voltage sources of zero internal resistances. Use Superposition Principle to find current flowing through the common resistance R_3 and voltage drop across it.*

Solution. Of course, it is understood in Fig. 4.3 (*a*) that negative terminal of each voltage source is grounded.

We will first replace V_2 by short-circuit and then V_1.

V_2 short-circuited

When V_2 is shorted, circuit becomes as shown in Fig. 4.3 (*b*) which further simplifies to that shown in Fig. 4.3 (*c*).

$I_1 = 20/(6+4) = 2$ A

$V_{R4} = 6 \times 2 = 12$ V

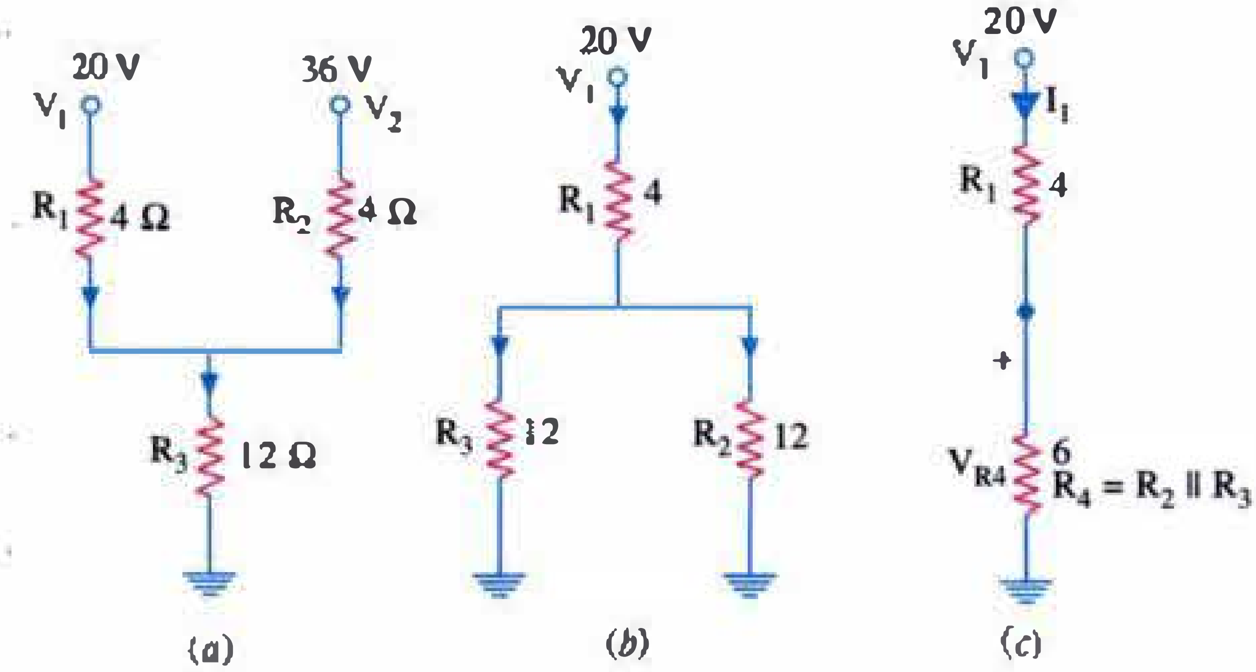


Fig. 4.3

V_1 short-circuited

Now, when source V_1 is shorted out leaving behind only V_2, the circuit becomes as shown in Fig. 4.4 (*a*) which further reduces to that shown in Fig. 4.4 (*b*).

$I_2 = 36/15 = 2.4$ A ; $V_{R5} = 3 \times 2.4 = 7.2$ V

Drop across R_3 due to both sources V_1 and V_2

$= 12 + 7.2 = \mathbf{19.2\ V}$

Current through $R_3 = \dfrac{19.2}{12} = \mathbf{1.6\ A}$

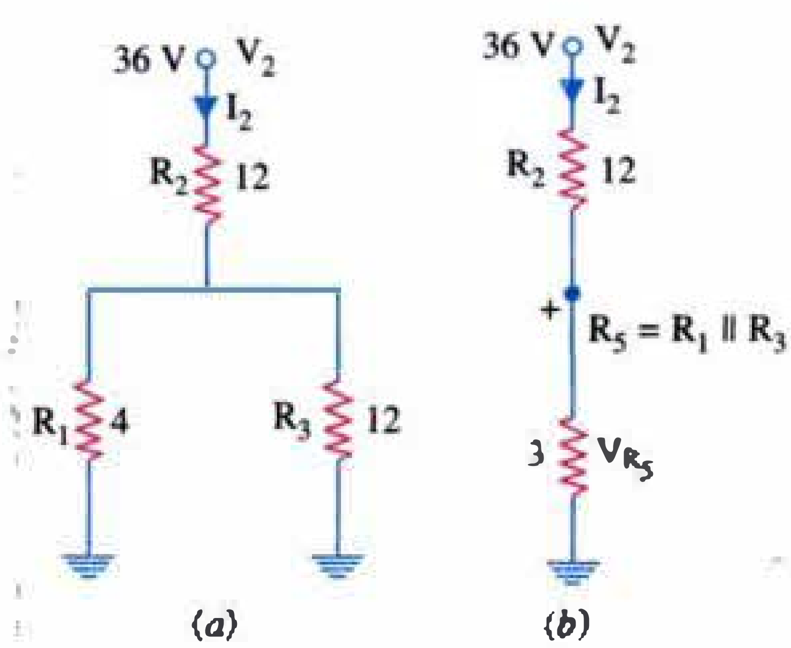


Fig. 4.4

4.3. Ideal Constant-Voltage Source

It is that voltage source or generator whose output voltage remains absolutely constant whatever the change in load current. Such a voltage source must possess *zero internal resistance so that internal voltage drop in the source is zero.* In that case, output voltage

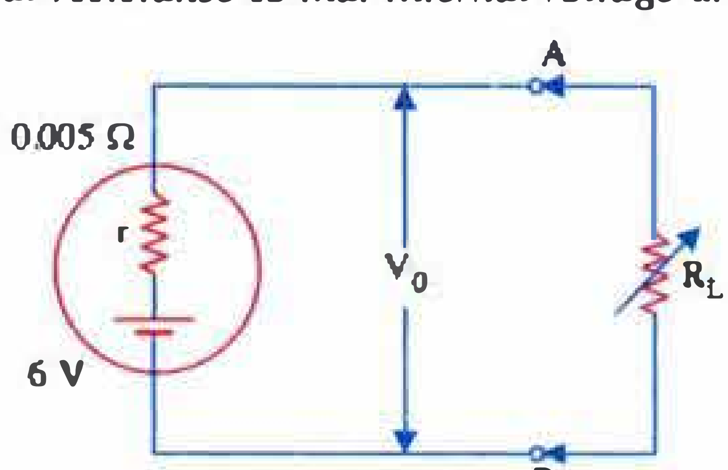


Fig. 4.5

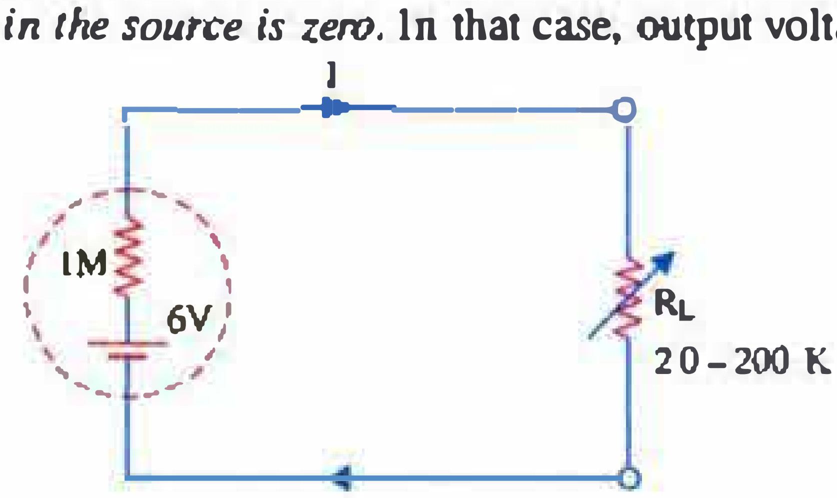


Fig. 4.6

provided by the source would remain *constant irrespective of the amount of current drawn from it.* In practice, none such ideal constant-voltage source can be obtained. However, smaller the internal resistance r of a voltage source, closer it comes to an ideal source described above.

Suppose, a 6 V battery has an internal resistance of 0.005 Ω (Fig. 4.5). When it supplies no current *i.e.*, it is on no-load, $V_0 = 6$ V *i.e.*, output voltage provided by it at its output terminals A and B is 6 V. If load current increases to 100 A, internal drop = 100 × 0.005 = 0.5 V. Hence, $V_0 = 6 - 0.5$ = 5.5 V.

Obviously, an output voltage of 5.5 – 6 V can be considered constant as compared to wide variation in load current from 0 A to 100 A.

4.4. Ideal Constant-Current Source

It is that voltage source whose internal resistance is infinity. In practice, it is approached by a source which possesses very high resistance as compared to that of the external load resistance. As shown in Fig. 4.6, let the 6 V battery have an internal resistance of 1 MΩ and let load resistance vary from 20 K to 200 K. The current supplied by the source varies from 6/1.02 = 5.9 µA to 6/1.2 = 5 µA. As seen, even when load resistance increases 10 times, current decreases by 0.9 µA. Hence, the source can be considered, for all practical purposes, to be a constant-current source.

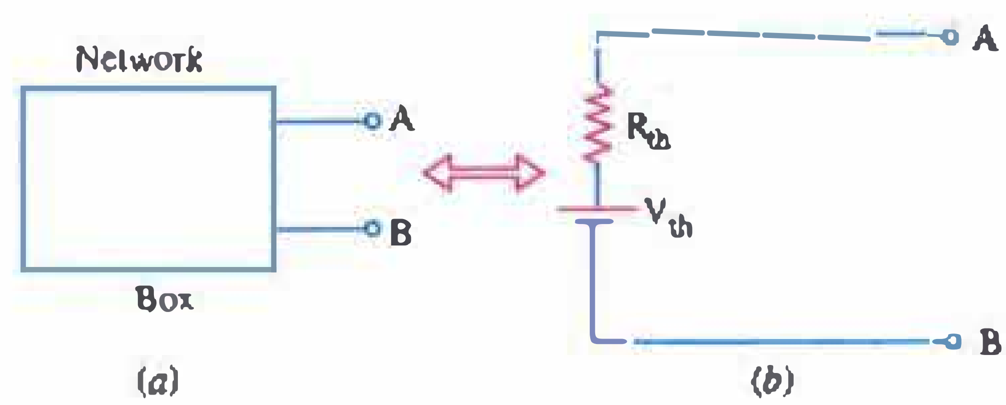


Fig. 4.7

4.5. Thevenin's Theorem

This theorem is very useful when we desire to know the amount of power, current or voltage drop in a particular component of a given circuit. With the help of this theorem, a normally complex circuit can be simplified to a *series* circuit* consisting of

(*i*) an ideal voltage source and

(*ii*) a resistance connected in series with it.

In Fig. 4.7 (*a*), imagine that the block contains a network connected to its terminals A and B. According to this theorem, the *entire* network connected to A and B can be replaced by a single voltage source V_{th} connected in series with a single resistance R_{th} across the same terminals.

V_{th} is actually the open-circuit voltage (V_{oc}) existing across terminals A and B and R_{th} is the resistance of the network as looked into or viewed back from the same terminals with all sources removed leaving behind their internal resistance if any. Actually, an ohmmeter connected across A and B would read this resistance.

4.6. How to Thevenize a Circuit ?

Suppose we are asked to find current through the 15 Ω load resistor in Fig. 5.8 by a using Thevenin's theorem. The procedure for Thevenizing this circuit would be as follows :

1. First Step. Disconnect the 15 Ω resistor from terminals A and B (incidentally, don't throw it away, we will need it again towards the end !).

* Norton's theorem reduces it to a parallel circuit (Art. 5.7).

2. Second Step. With load terminals A and B open, calculate the open-circuit voltage (V_{oc}) between them by any convenient method.

In the present case, V_{oc} is equal to the voltage drop across 12 Ω resistor because point A is at the same potential as point C.

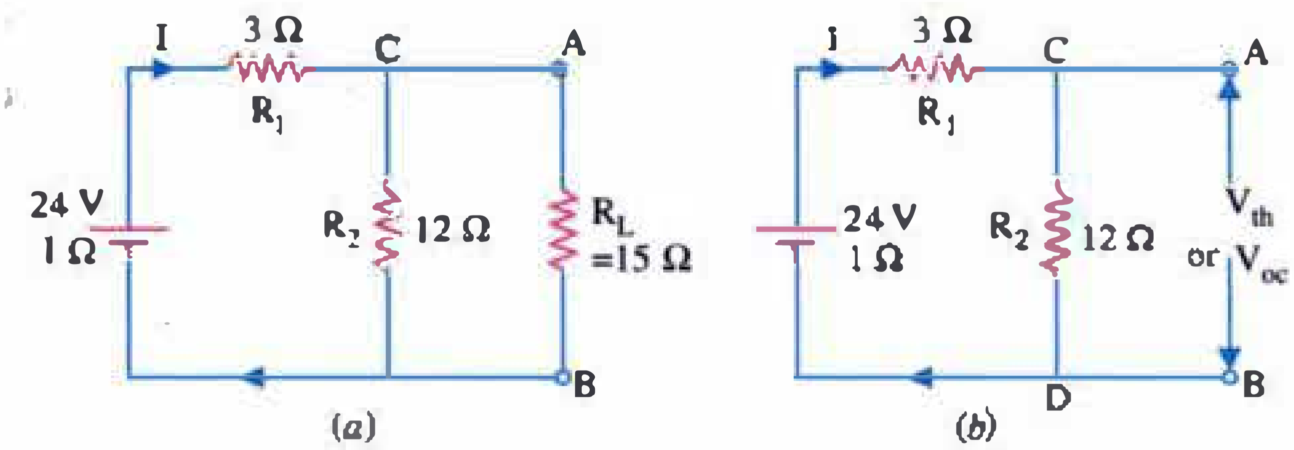


Fig. 4.8

$$V_{CD} = V_{AB} = V_{OC} = IR_2$$

Now, $\quad I = 24/(1 + 3 + 12) = 1.5$ A

$\therefore \quad V_{CC} = 1.5 \times 12 = 18$ V

It is also called Thevenin voltage V_{th}.

3. Third Step. Now, remove the 24 V battery leaving behind its internal resistance of 1 Ω as shown in Fig. 4.9 (a).

When looked into from open-circuit terminals A and B, the circuit consists of two parallel paths : one having a resistance of 12 Ω and the other of (3 + 1) = 4 Ω. Hence, equivalent resistance of the network when viewed back from these two terminals is

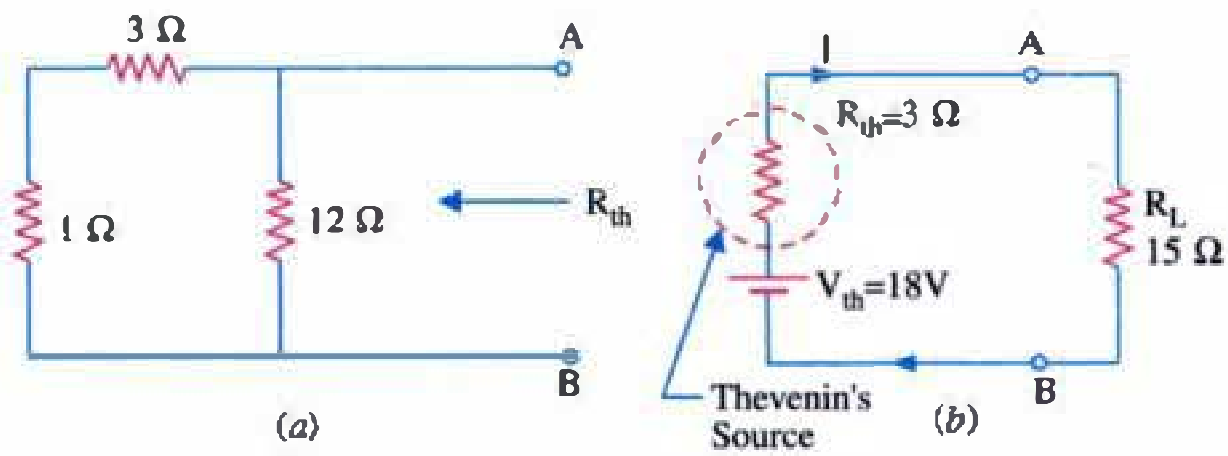


Fig. 4.9

$$= \frac{12 \times 4}{(12 + 4)} = 3 \ \Omega$$

It is also called Thevenin resistance R_{th}.

Consequently, as seen from points A and B, the given network can be reduced to a single voltage source (called Thevenin's source) of 18 V whose internal resistance R_{th} equals 3 Ω [Fig. 4.9 (b)].

4. Fourth step. Finally, connect back the load resistor to the terminals A and B thereby giving a simple series circuit shown in Fig. 4.9 (b). Finding current I through R_L should be no problem now.

$$I = 18/(3 + 15) = 1 \text{ A}$$

Example 4.3. *Apply Thevenin's theorem to find current through the 12 Ω resistor of the circuit shown in Fig. 4.10 (a).*

Solution. In Fig. 4.10 (b), point A is at the same potential as point C since there is no current through the 4 Ω resistor and hence no drop across it.

$$V_{th} = V_{CD} = I \times 6$$

Now $\quad I = 36/(3 + 6) = 4$ A

$\therefore \quad V_{th} = 4 \times 6 = 24$ V

Since, 36 V battery has no internal resistance, it has been replaced by a short-circuit in Fig. 4.11 (a).

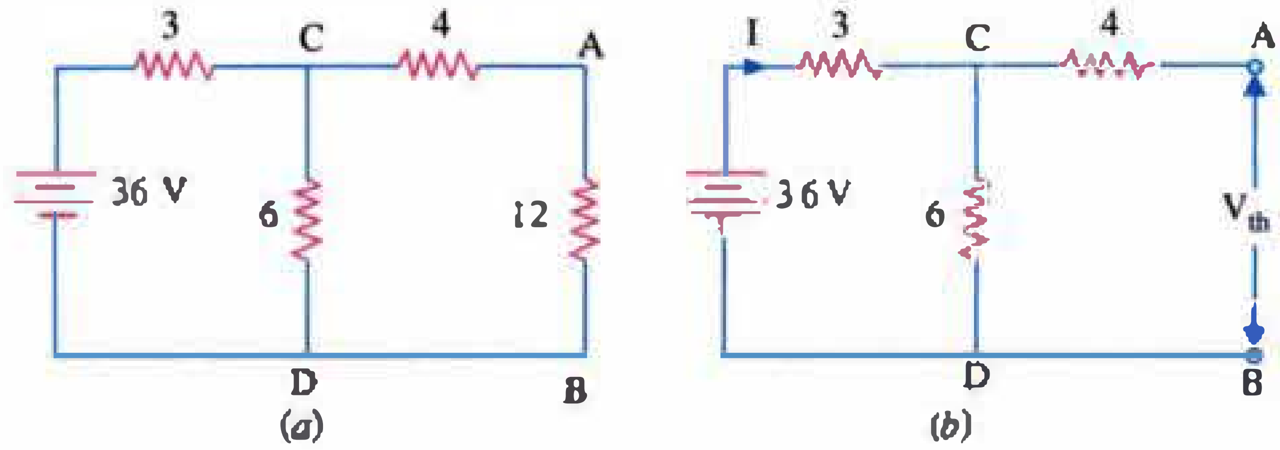


Fig. 4.10

$$R_{th} = 4 + \frac{6 \times 3}{(6+3)} = 6\ \Omega$$

Having found the Thevenin's source, the 12 Ω resistor is connected back in series with this source as shown in Fig. 4.11 (*b*). Current flowing through it is

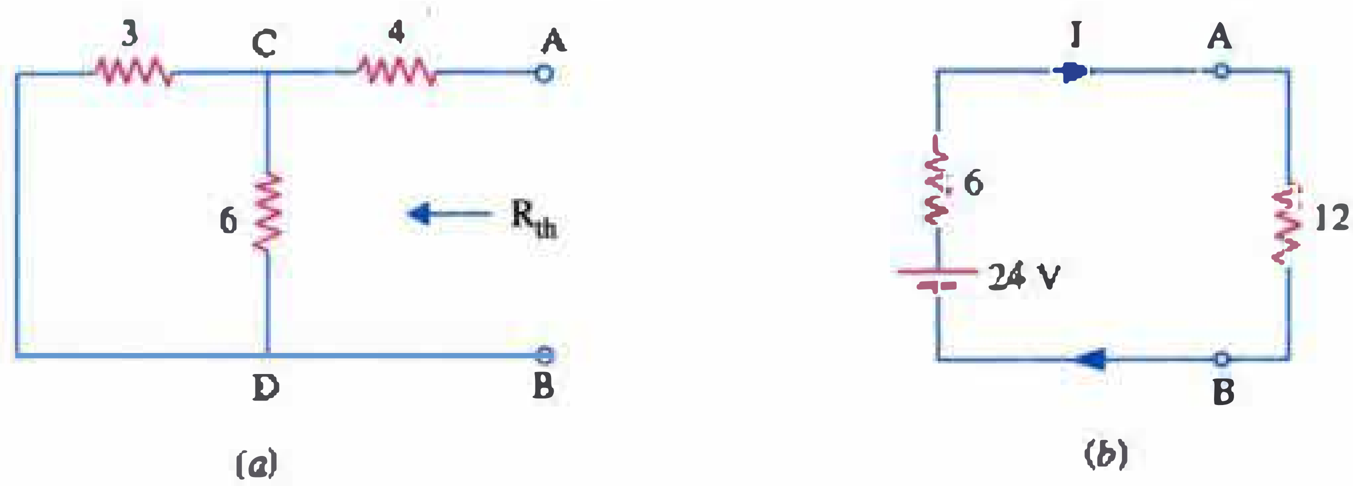


Fig. 4.11

$I = 24/(12 + 6) = \mathbf{1.33\ A}$ — from A to B

Example 4.4. *Using Thevenin's theorem, calculate the current through the 4 K resistor of Fig. 4.12 (a).*

Solution. If we remove 4 K resistor, circuit becomes as shown in Fig. 4.12 (*b*). As seen, full current of 10 mA passes through 2 K resistor producing a drop of 10 × 2 = 20 V. Hence, $V_B = 20$ V. w.r.t. ground. Now, 12 V battery is connected in series with two resistors 3 K and 6 K which form a voltage divider circuit.

V_A = drop across 6 K resistor*
$= 12 \times 6/(6 + 3) = +8$ V — w.r.t. ground

p.d. between points *A* and *B* is

$V_{th} = 20 - 8 = 12$ V — with *B* at a higher potential

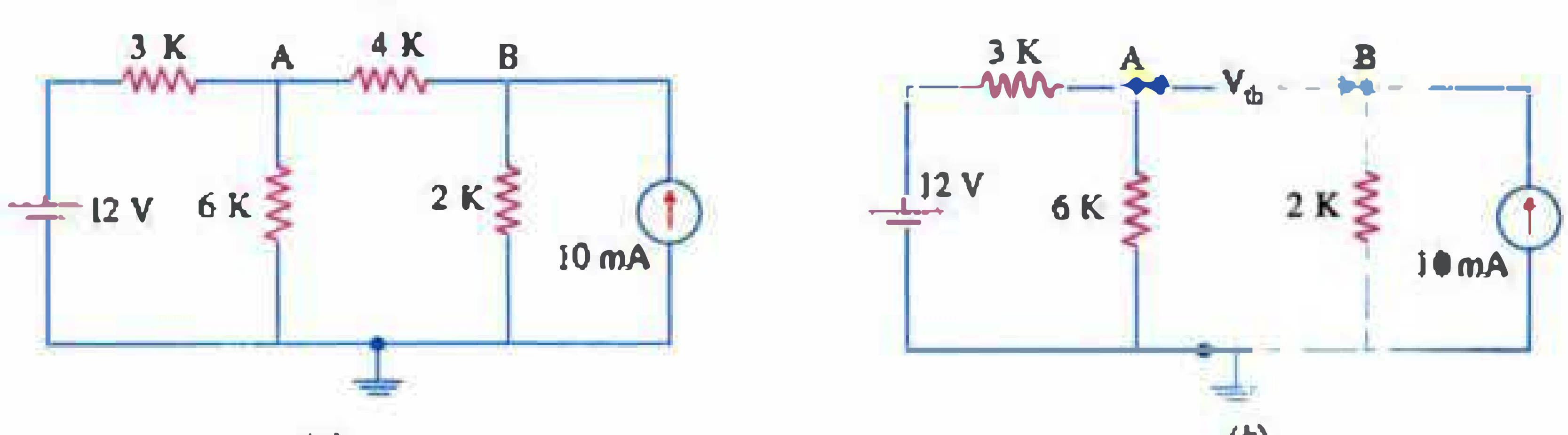
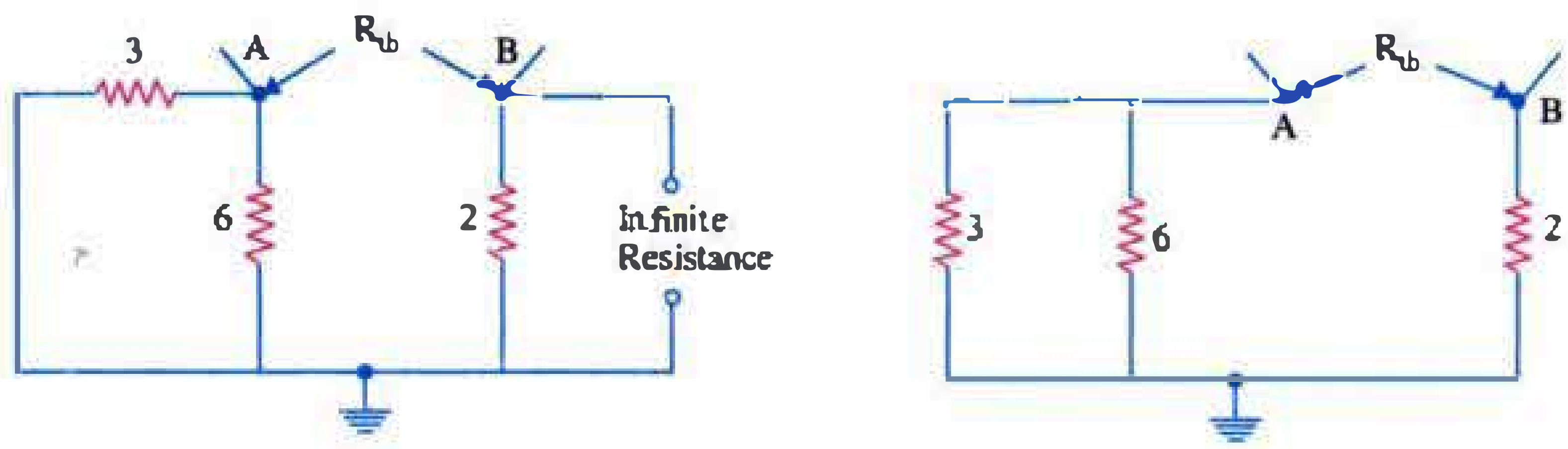


Fig. 4.12

* Or $V_A = 12$ —drop across 3 K resistor.

Now, we will find R_{th} *i.e.*, resistance of the network as looked back into the open-circuited terminals *A* and *B*. For this purpose, we will replace both the voltage and current sources. Since voltage source has no internal resistance, it would be replaced by a short-circuit *i.e.*, zero resistance. However, current source would be removed and replaced by an infinite resistance *i.e.*, an 'open' (Art. 4.4). In that case, the circuit becomes as shown in Fig. 4.13 (*a*).



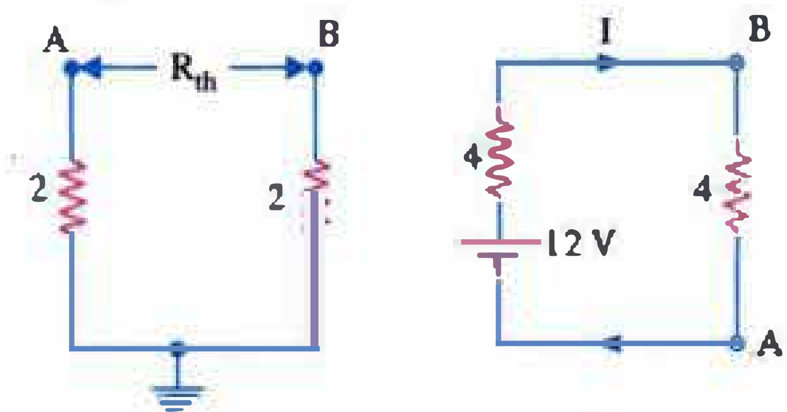
(*a*) (*b*)

Fig. 4.13

As seen from Fig. 4.13 and Fig. 4.14 (*a*), the value of $R_{th} = 2 + 2 = 4\ \Omega$.

Hence, Thevenin source has a voltage of 12 V and an internal resistance of 4 Ω as shown in Fig. 4.14 (*b*).

$\therefore \qquad I = 12/(4 + 4) = \mathbf{1.5\ A}$



(*a*) (*b*)

Fig. 4.14

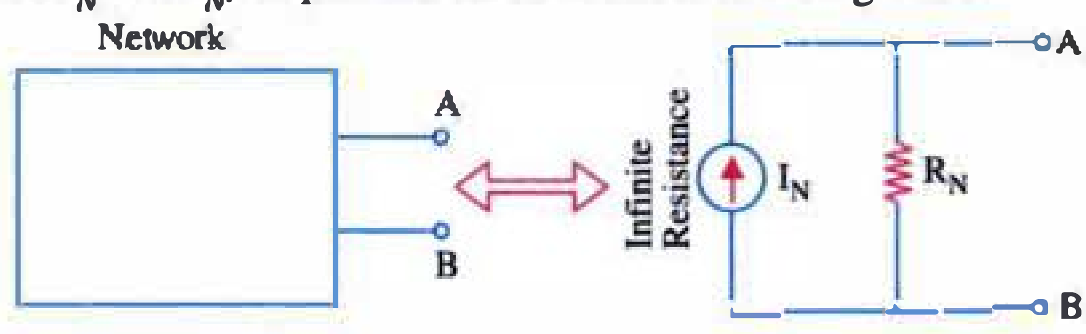
4.7. Norton's Theorem

This theorem is used where it is easier to simplify a network in terms of currents instead of voltage. This theorem reduces a normally complicated network to a simple *parallel* circuit consisting of

(*a*) an ideal current source I_N of infinite internal resistance and

(*b*) a resistance R_N (or conductance $G_N = I/R_N$) in parallel with it as shown in Fig. 4.15.

Here, I_N is the current which would flow through a short circuit placed across terminals *A* and *B*. R_N is the circuit resistance looking back from the open *A*-*B* terminals. These terminals are not short-circuited for finding R_N but are 'open' as for calculating R_{th} for Thevenin's Theorem*.



(*a*) (*b*)

Fig. 4.15

4.8. How to Nortonise a Given Circuit

Suppose we want to Nortonise the circuit shown in Fig. 4.16 (*a*) *i.e.*, we want to find Norton's equivalent of this circuit between terminals *A* and *B*.

The different steps are as under :

I. First Step. Put a short across terminals *A* and *B* [Fig. 4.16 (*b*)]. As seen, it results in shorting out 12 Ω resistor as

* In fact, this resistance is the same both for Thevenin and Norton equivalent circuits. In Norton's case, this resistor is in parallel with the current source whereas in Thevenin's case, it is in series with V_{th} (Art. 4.6).

shown separately in Fig. 4.16 (*c*).

$\therefore \qquad I_{SC} = 24/4 = 6$ A

This current is usually called Norton current I_N.

2. Second Step. Remove the short from terminals *A* and *B* so that they are again open.

3. Third Step. Remove the battery and replace it by its internal resistance which, in the present case, is zero. The resistance R_N of the circuit as viewed back or looked into from open terminals *A* and *B* is

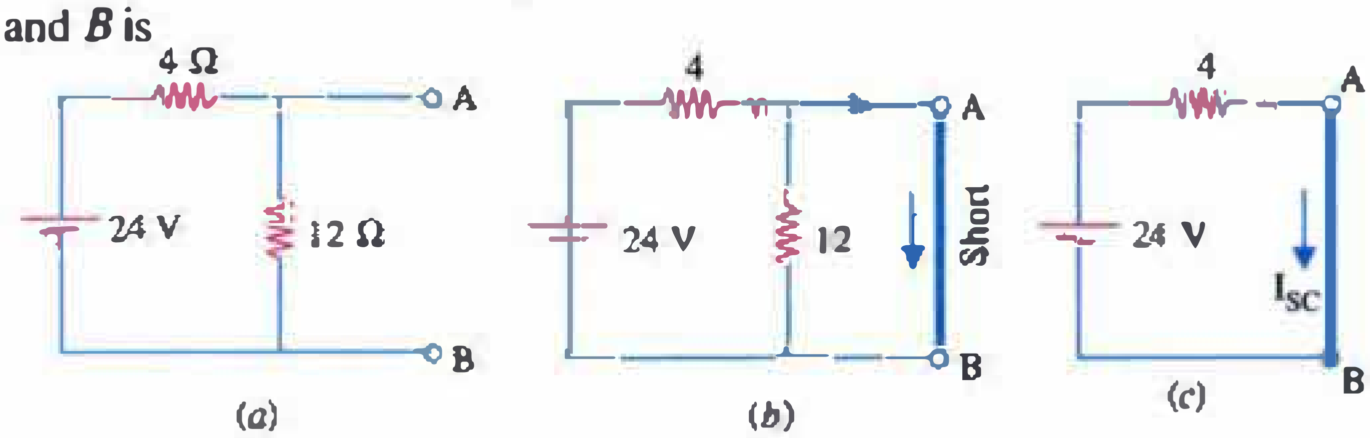


Fig. 4.16

$R_N = 12 \| 4 = 3\ \Omega$

Hence, Norton's equivalent of the given circuit in Fig. 4.16 (*a*) becomes that shown in Fig. 4.17 (*b*). It consists of a 6 A constant-current source (of infinite resistance) in parallel with a 3 Ω resistance.

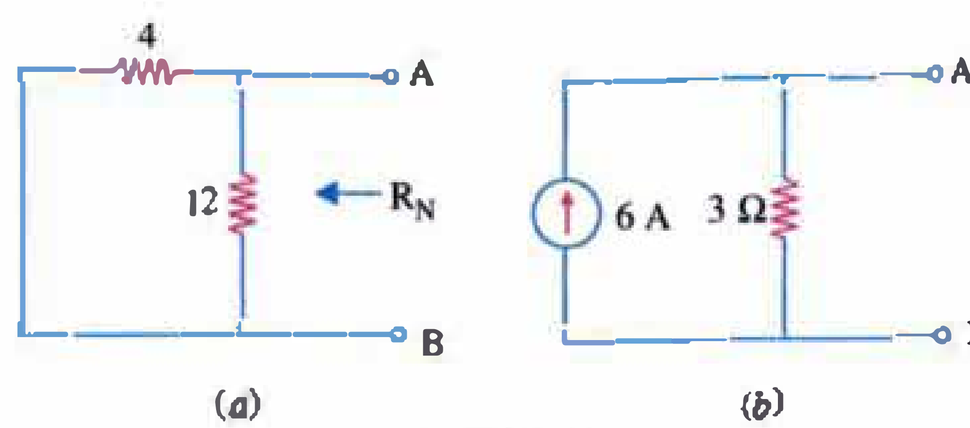


Fig. 4.17

Example 4.5. *Using Norton's theorem, calculate the current flowing through the 12 Ω resistor in Fig. 4.18 (a).*

Solution. It is the same circuit as shown in Fig. 4.10 (*a*) and solved earlier with the help of Thevenin's theorem (Example 4.3). When applying Norton's theorem, the procedure would be as under :

1. First Step. Remove 12 Ω resistor from terminals *A* and *B* and then put a short-circuit across them as shown in Fig. 4.18 (*b*).

The current passing through 4 Ω resistor is also the short-circuit current I_{SC} (also written as I_N). For finding this current, we have first to find *I* by simplifying the circuit. As seen, total circuit resistance

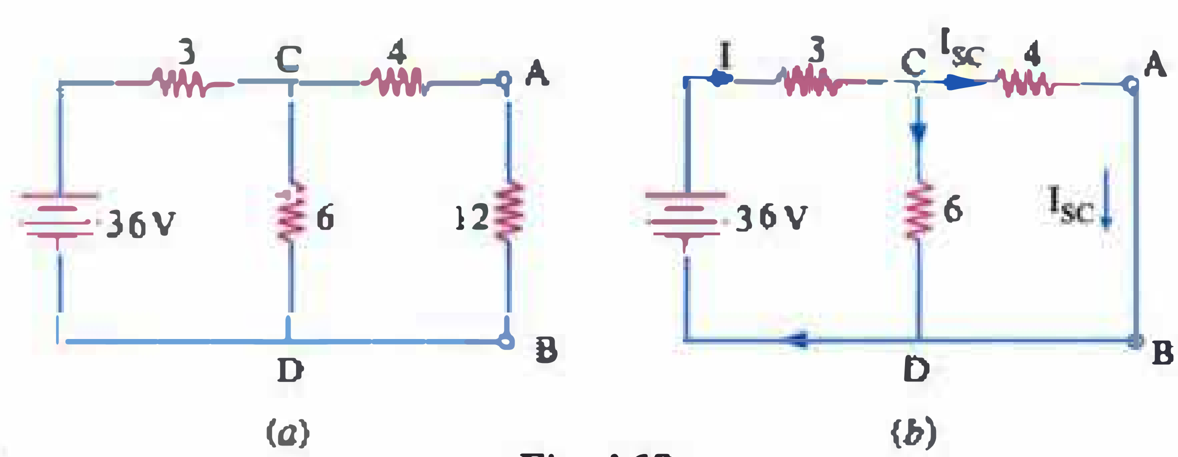


Fig. 4.18

$= 3 + 6 \| 4 = 3 + 2.4$

$= 5.4\ \Omega$

$I = 36/5.4 = 20/3$ A

This current divides at point *C* into two unequal parts.

$$I_{SC} = \frac{20}{3} \times \frac{6}{10} = 4 \text{ A}$$

2. Second Step. Remove the short circuit, thereby leaving terminals *A* and *B* open. Also remove the battery. Since its internal resistance is zero, it is replaced by a resistanceless piece of connecting wire thereby closing the circuit [Fig. 4.19 (*a*)]. The resistance R_N of the circuit as viewed from terminals *A* and *B* is

$= 4 + 6 \parallel 3 = 6\ \Omega$

Hence, the Norton's equivalent of the given circuit is as shown in Fig. 4.19 (*b*). Load current I_L through 12 Ω resistor can be found by using the Proportional Current Formula (Art. 2.16).

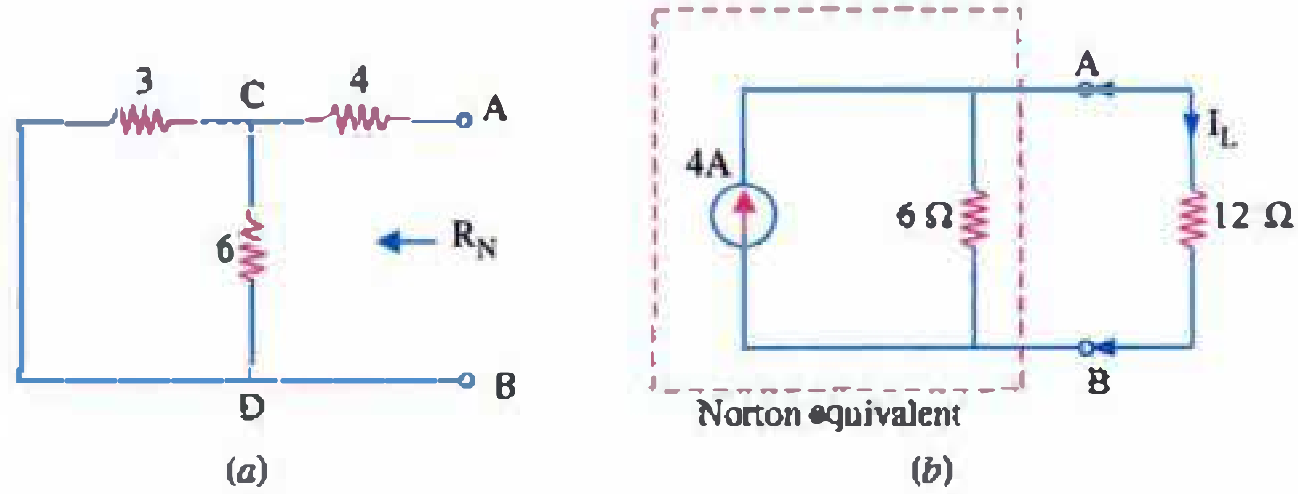


Fig. 4.19

$$\therefore \quad I_L = 4 \times \frac{6}{(6+12)} = 1.33\ \text{A} \qquad \text{— from A and B.}$$

It is the same value as found in Example 4.3 earlier.

Example 4.6. *The circuit of Fig. 4.20 (a) is excited by a voltage source and a current source. Using Norton's theorem, calculate current through the 6 Ω resistor.*

Solution. Io Fig. 4.20 (*b*), 6 Ω resistor has been removed and a short placed across terminals *A* and *B*. Short-circuit current I_{SC} (or I_N) is

= current from voltage source + current of current-source.

$$= \frac{60}{20} + 12 = 15\ \text{A}$$

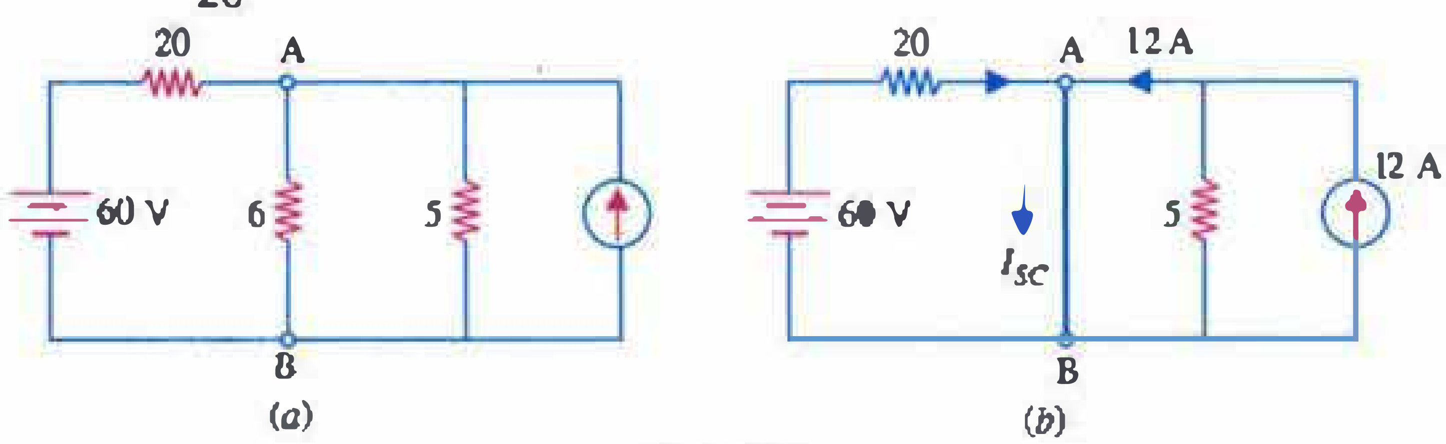


Fig. 4.20

It should be noted that short across *AB* also shorts out 5 Ω resistor. Hence, all the 12 A current passes through short-circuit and none through 4 Ω resistor.

In Fig. 4.21 (*a*), 'short' has been removed leaving terminals *A* and *B* open. Voltage source has been replaced by a connecting wire of zero resistance (since its internal resistance is zero). Current source has been replaced by an 'open' since it has infinite resistance.

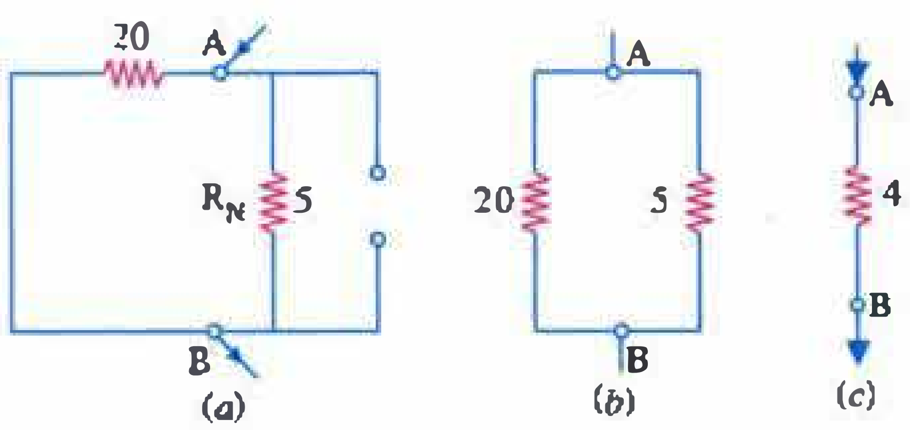


Fig. 4.21

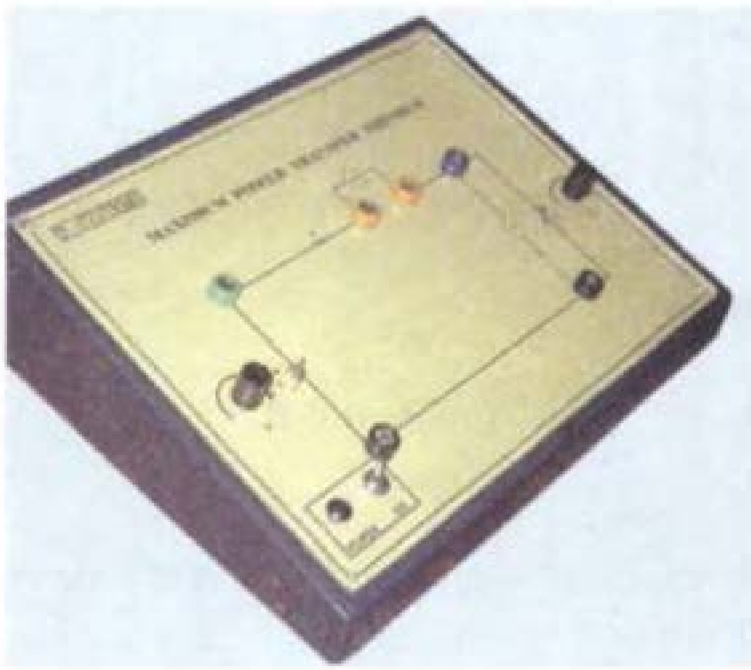
When looked into the circuit from terminals *A* and *B*, there are two parallel paths between points *A* and *B* having resistances of 20 Ω and 5 Ω. Their combined resistance, as seen from Fig. 4.21 (*c*) is $= 20 \parallel 5 = 4\ \Omega$. Hence, $R_N = 4\ \Omega$.

The Norton's equivalent of the original circuit with respect to terminals *A* and *B* is shown in Fig. 4.22. The 6 Ω resistance has been connected back to the terminals *A* and *B* (from where it was removed earlier).

$$I_L = 15 \times 4/(6+4) = 6\ \text{A}$$

4.9. Maximum Power Transfer Theorem

This theorem is very useful for analysing electronic and communication networks where main consideration is to transfer maximum power to the load irrespective of the efficiency. Its application to power transmission and distribution networks is limited because in their case, the goal is high efficiency and not maximum power transfer.



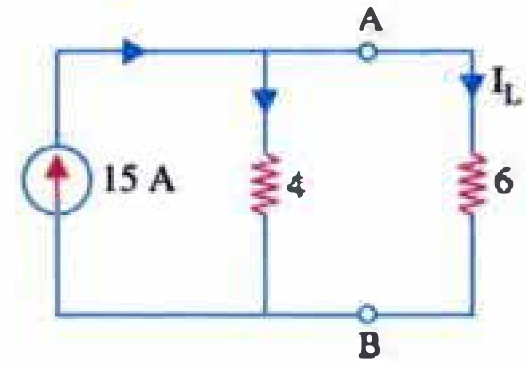


Fig. 4.22

When applied to dc networks, this theorem states that *a resistive load will abstract maximum power from a network when its resistance equals the resistance of the network as viewed from the output terminals with all voltage and current sources removed leaving behind their internal resistances if any.*

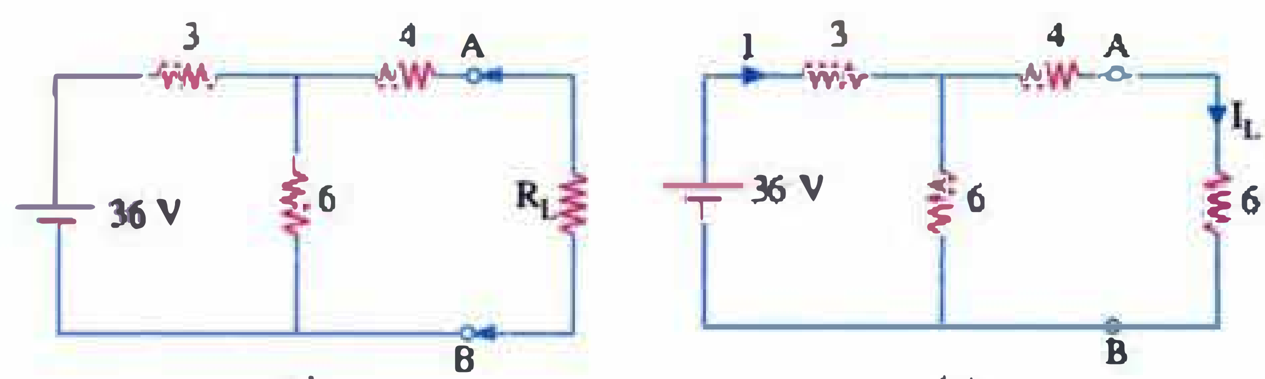
Example 4.7. *In the circuit of Fig. 4.23, find the value of load resistance R_L to be connected across terminals A and B which would abstract maximum power from the circuit. Also find the value of this maximum power.*

Solution. As seen, resistance of the network as viewed back from terminals A and B (with battery removed) is

$= 4 + 6 \| 3 = 6\,\Omega$

Hence, R_L should be equal to **6 Ω**.

Let us now find power developed in R_L for which purpose we have to find I_L.



(a) (b)

Fig. 4.23

In Fig. 4.23 (*b*),

Total circuit resistance $= 3 + 6 \| 10$

$= 27/4\ \Omega$

$\therefore \quad I = 3 \div 27/4 = 16/3$ A

$$\therefore \quad I_L = \frac{16}{3} \times \frac{6}{(6+10)} = 2 \text{ A}$$

Max. power possible in load resistance $R_L = 2^2 \times 6 = 24$ W

It can be verified that if we have any other value of R_L, power drawn will be less than 24W.

CONVENTIONAL PROBLEMS

1. Use Superposition Principle to find current through 12 Ω resistor of Fig. 4.24. All resistance values are in ohms. **[34/21 A]**

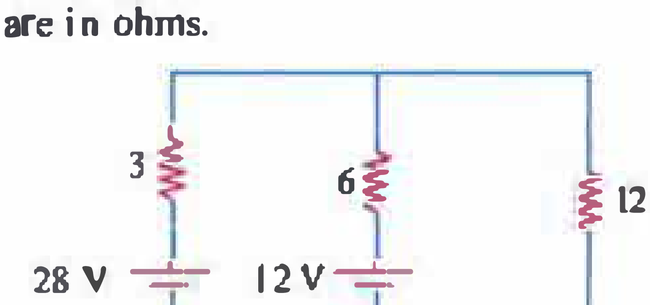


Fig. 4.24

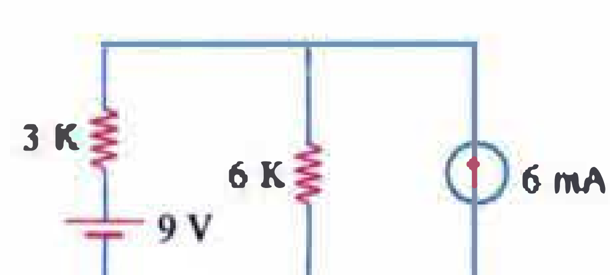


Fig. 4.25

2. Using Superposition Theorem, calculate the current flowing through 6 K resistor of the circuit shown in Fig. 4.25. **[3 mA]**
3. Make use of Thevenin's theorem to find current in the 12 Ω resistor of Fig. 4.26. **[0.6 A]**

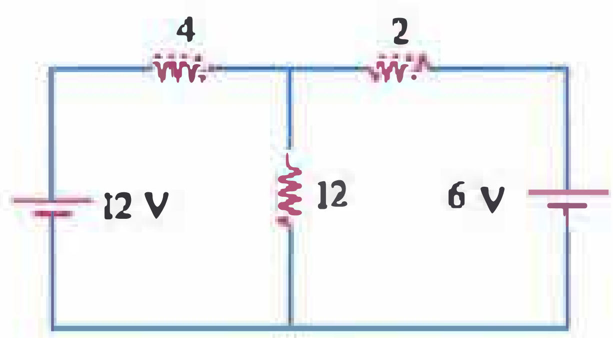


Fig. 4.26

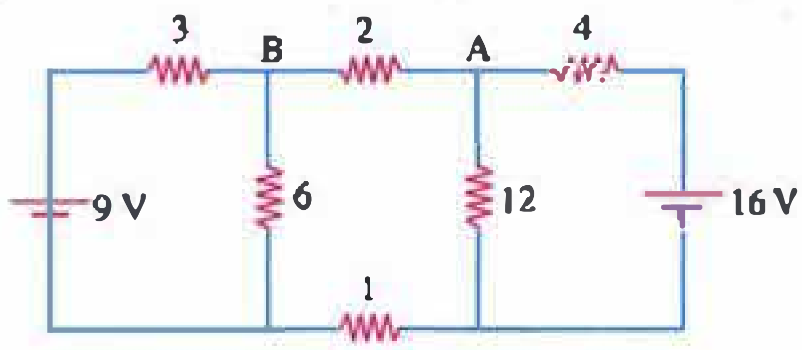


Fig. 4.27

4. In the circuit of Fig. 4.27, use Thevenin's theorem to find the magnitude and direction of flow of current through 2 Ω resistor. **[0.75 A from A to B]**
5. For the circuit of Fig. 4.25, find Norton's equivalent and hence find circuit through the 6 K resistor. **[I_N = 9 mA, R_N = 3 Ω, 3 mA]**
6. What is the Norton equivalent for the circuit shown in Fig. 4.26 ? Use it to find current flowing through 12 Ω resistor. **[I_N = 6 mA, R_N = 4/3 Ω; 0.6 A]**

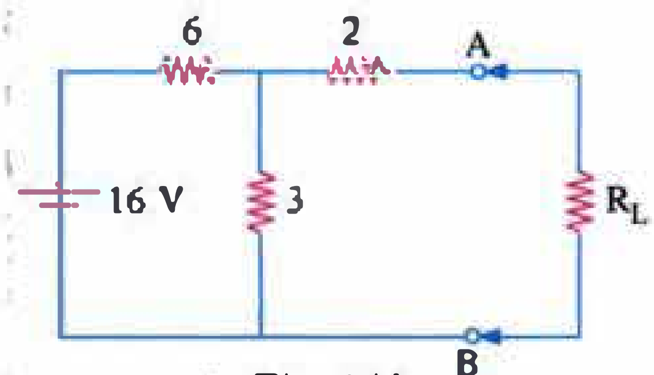


Fig. 4.28

7. According to Maximum Power Transfer Theorem, what should be the value of load resistance R_L to abstract maximum power from the 16 V battery shown in Fig. 4.28 ? What is the value of this power ? **[4 Ω, 16/9 W]**

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word(s) or numerical value (s).

1. While using Superposition Theorem, all voltage sources except one are removed leaving behind their .... resistances if any.
2. An ideal constant-voltage source has .... resistance.
3. An ideal constant-current source has .... resistance.
4. According to Thevenin's theorem, any network with two open terminals can be replaced by a single voltage source V_{th} in .... with a single resistance R_{th}.
5. While finding R_{th}, all voltage sources are removed but not their .... resistances.
6. Norton's equivalent of a circuit consists of a constant-current source and a resistance in .... with it.
7. A load draws maximum power from a circuit when its resistance .... the circuit resistance when viewed back from output terminals.

B. Answer True or False

1. V_{th} is an open-circuit voltage.
2. I_N is an open-circuit current.
3. Superposition principle treats each voltage source as if it acts independently of others in a circuit.
4. A constant-voltage source has infinite resistance.
5. A constant-current source has zero resistance.
6. R_{th} is the same as R_N.

C. Multiple Choice Items

1. According to Superposition theorem as applied to circuits excited by more than one voltage source
   (*a*) current is contributed by each source
   (*b*) all voltage sources sends their currents in the same direction
   (*c*) current in any resistor equals the algebraic sum of currents which each source would send if acting alone
   (*d*) algebraic sum of voltage drops equals the sum of total applied voltage
2. Superposition theorem can be applied only to circuit having .... elements.
   (*a*) non-linear (*b*) passive
   (*c*) linear bilateral (*d*) resistive

3. The Superposition theorem is essentially based on the concept of

(a) duality (b) linearity

(c) reciprocity (d) non-linearity

4. While Thevenizing a circuit between two terminals, V_{th} equals

(a) short-circuit terminal voltage

(b) open-circuit terminal voltage

(c) EMF of the battery nearest to the terminals

(d) net voltage available in the circuit

5. Thevenin resistance R_{th} is found

(a) between any two 'open' terminals

(b) by short-circuiting the given two terminals

(c) by removing voltage sources along with their internal resistances

(d) between same open terminals as for V_{th}

6. Norton's equivalent of a circuit consists of a

(a) constant-current source with a conductance in parallel

(b) constant-current source in series with an infinite resistance

(c) constant-voltage source in parallel with a high resistance

(d) single current source and a single voltage source

7. While calculating R_{th}, constant-current sources in the circuit are

(a) replaced by 'opens'

(b) replaced by 'shorts'

(c) treated in parallel with other voltage sources

(d) converted into equivalent voltage sources

8. The Norton equivalent of a circuit consists of a 2 A current source in parallel with a 4 Ω resistor. Thevenin equivalent of this circuit is a .... volt source in series with a 4 Ω resistor.

(a) 2 (b) 0.5

(c) 6 (d) 8

9. If two identical 3 A, 4 Ω Norton equivalent circuits are connected in parallel with like polarity to like, the combined Norton equivalent circuit is

(a) 6 A, 4 Ω (b) 6 A, 2 Ω

(c) 3 A, 2 Ω (d) 6 A, 8 Ω

10. For abstracting maximum power from any two given terminals of a circuit, the load resistance across the terminals should be

(a) four times the internal resistance of the network

(b) equal to the circuit resistance when viewed back from the two terminals

(c) less than the circuit resistance

(d) greater than the circuit resistance.

ANSWERS

A. Fill in the blanks

1. internal 2. zero 3. infinite 4. series 5. internal
6. parallel 7. equals

B. True or False

1. T 2. F 3. T 4. F 5. F 6. T

C. Multiple Choice Items

1. *c* 2. *c* 3. *b* 4. *b* 5. *d* 6. *a* 7. *a* 8. *d* 9. *d* 10. *b*.

CHAPTER 5

Passive Circuit Elements

1. Resistors
2. Wire-Wound Resistors
3. Carbon Composition Resistors
4. Carbon Film Resistors
5. Cermet Film Resistors
6. Metal Film Resistors
7. Variable Resistors
8. Fusible Resistors
9. Resistor Colour Code
10. Inductor
11. Variable Inductors
12. Inductors in Series
13. Energy Stored in a Magnetic Field
14. Capacitors
15. Capacitor Connected to a Battery
16. Capacitance
17. Variable Capacitors
18. Leakage Resistance
19. Capacitors in Series
20. Two Capacitors in Series
21. Capacitors in Parallel
22. Energy Stored in a Capacitor

5.1. General

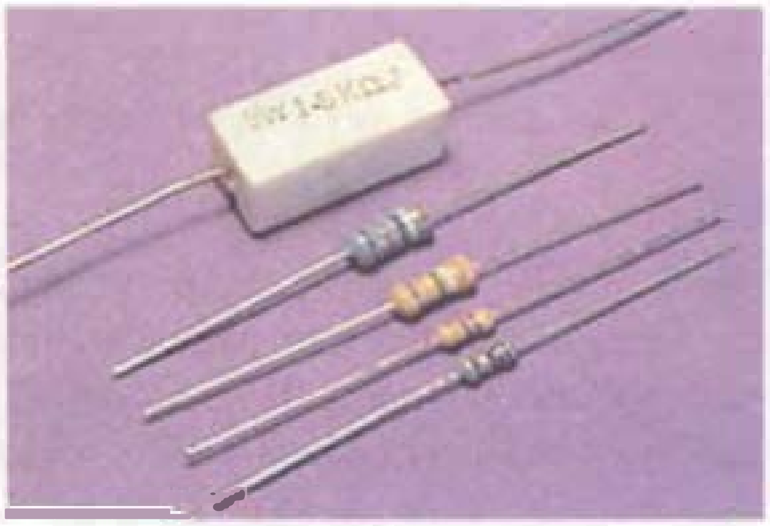
Individual components which make up an electronic circuit are called *elements* or *parameters*. Most commonly-used elements in such circuits are :

1. resistors 2. inductors 3. capacitors

In resistors, current is *directly* proportional to the *applied voltage*. In inductors, voltage required is *directly* proportional to the rate of change of *current* whereas capacitors require current which is *directly* proportional to the rate of change of *voltage*.

5.2. Resistors

A resistor is an electrical component with a known specified value of resistance. It is probably the most common component in all kinds of electronic equipment ranging from a small radio to a colour television receiver. As its name suggests, a resistor *resists* or *opposes* the flow of current through it. Resistance is necessary for any circuit to do useful work. In



Resistors.

fact, without resistance, *every circuit would be a short circuit* !

Some of the common uses of resistors are :

1. to establish proper values of circuit voltages due to *IR* drops
2. to limit current and
3. to provide load

The two main characteristics of a resistor are its resistance and power rating. Resistors can be connected in the circuit in either direction because they have no 'polarity'.

5.3. Resistor Types

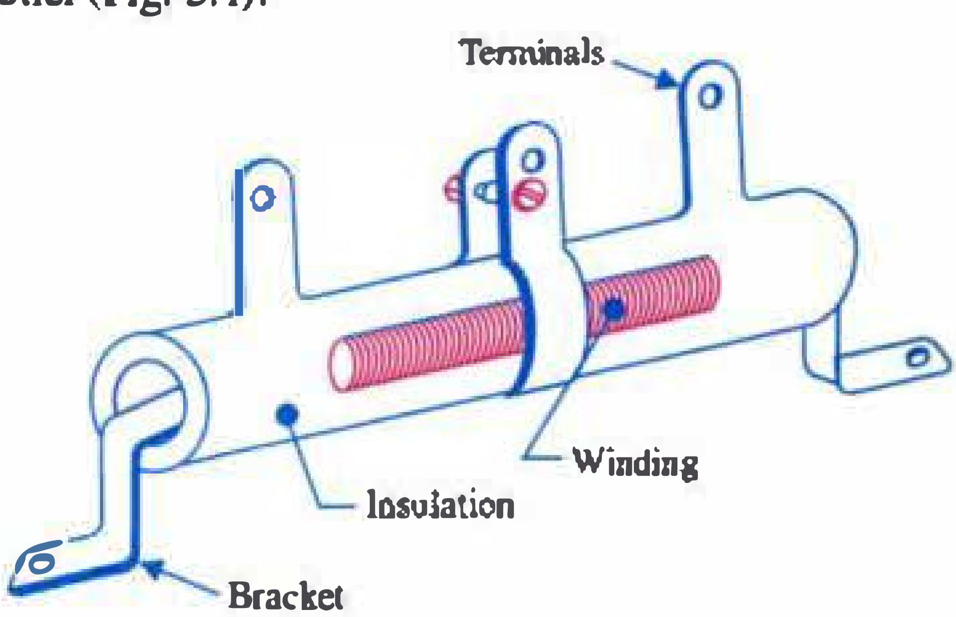
Resistors are mainly of two types and can be either of fixed or variable value.

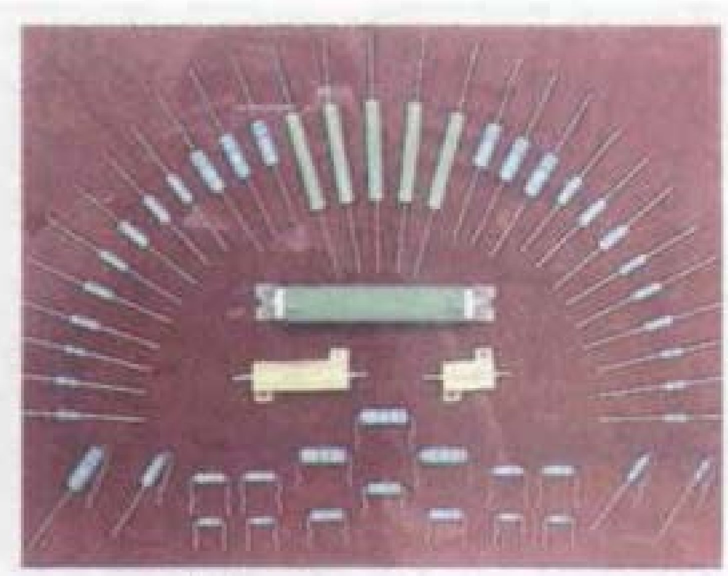
1. wire-wound resistors
2. carbon resistors
   (*a*) carbon-composition type
   (*b*) carbon-film type
   (*c*) cermet-film type

Another type is called metal thin-film resistor.

5.4. Wire-Wound Resistors

They are constructed from a long fine wire (usually nickel-chromium wire) wound on a ceramic core. The length of the wire used and its resistivity determine the resistance of the unit. The wire is bare but the entire assembly is covered or coated with a ceramic material or special vitreous enamel (Fig. 5.1).





Wire wound resistor

Fig. 5.1

Such resistors are generally available in power ratings from 5 W to several hundred watts and resistance values from 1 Ω to 100 K. These can be of either fixed value or variable type.

Wire-wound resistors are used where

(*a*) large power dissipation is necessary
(*b*) precise and stable resistance values are required as for meter shunts and multipliers.

5.5. Carbon Composition Resistors

They are made of finely-divided carbon mixed with a powdered insulating material in suitable proportion. Often, the resistance element is a simple rod of pressed carbon granules which is usually enclosed in a plastic case for insulation and mechanical strength [Fig. 5.2 (*a*)]. The two ends of the carbon resistance element are joined to metal caps with leads of tinned wire for soldering its connections into a circuit.

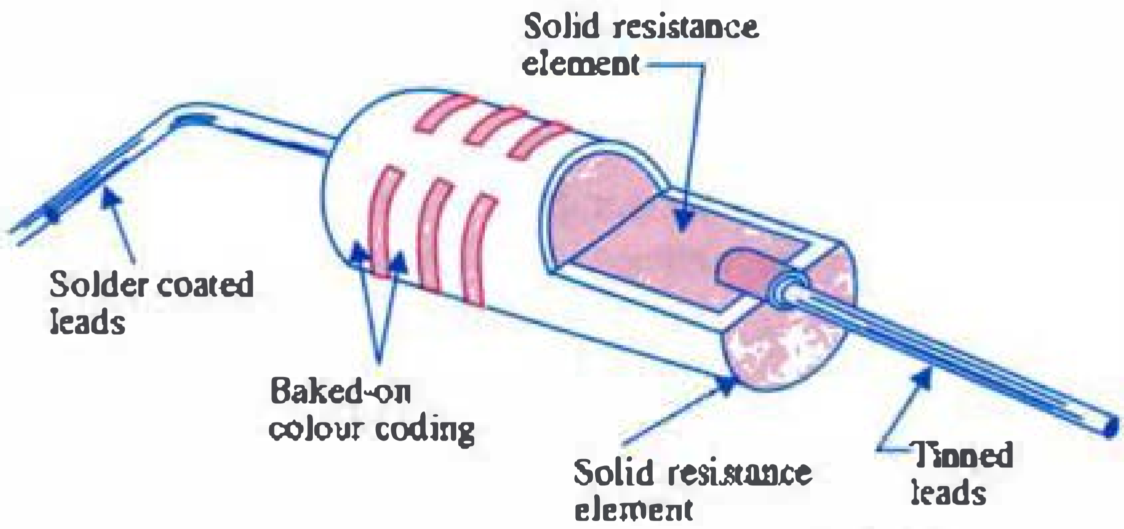


Fig. 5.2


Carbon composition resistors.

Such resistors are available in power ratings of 1/10, 1/8, 1/4, 1/2, 1, 2 watt and in resistance values ranging from 1 Ω to 20 MΩ. Where power dissipation is 2 W or less, such resistors are preferred because they are smaller and cost less. Carbon resistors with power rating of 1 W or less are most common in electronic equipment.

5.6. Carbon Film Resistors

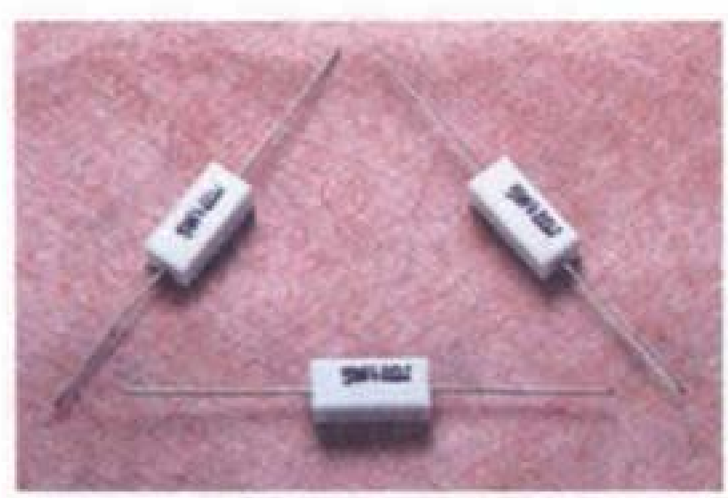
They consist of a high-grade ceramic rod or core (called the substrate) on which is deposited a thin resistive film of carbon. They are cheaper than composition resistors.

5.7. Cermet Film Resistors

They consist of thin carbon coating fired on to a solid ceramic substrate. The main purpose is to have more precise resistance values and greater stability with heat. Very often, they are made in a small square with leads to fit into a printed circuit board (PCB).

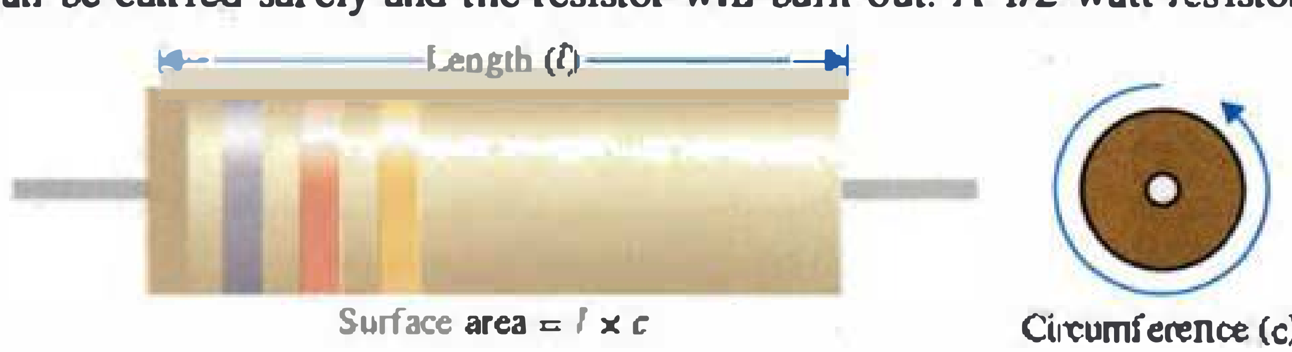
5.8. Metal Film Resistors

They are also referred to as thin-film resistors. They consist of a thin metal coating deposited on a cylindrical insulating support. The high resistance values are due to thinness of the film. Because it is difficult to produce films of uniform thickness, it is not possible to control their resistance values as accurately as in the case of wire-wound resistors. However, such resistors are free of trouble-some inductance effects so common in wire-wound resistors particularly at high frequencies.


Metal oxide film resistors.

5.9. Power Rating

The power rating of a resistor is given by the maximum wattage it can dissipate without excessive heat. Since it is current which produces heat, power rating also gives some indication of the maximum current a resistor can safely carry. If the current exceeds this value, more heat will be produced than can be carried safely and the resistor will burn out. A 1/2 watt resistor, for example, can dissipate 1/2 watt of heat without damage whereas a 1W resistor can throw off twice as much heat. In a circuit, you may substitute 1 watt resistor of same resistance value for a 1/2 watt resistor but not *vice-versa*.



The larger the surface area of a resistor, the more power it can dissipate. The power rating of a resistor is directly related to its surface area.

The physical size of a resistor is no indication of its resistance though it does give some indication of its wattage rating. For a given value of resistance, greater the physical size, higher the power rating.

Also, higher-wattage resistors can operate at higher temperatures. Moreover, a higher power rating allows a higher voltage rating. This rating gives the highest voltage that may be applied across the resistor without internal arcing.

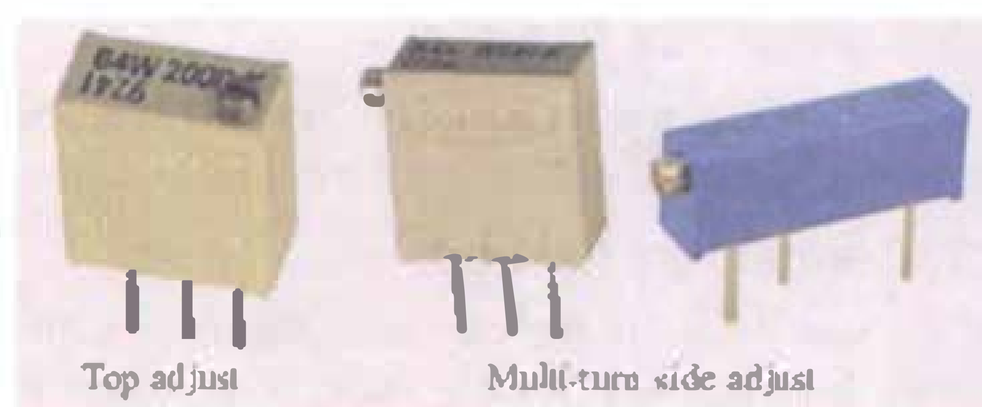
5.10. Value Tolerance

By tolerance is meant the possible variation from the nominal or marked resistance value of a resistor. It means that actual resistance of a resistor may be greater or lesser than its indicated value. All resistors are manufactured and sold with a specified tolerance. For example, a 1000 Ω resistor with a tolerance of 10% will have an actual resistance anywhere between 900 Ω and 1100 Ω *i.e.*, 100 Ω more or less than the rated value.

Carbon-composition resistors have tolerances of ± 5%; ± 10% and ± 20% whereas general-purpose wire-wound resistors usually have a tolerance of ± 5%.

5.11. Variable Resistors

These are the resistors whose resistance can be changed between zero and a certain maximum value. They can be wire wound or carbon type. As shown in Fig. 5.3, the sliding arm has been attached to a shaft which can be rotated in almost a complete circle. As the shaft rotates, the point of



Variable resistors.

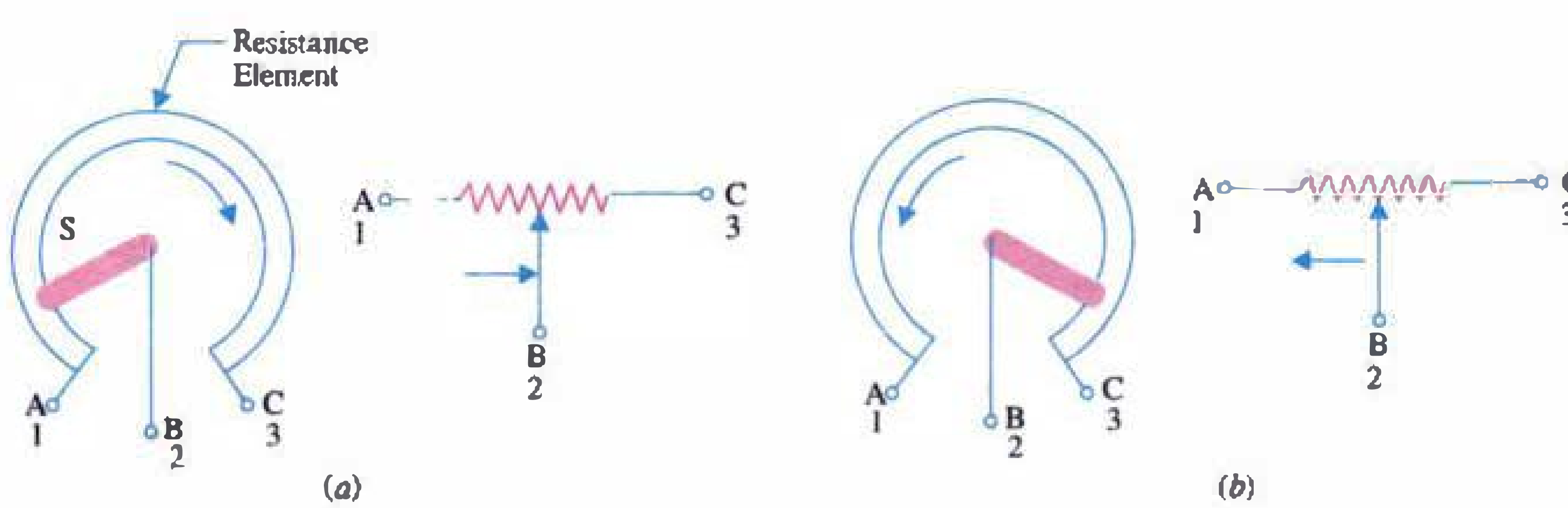


Fig. 5.3

contact of the sliding arm on the circular carbon-composition resistance element changes thus changing the resistance between arm terminal *B* and terminals of the stationary resistance *A C*. In Fig. 5.3 (*a*) as we move the sliding arm, the resistance between *B* and *A* increases whereas that between *B* and *C* decreases. In Fig. 5.3 (*b*), with the rotating of the arm, resistance between *B* and *C* increases whereas that between *B* and *A* decreases.

Carbon variable resistors of power ratings 1/2 W to 2 W and resistances of 1 kΩ to 5 MΩ are commonly available. Such controls are often combined with an OFF-ON switch—a common example being the power OFF-ON switch and volume control of a radio receiver.

5.12. Potentiometers and Rheostats

These are variable resistors either of carbon or wire-wound type often used for controlling voltage and current in a circuit.

(a) Potentiometers

They generally have carbon composition resistance element and are connected across a voltage source. They have *three* terminals, the centre one being connected to the variable arm which is used for varying voltage division in the circuit as shown in Fig. 5.4. By moving the variable arm *B* over the fixed resistance *R* between points *A* and *C*, any part of the input voltage can be tapped off. Since in Fig. 5.4, *B* happens to be at the middle value of *R*, output voltage is half the input voltage.

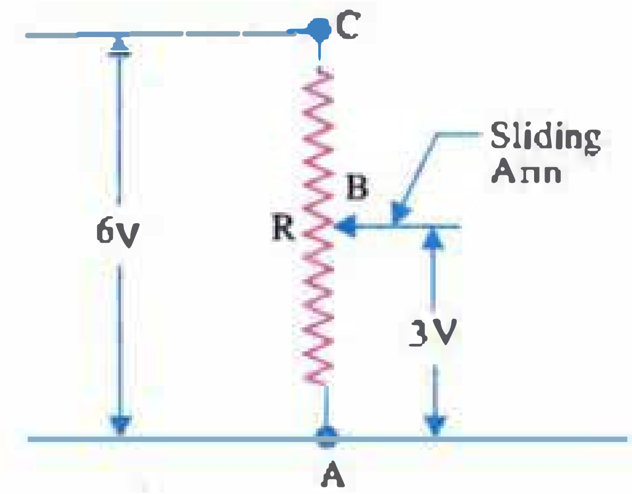


Fig. 5.4

Most variable resistors used in radios are potentiometers meant for controlling volume or tone. When used as a volume control, it picks off a voltage between zero and the full available voltage as shown in Fig. 5.5. By moving *B* up and down, any desired amount of voltage (signal) can be picked up between maximum signal value at point *A* and zero signal value at *C*.

The tone control circuit shown in Fig. 5.6 uses only two terminals on the potentiometer. The resistor allows the capacitor to by-pass to ground either more or less of high frequencies in an audio circuit. When *B* is at point *A*, the capacitor becomes a direct by-pass to ground for higher frequencies in the audio signal. Consequently, radio sound becomes 'bassy'. When *B* is at terminal *C*, it increases the amount of resistance in series with the capacitor. Hence, less amount of high frequencies is by-passed to ground and consequently, there is more trebble in the sound.

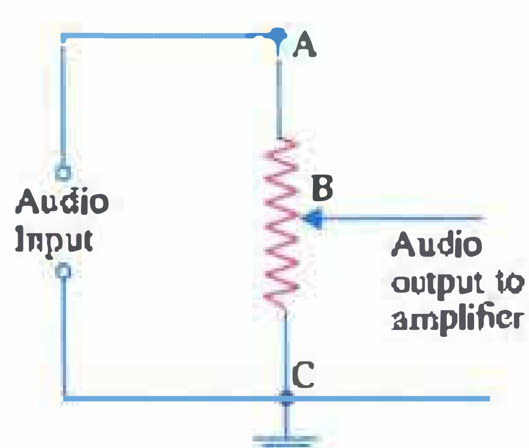


Fig. 5.5

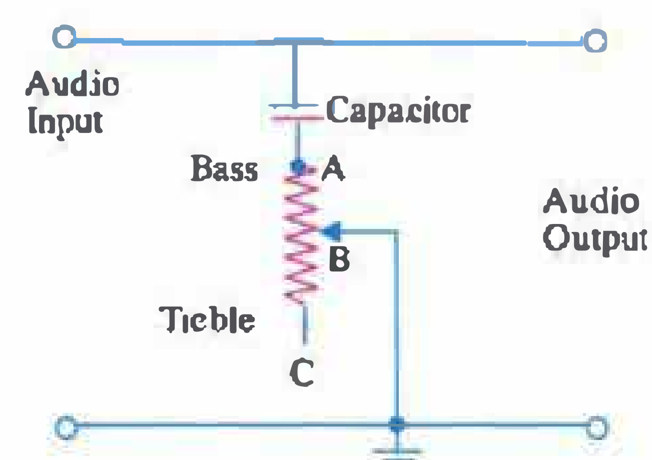


Fig. 5.6

As illustrated above, potentiometers are commonly used as control devices in amplifiers, TV sets and various types of meters. Typical applications include volume and tone controls, balance controls, linearity and brightness control in TV receivers etc.

(b) Rheostats

The resistance element of rheostats is made of high-resistance wire. It has two terminals and is connected in *series* with a circuit for adjusting the amount of current flowing through it. Rheostats are commonly used to control relatively high currents such as those found in motor and lamp loads. Fig. 5.7 shows how a rheostat can be connected into a lamp circuit for controlling its current. As seen, only resistance *BC* is connected into the circuit.

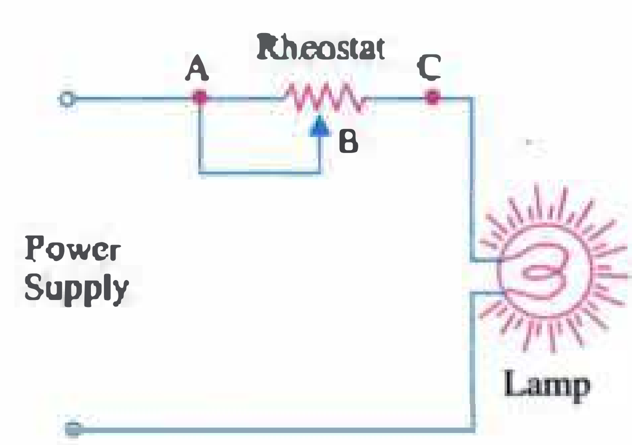


Fig. 5.7


A rheostat.

Though similar in construction to potentiometers, they are usually larger in size because they possess much higher power rating.

A given potentiometer can be used as a rheostat. One method is just to use two ends only leaving the third end unconnected as shown in Fig. 5.8 (*a*). The other method is to wire the third unused terminal to the central terminal as shown in Fig. 5.8 (*b*).

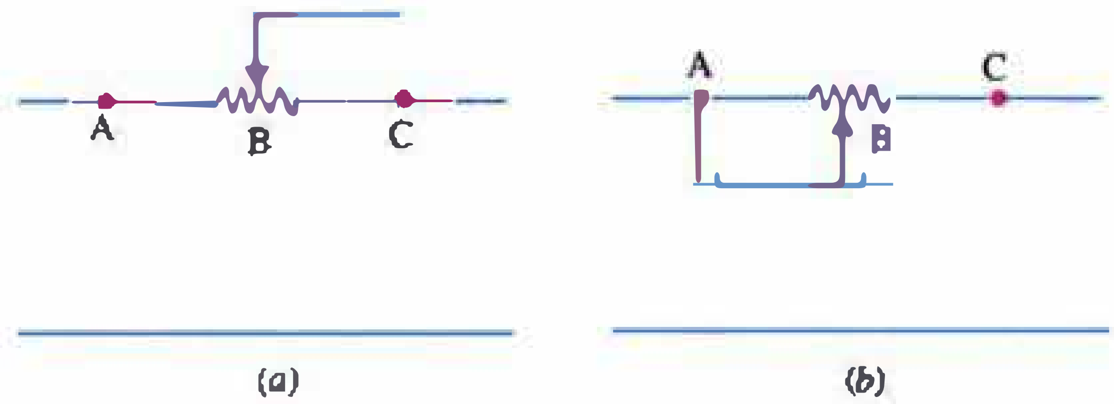
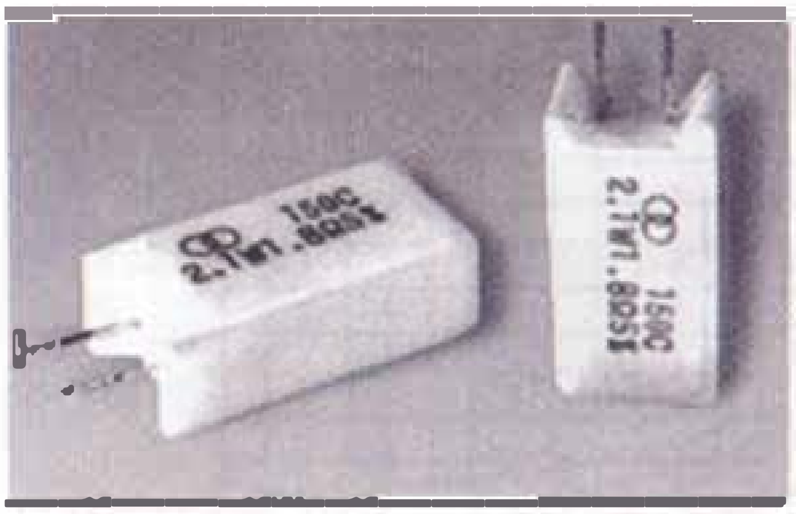


Fig. 5.8

5.13. Fusible Resistors

These are wire-wound devices similar in appearance to ordinary wire-wound resistors. They are sometimes used in amplifiers and TV sets to protect certain circuits. They have resistance of less than 15 Ω. Their resistance element is quite similar to the fuse link in a cartridge fuse and is designed to burn out whenever current in the circuit exceeds a certain predetermined value.



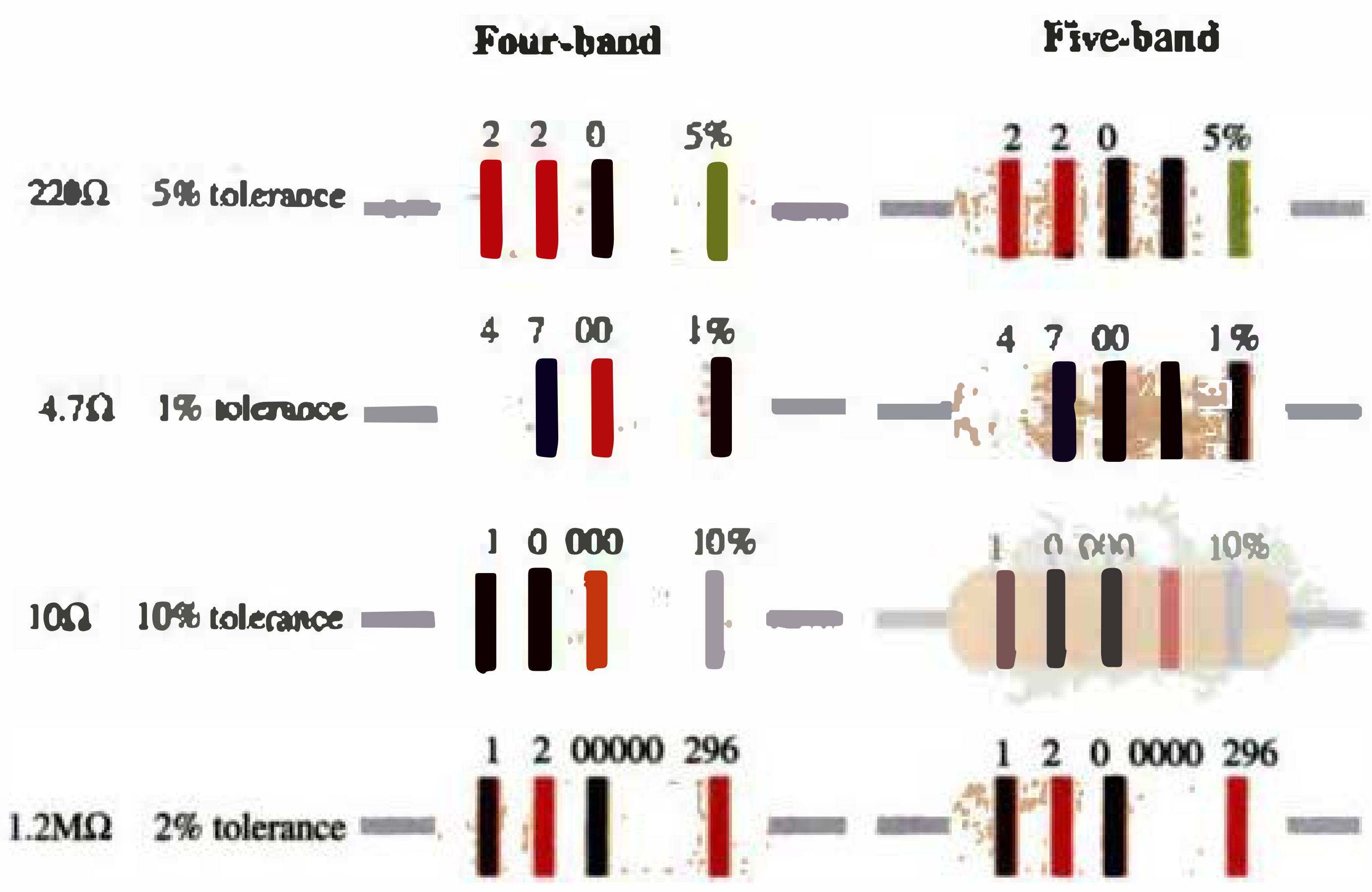
Fusible resistors.

Table 5.1

Colour	*Value*
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

5.14. Resistor Colour Code

Since fixed carbon-composition resistors having axial leads are physically small, they are colour-coded to indicate their resistance in ohms. The system is based on the use of colours (painted on the body of the resistor) as numerical values. In general, it should be remembered that dark colours like black and brown correspond to lowest numbers of zero and one respectively, the light colours to next higher numbers and lastly, white colour to nine. The colours used with the code and the numbers they represent are given in Table 5.1.



Some examples of the resistor colour code.

5.15. Resistance Colour Bands

These bands are printed around the body of the resistor near its one end (Fig. 5.9). Each colour stands for a digit. Often, there are four bands though sometime there may be five. In eachcase, *the first three bands give the resistance value.*

(a) Three Bands Only

They represent the resistance value as per the colour code. Absence of fourth band means a resistance tolerance of ± 20%.

(b) Four Bands Only

As before, the first three bands give resistance value and the fourth one gives tolerance.

Fourth gold ring means a tolerance of ± 5% whereas a fourth silver ring means a resistance tolerance of ± 10%.

(c) Five Bands

The first three bands, as usual, give resistance, fourth one gives tolerance and the fifth one indicates reliability level or failure rate for which colour code is,

Brown = 1% ; Red = 0.1%; Orange = 0.01% ; Yellow = 0.001%

Starting from left to right, the colour bands (Fig. 5.9) are interpreted as follows :

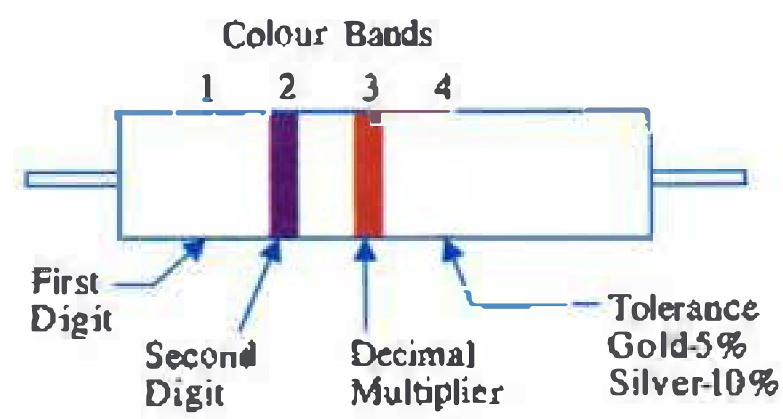
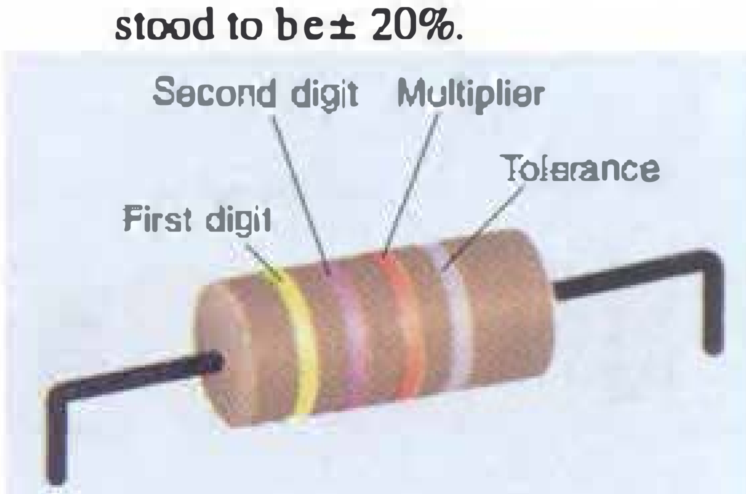


Fig. 5.9

1. The first band close to the edge indicates the first digit in the numerical value of the resistance.
2. The second band gives the second digit.
3. The third band is *decimal multiplier i.e.*, it gives the number of zeros after the two digits. It is important to note that if the third band is black, it means "*do not add zeros to the first two digits*". The resulting number is the resistance in ohms.
4. The fourth band gives resistance tolerance. If there is no fourth band, tolerance is understood to be ± 20%.



This Resistor has a value of 47,000Ω , ± 10%

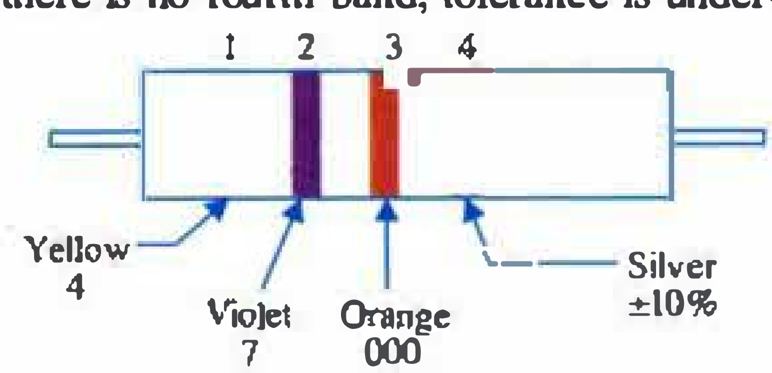


Fig. 5.10

The resistance value of the carbon-composition resistor shown in Fig. 5.10 is 47,000Ω ± 10%. It means that its value is 47,000 ± 4,700 Ω *i.e.*, it can lie anywhere between 42,300 Ω and 51,700 Ω.

5.16. Resistors under Ten Ohm

In their case, the third band is either gold or silver which serves as *fractional* multiplier. If third band is gold, multiply the first two digits by 0.1. If it is silver, then multiply by 0.01. However, fourth band, as before, gives tolerance.

As seen from Fig. 5.11, the value of resistor is 6.9 ± 10% ohm.

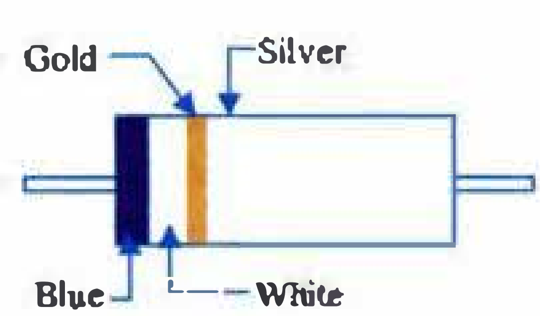


Fig. 5.11

5.17. Resistor Troubles

The most common trouble with resistors is 'open' which happens due to excessive current and heat. A charred or discoloured resistor should be discarded straight away *though it will usually check good with an ohmmeter.*

5.18. Checking Resistors with an Ohmmeter

Since an ohmmeter has it own voltage source, it is always used without any external power being supplied to the resistance under measurement.

The ohmmeter must have an ohm scale appropriate to the value of resistance being measured, otherwise it will not give correct value. In checking a 10 MΩ resistor, if the highest reading of the meter scale used is 1 MΩ resistor, the instrument will read infinity even if the resistor has its normal value of 10 MΩ. It is essential to use a scale of 100 MΩ for checking such high resistances.

Similarly, for checking resistances of value 10 Ω or less, a low ohm scale of 100 Ω or less should be used. Otherwise, the ohmmeter will read a low resistance such as zero thus indicating a short.

Another very important precaution one should take while checking a resistance is to make sure that there are no parallel paths across the resistance being measured. Otherwise, the measured resistance can be much lower than the actual resistance. As shown in Fig. 5.12 (*a*), the ohmmeter reads $R_1 \parallel R_2$ *i.e.*, $10/2 = 5$ K. To check R_2 alone, its one end should be disconnected as shown in Fig. 5.12 (*b*).

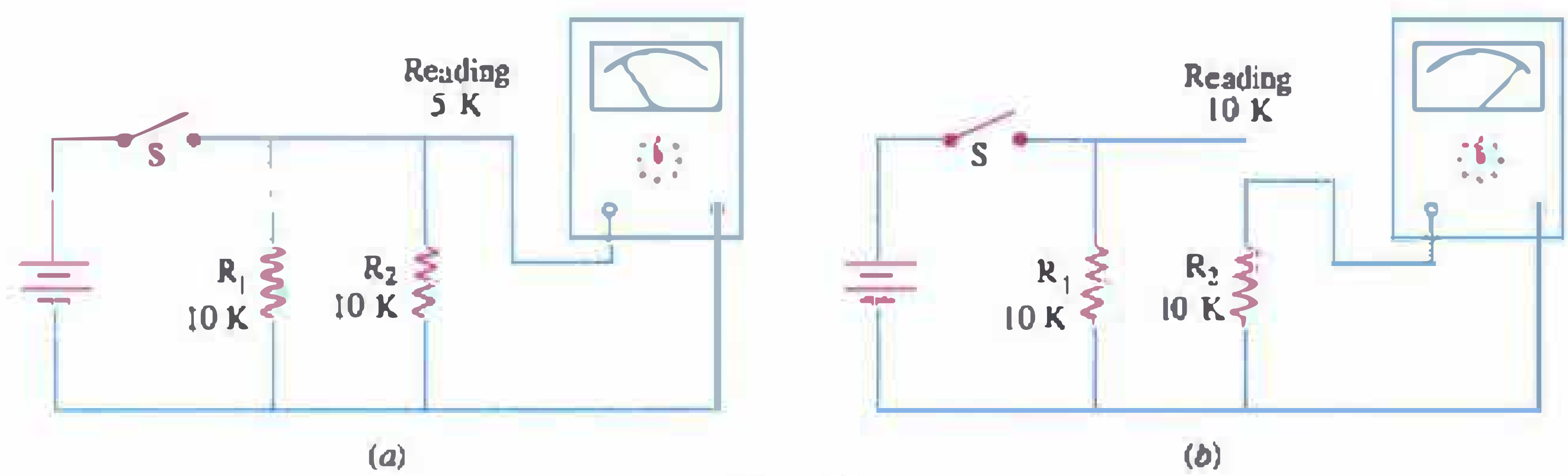
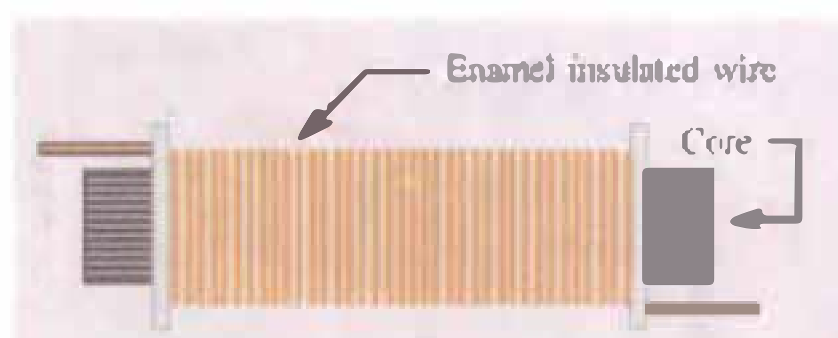


Fig. 5.12

Another point worth remembering is : not to touch the ohmmeter leads. There is no danger of electric shock but body resistance of about 50 K acting in parallel with the resistance being measured will lower the ohmmeter reading.

5.19. Inductor



This one example of what an inductor might look like.

It is another basic component commonly used in electronic circuits. It is nothing else but a coil wound on a core or former of some suitable material.

(*a*) Air-core Inductor

It consists of number of turns of wire wound on a former made of ordinary cardboard [Fig. 5.13 (*a*)]. Since there is nothing but air inside of the coil, an air-core inductor has the least inductance for a given number of turns and core length.

(*b*) Iron-core Inductor

It is that inductor in which a coil of wire is wound over a solid or laminated iron core [Fig. 5.13 (*b*)]. Putting iron inside an inductor has the effect of increasing its inductance as many times as the relative permeability (μ_r) of iron. In order to avoid eddy current loss, iron core is laminated *i.e.*, it is made up of thin iron laminations pressed together but

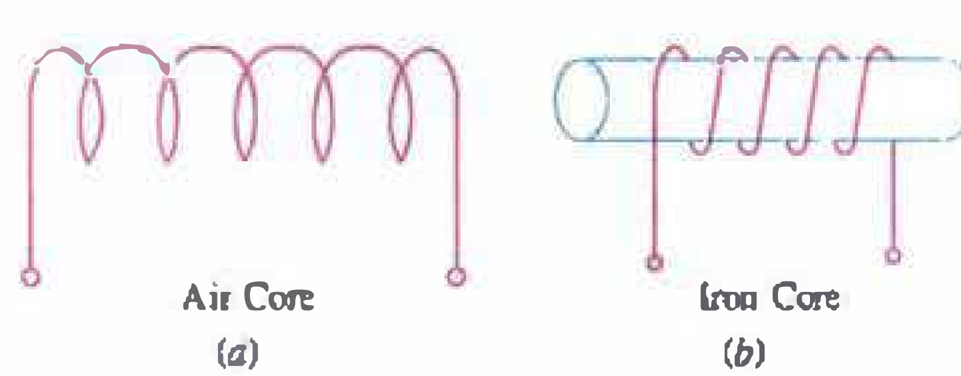
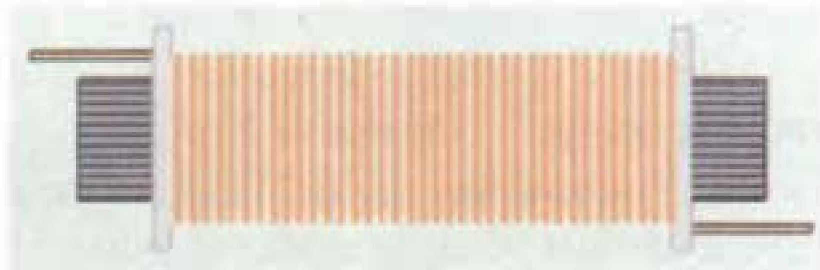


Fig. 5.13

insulated from each other. Sometimes, such an inductor is also called a choke.

The iron core has been found to work more efficiently particularly at low frequencies if it is in the form of a closed core *i.e.*, if the core not only goes through the centre of the coil but also surrounds it on its two sides as shown in Fig. 5.14.



Laminated iron cores are generally used in low cost, low power inductors.

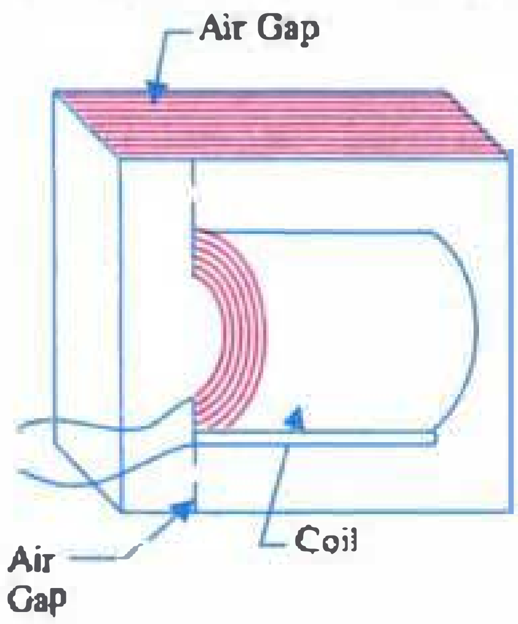
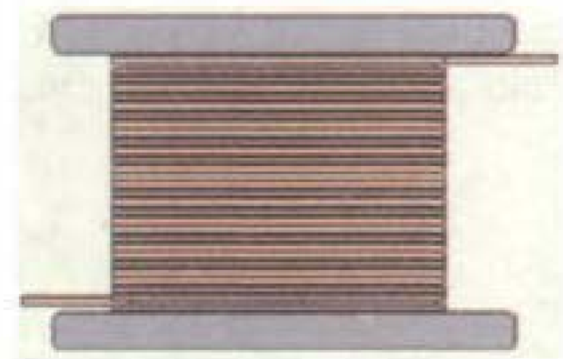


Fig. 5.14

(c) Ferrite-core Inductor

In this case, coil of wire is wound on a solid core made of highly ferromagnetic substance called ferrite. Ferrite is a solid material consisting of fine particles of iron powder embedded in an insulating binder. A ferrite core has minimum eddy current loss.



Ferrite core inductors are used in moderately high power systems.

The symbols for different types of inductors discussed below are shown in Fig. 5.15.

5.20. Comparison of Different Cores

In air-core coils, there are no core losses even at high frequencies but their inductances are limited to low values in the μH or mH range.

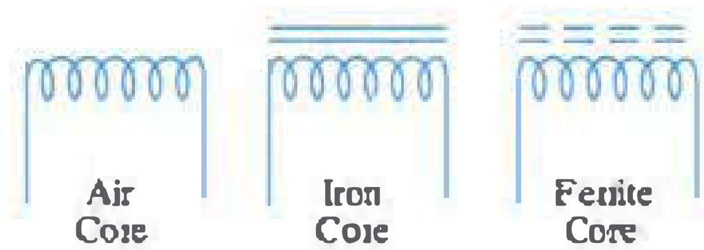


Fig. 5.15

In iron-core coils, losses are minimal at low *i.e.*, audio frequencies but become considerable at high frequencies even when iron core is laminated. They possess comparatively much larger inductance as compared to air-core coils.

Ferrite-core coils have high inductance value with minimum eddy current and hysteresis losses even at very high frequencies. The built-in antennas used in transistor radios have ferrite core.

5.21. Inductance of an Inductor

It is found that whenever current through an inductor changes (*i.e.*, increases or decreases), a counter emf is induced in it which tends to oppose this change. This property of the coil due to which it opposes any change of current through it is called inductance (L). Its unit is henry (H). The inductance of a coil is given by

$$L = \frac{\mu_0 \mu_r A N^2}{l} \text{ henrys}$$

It is seen that L varies

1. directly as relative permeability of the core material,
2. directly as core cross-sectional area,
3. directly as square of the number of turns of the coil,
4. inversely as core length.

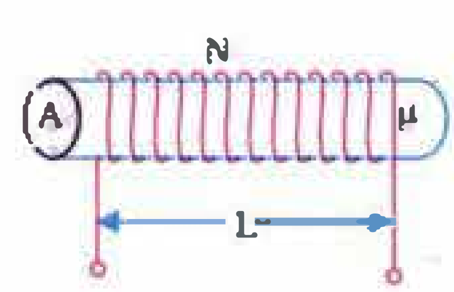


Fig. 5.16

5.22. Another Definition of Inductance

Suppose, current through an inductor is changed at the rate of di/dt because of which a counter emf of 'e' is induced in it. Then, it is found that

$$e = L\frac{di}{dt} \quad \text{or} \quad L = \frac{e}{di/dt}$$

If $di/dt = 1$ A/s and $e = 1$V, then $L = 1$H

Hence, a coil has an inductance of one henry if an emf of one volt is induced in it when current through it changes at the rate of 1 A/s.

The radio-frequency (RF) coil for the radio broadcast band 550-1650 kHz has an inductance of about 250 μH whereas iron-core inductors used for audio frequency have inductance values of about 1 to 25 H.

5.23. Mutual Inductance

When two coils are placed so close to each other (Fig. 5.17) that the expanding and collapsing magnetic flux of one coil links with the other, an induced emf is produced in the other coil. These two coils are then said to have mutual inductance (M).

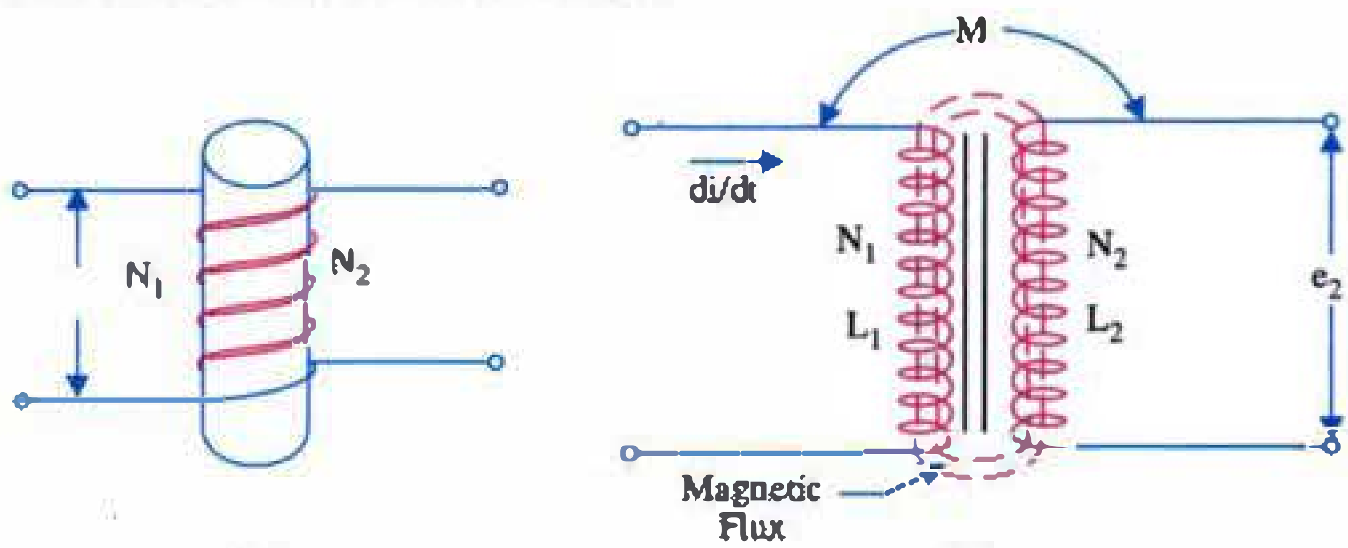


Fig. 5.17

In terms of physical factors

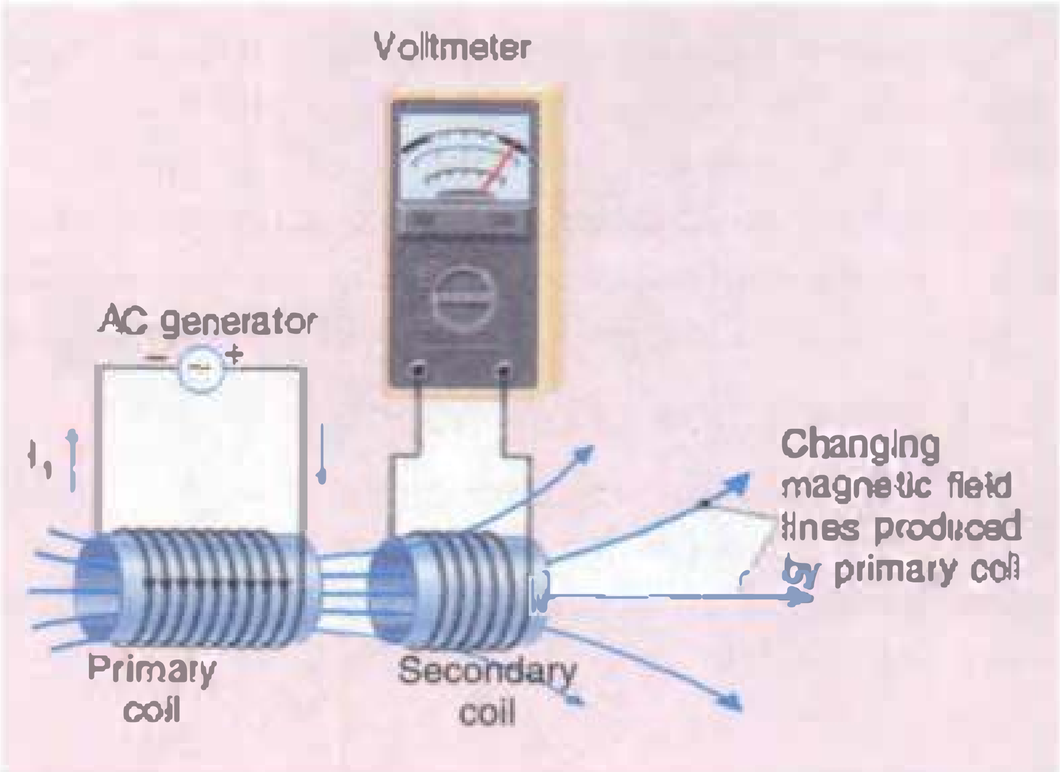
$$M = \frac{\mu_0 \mu_r A N_1 N_2}{l}$$

where l is the length of the magnetic path.

As shown in Fig. 5.17 (b), let the rate of current change through the first coil be di/dt. This changing current will produce a changing magnetic flux through it which will link partly or fully with the second coil. Hence, an induced emf 'e_2' (called mutually-induced emf) will be produced in the second coil. Its value is given by

$$e_2 = M \frac{di}{dt}$$

if $di/dt = 1$ A/s and $e_2 = 1$ V, then $M = 1$ H



An alternating current i_1 in the primary coil creates an alternating magnetic field. This changing field induces an emf in the secondary coil.

Hence, two coils have a mutual inductance of one henry if a current change of one ampere/ second in one coil induces one volt in the other.

5.24. Coefficient of Coupling

Two coils are said to be magnetically coupled if full or part of the flux produced by one coil links with the other. Closer they are, tighter the coupling between them. If, on the other hand, no flux from one coil links with the other, then coupling between the two is zero.

This coupling effect is measured in terms of coefficient of coupling given by

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

where L_1 = inductance of the first coil

L_2 = inductance of the second coil

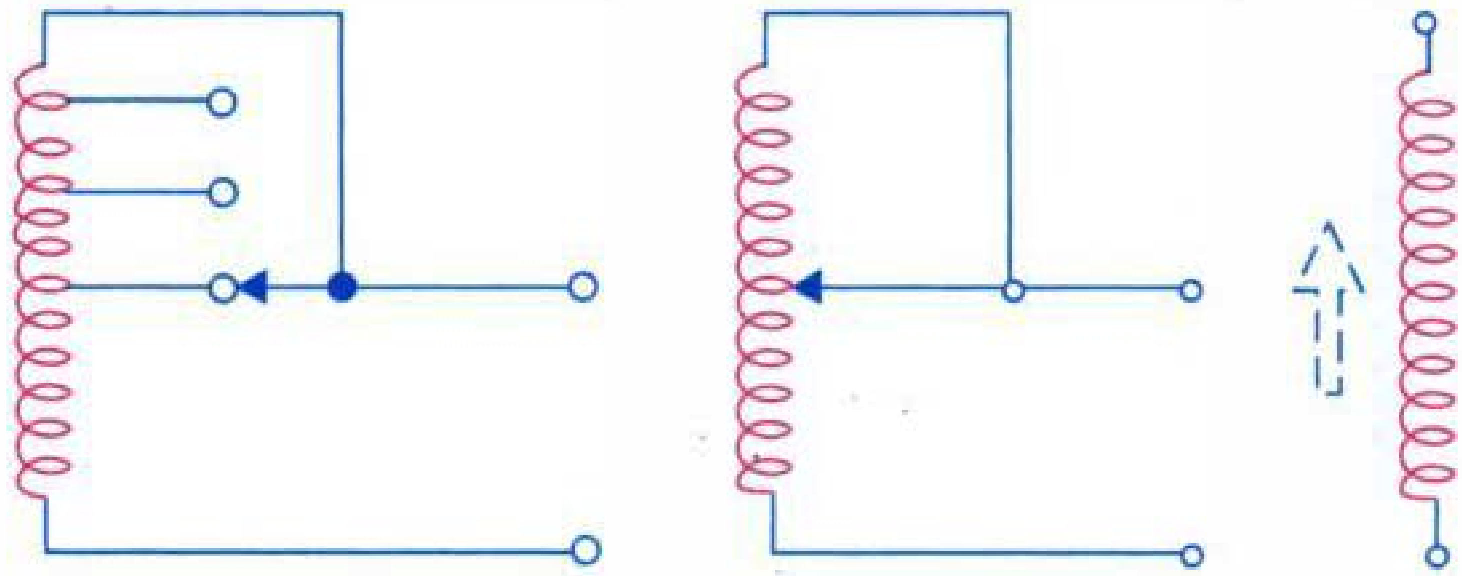
M = mutual inductance between the two coils

When magnetic flux produced by one coil does not link with the other coil, then $k = 0$. If all the flux produced by one coil links with the other, $k = 1$. Air-core coils wound on the same former have k value of 0.05 to 0.3. Coils on iron core have k almost equal to unity.

5.25. Variable Inductors

The inductance of a coil can be varied by the three different methods shown in Fig. 5.18.

1. By using a tapped coil as shown in Fig. 5.18 (*a*). Here, either more or fewer turns of the coil can be used by connection to one of the taps on the coil.
2. By using a slider contact to vary the number of turn used as in Fig. 5.18 (*b*).



(*a*) (*b*) (*c*)

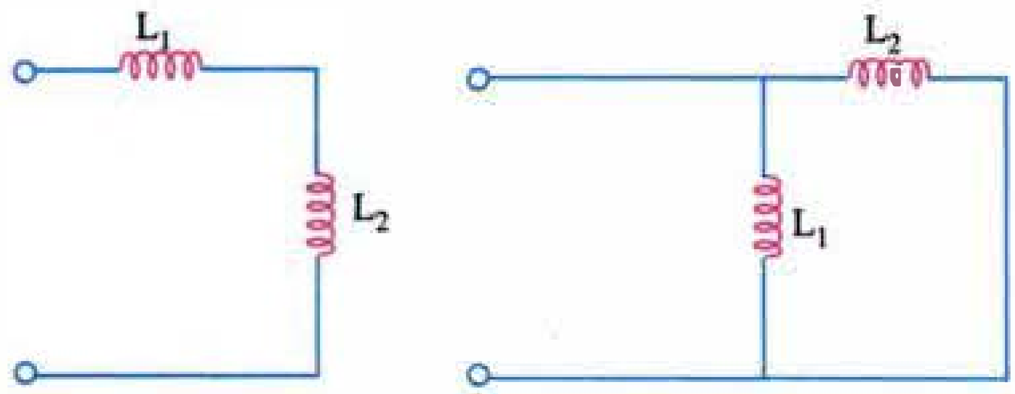
Fig. 5.18

These methods are used for large coils. It will be noted that the unused turns have been short-circuited to prevent the tapped coil from acting as an autotransformer otherwise the stepped up voltage could cause arcing across the turns.

3. Fig. 5.18 (*c*) shows the symbol for a coil with a ferrite slug which can be screwed in or out of the coil to vary its inductance.

5.26. Inductors In Series or Parallel without M

We will assume that the different coils connected in series or parallel have no mutual inductance M.



(*a*) (*b*)

Fig. 5.19

(a) **Series Combination**

Here, $L = L_1 + L_2$ — Fig. 5.19 (a)

In general, $L = L_1 + L_2 + L_3 + \ldots$

(b) **Parallel Combination**

Here, $L = L_1 \parallel L_2 = \dfrac{L_1 L_2}{L_1 + L_2}$ — Fig. 5.19 (b)

In general, $\dfrac{1}{L} = \dfrac{1}{L_1} + \dfrac{1}{L_2} + \dfrac{1}{L_3} + \ldots$

5.27. Series Combination with M

In this case, value of total inductance will depend upon

1. amount of mutual inductance present, and
2. whether the combination is series-aiding or series-opposing.

In series-aiding, the direction of the common current through the two coils is such that their magnetic fields are in the same direction *i.e.*, they aid each other as shown in Fig. 5.20 (*a*). In series-opposing, the direction of current flow is such that the two fields oppose each other as shown in Fig. 5.20 (*b*).

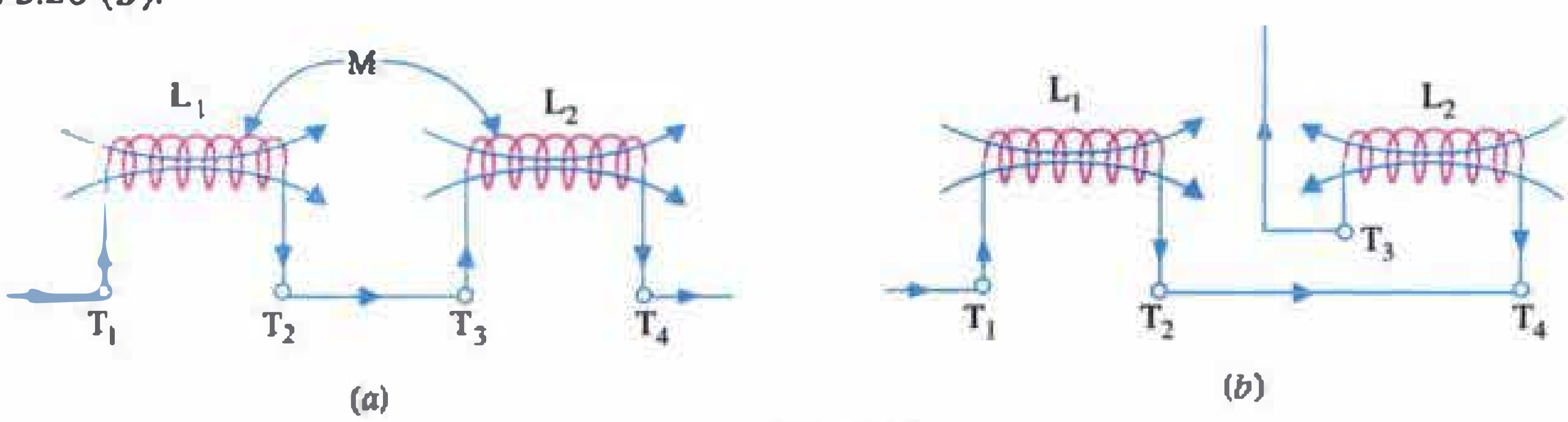


Fig. 5.20

For the circuit of Fig. 5.20 (*a*)

$$L_a = L_1 + L_2 + 2M$$

For the circuit of Fig. 5.20 (*b*)

$$L_o = L_1 + L_2 - 2M$$

Incidentally, it can be deduced from the above two equations that

$$M = \frac{L_a - L_o}{4}$$

Example 5.1. *Two coils each having an inductance of 250 μH have combined inductance of 550 μH when connected series-aiding and 450 μH when connected series-opposing. Calculate (i) their mutual inductance, and (ii) coefficient of coupling.*

Solution. (*i*) $M = \dfrac{L_a - L_o}{4} = \dfrac{550 - 450}{4} = \mathbf{25\ \mu H}$

(*ii*) $k = \dfrac{M}{\sqrt{L_1 L_2}} = \dfrac{25}{\sqrt{250 \times 250}} = \mathbf{0.1}$

5.28. Stray Inductance

It is the unwanted inductance inherently present in the connecting leads and wire-wound resistors.

For example, a connecting wire 10 cm long and 1 mm in diameter has an inductance of about 0.1 μH. It is negligible at low frequencies but can be troublesome at MHz frequency range. That is why connecting leads are kept very short in high-frequency circuits.

Since ordinary wire-wound resistors have considerable stray inductance, non-inductive wire-wound resistors are used instead. These are wound in such a way that adjacent turns have currents in the opposite direction so that opposing magnetic fields cancel out the inductance.

5.29. Energy Stored in a Magnetic Field

When current passes through an inductor, magnetic flux is produced for which energy is supplied by the voltage source. This energy is safely stored in the field itself and is recoverable. The amount of energy stored is

$$E = \frac{1}{2} L I^2 \text{ Joules}$$

where L is inductance in henrys and I is the steady current in amperes.

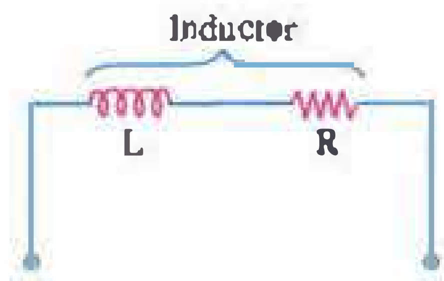


Fig. 5.21

5.30. DC Resistance of a Coil

It is the ohmic resistance of the wire used in making the coil. This resistance will depend on the thickness of the wire and its length *i.e.*, total number of turns. For radio-frequency coils with inductance values upto several mH requiring 10 to 100 turns of fine wire, the dc resistance is from 1 to 20 Ω approximately.

5.31. Troubles in Coils

The most common trouble is an 'open' in the winding. An ohmmeter connected across the coil will read infinity for the open circuit. As usual, while checking its resistance, the coil should be disconnected from the external circuit to eliminate any parallel paths which could affect the resistance reading.

5.32. Reactance Offered by a Coil

An inductor offers opposition to the passage of any *changing* or *alternating* current through it. This opposition is given the name of inductive reactance, X_L.

$$X_L = 2\pi f L = \omega L \text{ ohm}$$

where L = coil inductance in henrys

f = frequency of alternating current in Hz

ω = angular frequency in radian/second.

Like resistance, unit of inductive reactance is also ohm.

Obviously, $X_L = 0$ if $f = 0$, *i.e.*, a coil offers no reactance to the passage of direct current through it since frequency of such a nonchanging current is zero. Of course, it does offer dc resistance possessed by it.

It may be noted that, unlike resistance, inductive reactance offered by a coil is not constant but depends on frequency of the alternating current passing through it. Higher the frequency, greater the reactance. Moreover, for a given frequency, X_L depends directly on coil inductance L.

Example 5.2. *Calculate the inductive reactance offered by a coil of inductance 250 μH to radio-frequency currents of frequencies (i) 1 MHz and (ii) 10 MHz.*

Solution. (*i*) $X_L = 2\pi f L$

$= 2\pi \times (1 \times 10^6) \times (250 \times 10^{-6}) = \mathbf{1570\ \Omega}$

(*ii*) $X_L = 2\pi \times (10 \times 10^6) \times (250 \times 10^{-6}) = \mathbf{15{,}700\ \Omega}$

As seen, X_L increase proportionally with increase in frequency.

5.33. Impedance Offered by a Coil

A coil having both inductance (L) and resistance offers opposition in the form of both X_L and R. The combined opposition of X_L and R is known as *impedance* (Z).

However, it should be noted that X_L and R are not added arithmetically but *vectorially* as shown in Fig. 5.22 (*a*).

Here, $Z = \sqrt{R^2 + X_L^2}$ (and $\neq R + X_L$)

The right-angled triangle of Fig. 5.22 (*a*) is known as impedance triangle.

For example, an inductor coil having a resistance of 3 Ω and an inductive reactance of 4 Ω offers an impedance of 5 Ω and not (4 + 3) = 7 Ω. The vector addition is shown in Fig. 5.22 (*b*).

Incidentally, the angle ϕ in Fig. 5.22 represents the phase difference between the applied alternating voltage and circuit current.

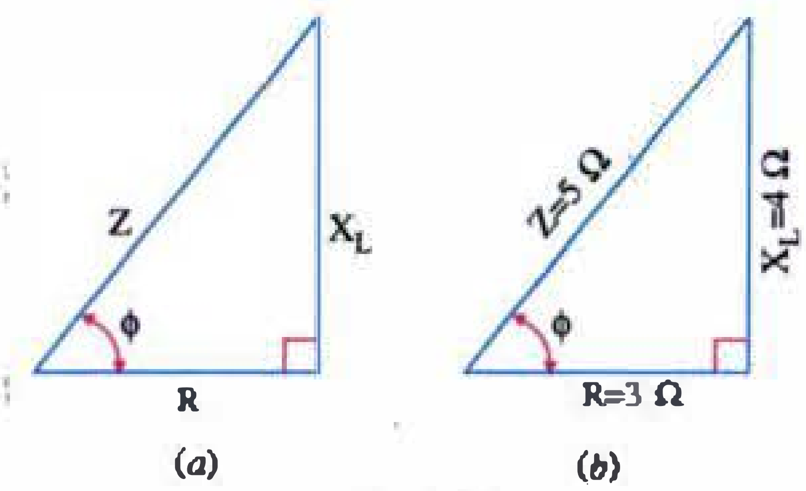


Fig. 5.22

Example 5.3. *A coil has a resistance of 30 Ω and an inductance of 127.3 mH. It is connected across a 200 V, 5 Hz ac supply. Find*

1. impedance *2. circuit current* *3. phase angle ϕ*

Solution.
$$X_L = 2\pi f L$$
$$= 2\pi \times 50 \times (127.3 \times 10^{-3}) = 40\,\Omega$$

1. $$Z = \sqrt{R^2 + X_L^2} = \sqrt{30^2 + 40^2} = 50\,\Omega$$

2. $$I = V/Z = 200/50 = 4\text{ A}$$

3. $$\tan\phi = \frac{X_L}{R} = \frac{40}{30} = 1.3333 \quad \therefore \phi = 53°$$

5.34. Q-Factor of a Coil

The quality or merit of a coil is measured in terms of its Q-value given by

$$Q = \frac{X_L}{R} = \frac{2\pi f L}{R}$$

As seen, smaller the d.c. resistance of a coil as compared to its inductance, higher its Q-factor. In tuned radio receiver circuits, a high Q-coil is preferred because

1. it increases sharpness of tuning *i.e.*, makes the tuned circuit more selective,
2. it additionally increases its sensitivity.

5.35. Capacitors

Apart from resistors and inductors, a capacitor is the other basic component commonly used in electronic circuits. It is a device which

1. has the ability to store charge which neither a resistor nor an inductor can do;
2. opposes any change of *voltage* in the circuit in which it is connected*;
3. blocks the passage of direct current through it.

Capacitors.

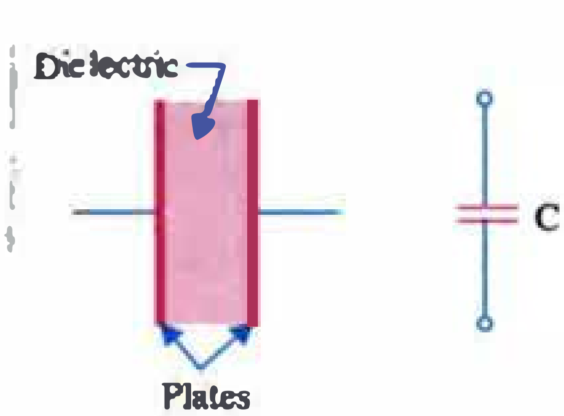


Fig. 5.23

* An inductor opposes change of current.

Capacitors are manufactured in various sizes, shapes, types and values and are used for hundreds of purposes.

Essentially, a capacitor consists of two conducting plates separated by an insulating medium called *dielectric* as shown in Fig. 5.23. The dielectric could be air, mica, ceramic, paper, polyester, polystyrene or polycarbonate plastics etc.

5.36. Capacitor Connected to a Battery

When switch *S* in Fig. 5.24 (*a*) is closed, the capacitor gets connected across the battery. There is momentary flow of electrons from plate *M* to plate *N*. The positive terminal of the battery attracts and pulls away negatively-charged electrons from plate *M* which consequently becomes positive. Similarly, as these electrons collect on plate *N*, it becomes negative. Hence, a potential difference is established between the two plates *M* and *N*. This *transient* flow of electrons from one plate to another through the connecting wires gives rise to charging current which establishes positive charge of $+Q$ coulomb on the plate *M*. The strength of this charging current is maximum in the beginning when the two plates are uncharged but it then decreases and finally ceases when p.d. across the two plates becomes slowly and slowly *equal and opposite* to the battery emf *i.e.*, *V* volts. The capacitor then becomes fully charged as shown in Fig. 5.24 (*b*).

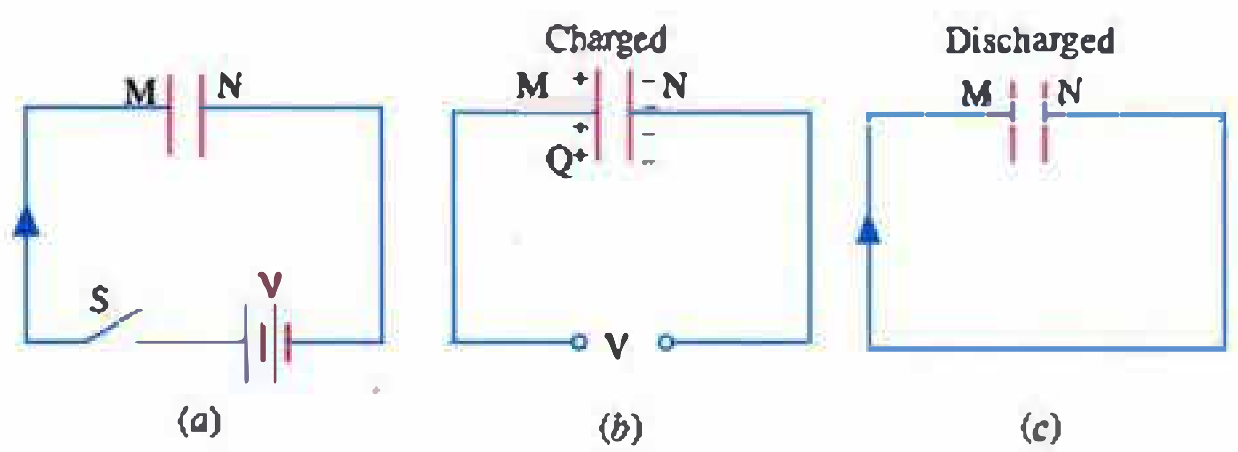


Fig. 5.24

Following two points should be noted :

1. no current can flow '*through*' the capacitor because of the presence of dielectric in the circuit which offers infinite resistance. The electric charge is momentarily displaced from one plate to another through the *external circuit only*;
2. as p.d. between the plates is increased, the dielectric medium comes under increasing stress. If this p.d. is increased, the stress in the dielectric increases till it can no longer bear it. At that stage, electrical breakdown occurs accompanied by a spark between the two capacitor plates. The maximum voltage per metre thickness which a medium can withstand without a rupture or breakdown is called its *dielectric strength*. Usually, it is given in kV/mm instead of the basic unit V/m. If the two leads of a charged capacitor are connected together as shown in Fig. 5.24 (c), the p.d. between the two plates is equalized and the capacitor becomes discharged;
3. since there exists a p.d. between the two plates, an electric field is set up between them whose strength is given by

$$E = V/d \text{ volt/metre}$$

5.37. Capacitance

It measures the ability of a capacitor to store charge. It may be defined as the amount of charge required to create a unit potential difference between its plates.

Suppose, we give $+Q$ coulomb of charge to one of the two plates of a capacitor and if a p.d. of V volts is established between them, then its capacitance is

$$C = \frac{Q}{V} \text{ farad}$$

If $Q = 1$ C and $V = 1$ volt, then $C = 1$ farad (F).

Hence, one farad is defined as the capacitance of a capacitor which requires a charge of one coulomb to establish a p.d. of one volt between its plates.

Capacitance of a capacitor may also be defined in terms of its property to oppose the change of voltage in the circuit. In that case,

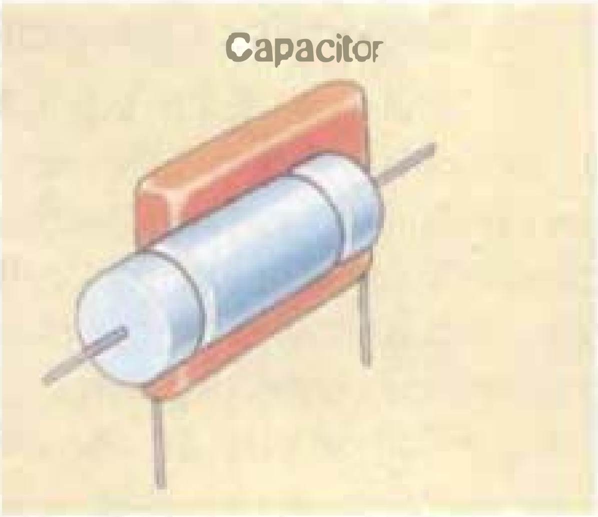
$$C = \frac{i}{dv/dt}$$

where i = charging current

dv/dt = rate of change of voltage

i = 1 ampere, dv/dt = 1 volt/second

then C = 1 farad



The amount of charge the device can store for a given voltage difference is called the capacitance.

Hence, one farad may be defined as the capacitance which will cause one ampere of charging current to flow when the applied voltage across the capacitor changes at the rate of one volt per second.

Farad is too large for practical purposes. Hence, much smaller units like microfarad (μF), nanofarad (nF) and micro-micro-farad (μμF) or picofarad (pF) are generally employed.

$$1 \text{ μF} = 10^{-6} \text{ F}$$

$$1 \text{ nF} = 10^{-9} \text{ F}$$

$$1 \text{ pF or } 1 \text{ μμF} = 10^{-12} \text{ F}$$

5.38. Factors Controlling Capacitance

The capacitance of a capacitor depends on the following factors :

1. Plate Area

Capacitance increases directly with increase in plate area (A).

2. Plate Separation

As plate separation (d) decreases, capacitance increases and *vice-versa*. Since plate separation often equals the thickness of the dielectric used, we may say that thinner the dielectric slab, greater the capacitance and *vice-versa*.

3. Type of Dielectric

It depends on the relative permittivity ε_r (previously called dielectric constant) of the dielectric medium used. Higher the value of ε_r, greater the value of capacitance.

Combining the above three factors, we get

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \text{ farad}$$

where ε_0 is the absolute permittivity of vacuum = 8.854×10^{-12} F/m.

The relative permittivities of some dielectric media are listed in Table 5.2 on next page.

Table 5.2

Material	*Dielectric Constant or relative permittivity* (ε_r)
Air or vacuum	1
Bakelite	4.5—5.5
Ceramic	50—3000
Fibre	5—8
Glass	7—8
Mica	3—6
Paper (waxed)	3—5
Polysterene	2.6
Porcelain	5—6

Example 5.4. *What is the capacitance of a capacitor if a charging current of 100 mA flows when the applied voltage changes 20 V at a frequency of 50 Hz?*

Solution.
$$C = \frac{i}{dv/dt}$$

Now,
$$i = 100 \text{ mA} = 100 \times 10^{-3} \text{ A} = 0.1 \text{ A}$$
$$dv = 20 \text{ V}, \; dt = 1/50 = 0.02 \text{ s}$$
$$C = \frac{0.1}{20/0.02} = 0.1 \times 10^{-3} \text{ F}$$
$$= 100 \times 10^{-6} \text{ F} = \mathbf{100\ \mu F}$$

Example 5.5. *What is the capacitance of a parallel-plate capacitor of plate area 0.01 m^2 and air dielectric of thickness 0.01 m ?*

If the capacitor is given a charge of 500 μμC, what will be the p.d. between its plates?

How will this be affected if space between the two plates is filled with wax which has a relative permittivity of 4 ?

Solution.
$$C = \frac{\varepsilon_0 \, \varepsilon_r \, A}{d}$$

Remembering that for air, $\varepsilon_r = 1$, we get
$$C = \frac{8.854 \times 10^{-12} \times 1 \times 0.01}{0.01} = 8.854 \times 10^{-12} \text{ F} = \mathbf{8.854\ \mu\mu F}$$

Now,
$$C = \frac{Q}{V} \quad \text{or} \quad V = \frac{Q}{C}$$

$\therefore$
$$V = \frac{500\ \mu\mu C}{8.854\ \mu\mu F} = \mathbf{56.5\ V}$$

When wax is introduced, capacitance will increase four times.

$\therefore$
$$C = 4 \times 8.854 = \mathbf{35.4\ \mu\mu F}$$

Since charge remains constant, p.d. will *decrease* to one-fourth of its previous value because $V \propto 1/C$

$\therefore$
$$V = 56.5/4 = \mathbf{14.1\ V}$$

5.39. Types of Capacitors

All capacitors commonly used in electronic circuits may be divided into two general classes (*a*) fixed capacitors and (*b*) variable capacitors.

Fixed capacitors may be further sub-divided into (*i*) electrolytic and (*ii*) non-electrolytic capacitors.

5.40. Fixed Capacitors

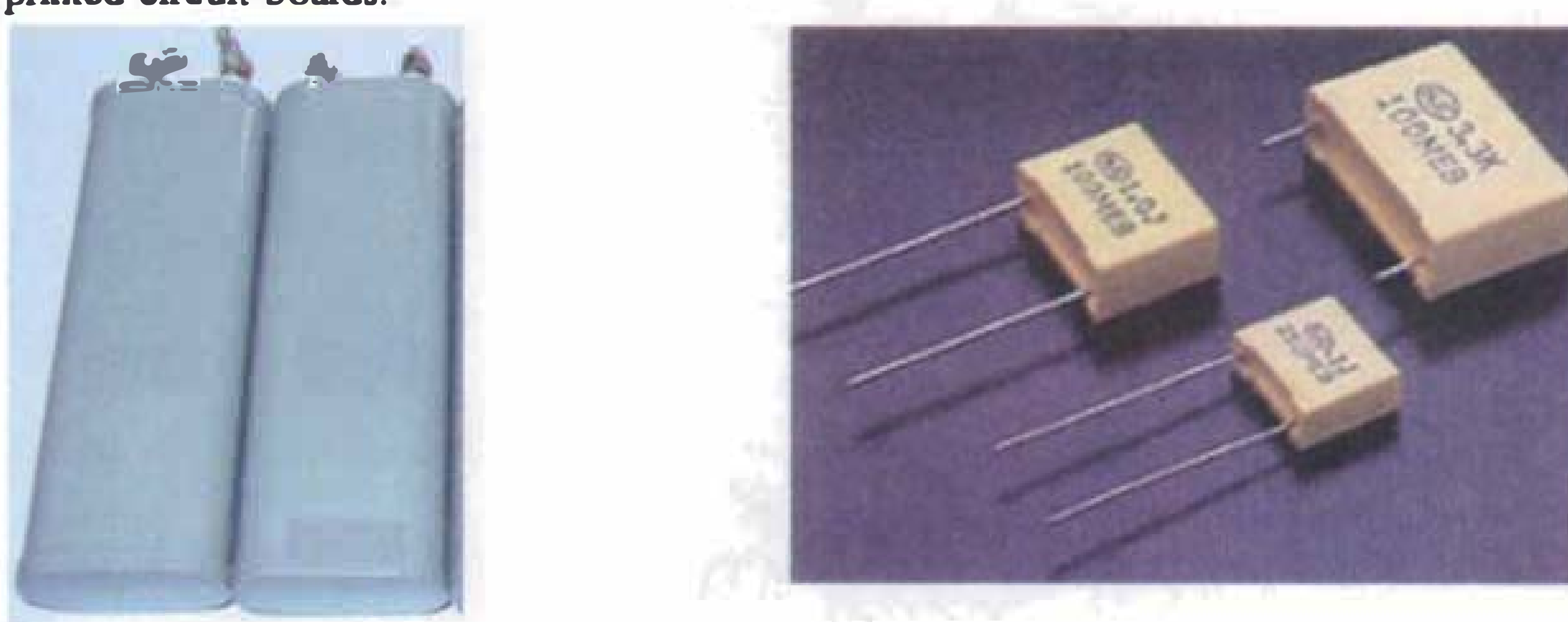
These can be grouped into two classes as detailed below :

(a) Non-electrolytic type

It includes paper, mica and ceramic capacitors. Such capacitors have no polarity requirement *i.e.*, they can be connected in either direction in a circuit.

(*i*) Paper Capacitor

It consists of two tinfoil sheets which are separated by thin tissue paper or waxed paper. The sandwich of foil and paper is then rolled into a cylindrical shape and enclosed in a paper tube or encased in a plastic capsule. The lead at each end of the capacitor is internally attached to the metal foil. Fig. 5.25 (*a*) shows a 2.0 μF tubular paper capacitor of maximum ac voltage rating of 2000 V whereas Fig. 5.25 (*b*), shows polyester capacitor having moulded plastic box encapsulation suitable for use in printed circuit boards.



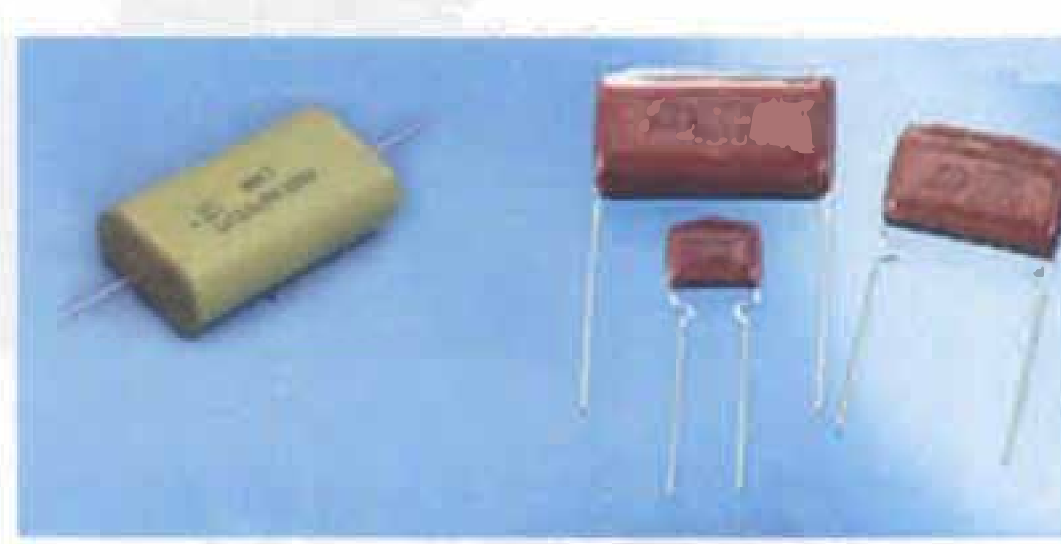
(*a*) (*b*)

Fig. 5.25

Paper capacitors have a capacitance range of 0.001 to 2.0 μF and working-voltage rating as high as 2000 V. These specifications are usually printed on the capacitor case. Paper capacitors have large physical size as compared to their capacitance and also become inefficient as the frequency of applied ac voltage exceeds a few megahertz. These facts prevent their use in most FM TV circuits except in low-frequency portions of the circuits *i.e.*, in audio stages.

These days such foil construction capacitors use thin plastic film instead of paper as the dielectric medium. Two most commonly-used plastic films have trademark names of Teflon and Mylar. Such capacitors have

1. high insulation resistance of 1000 M and above,
2. low losses, and
3. longer shelf life without breakdown as compared to paper capacitors.



(*c*) (*d*)

Fig. 5.25

Fig. 5.25 (*c*) and (*d*) show tubular and flat metallised polyester film capacitors which are ideal for coupling and by-pass applications in radio, TV, hi-fi equipment and instrumentation etc.

(*ii*) Mica Capacitor

It is a sandwhich of several thin metal plates separated by thin sheets of mica. Alternate plates are connected together and leads attached for outside connections. The total assembly is encased in a plastic capsule or bakelite case as shown in Fig. 5.26. Such capacitors have small capacitance values (50 to 500 pF) yet high working voltage ratings (500 V and above).

Fig. 5.26

Once such capacitors were used extensively in radio circuits but, of late, they have been superseded by ceramic capacitors because of excellent properties of ceramics and their economy.

Fig. 5.27. The small value ceramic capacitors.

(*iii*) Ceramic Capacitors

Such capacitors have disc- or hollow tubular-shaped dielectric made of ceramic material such as titanium dioxide and barium titanate. Thin coatings of silver compound are deposited on both sides of the dielectric disc which act as capacitor plates. Leads are attached to each side of the disc and the whole unit is encapsulated in a moisture-proof coating (Fig. 5.27).

Because of the very high value of the dielectric constant of ceramics ($\varepsilon_r = 1200$), disc type capacitors have very large capacitances (upto 0.01 μF) compared to their size.

In the case of tubular ceramics, the hollow ceramic tube has a silver coating on the inside and outside surfaces. The capacitance range varies from 1 to 500 pF with working voltage rating exceeding 10 kV. Ceramic capacitors have many advantages as compared to mica and paper capacitors. These capacitors

1. are economical,
2. have very small size but large capacitance. Hence, they occupy less space.
3. have very high working-voltage rating,
4. have very low power factor (*i.e.*, loss) which further *decreases with increase in the frequency*. Hence, they are very useful for short-wave work in radio.

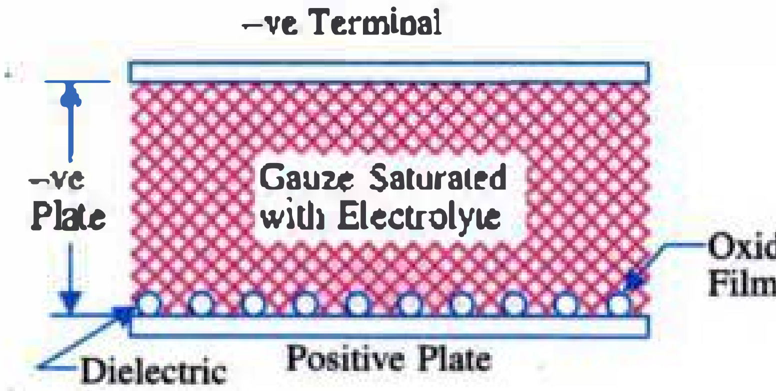


Fig. 5.28

(*b*) Electrolytic Capacitors

These capacitors are called *electrolytic* because they use an electrolyte (borax or a carbon salt) as *negative* plate. The capacitor consists of

1. a positive plate of aluminium;
2. an extremely thin (*i.e.*, molecular thin) insulating film of aluminium oxide (Al_2O_3) as dielectric medium. It is electrochemically deposited on the surface of anode itself (Fig. 5.28);
3. an electrolyte of borax (phosphorus or carbonate). As shown in Fig. 5.28, an absorbent gauze saturated with the electrolyte is kept in contact with the dielectric. The second aluminium plate serves merely as contact to the electrolyte. It forms the negative terminal.

Such a capacitor is made as described below:

A thin strip of aluminium is coated with a molecular-thin film of aluminium oxide by an electrochemical process. It is covered with a layer of gauze soaked in the electrolyte of borax. On top of this is another metal plate in contact with the electrolyte which, in reality, is the second plate of the capacitor (and not the top plate). The entire sandwhich is rolled up into a compact cylinder and placed inside a metal cylinder (Fig. 5.29) or can.

Fig. 5.29. The aluminium electrolytic capacitors.

This enclosing cylinder contacts the outside metal foil of the capacitor and serves as the negative terminal. Such capacitors are made as single capacitors or with two or three capacitors in a single container having a common negative terminal. The outside metal cylinder is usually enclosed in a paper tube in order to insulate it from components and to protect radio technicians from shock.

Because of extremely thin dielectric film, such capacitors possess very large capacitance ranging from 1 μF to 10,000 μF in very compact sizes. Hence, they are used where lot of capacitance is required in a small space. Since they use an electrolyte as the negative plate, electrolytic capacitors are classed as "*polarised*' capacitors *i.e.*, they must be connected in the circuit according to the plus (+) and minus (−) markings on the case. If this is not done, the capacitor may become short-circuited or get overheated due to excessive leakage current through its dielectric. Moreover, reversed polarity results in gas formation which may cause the capacitor to explode.

Electrolytic capacitors are frequently used in the filter circuits in order to remove the a.c. ripple from the power supply. They are also used as blocking or coupling capacitors for blocking d.c. in a circuit but allowing a.c. to pass through.

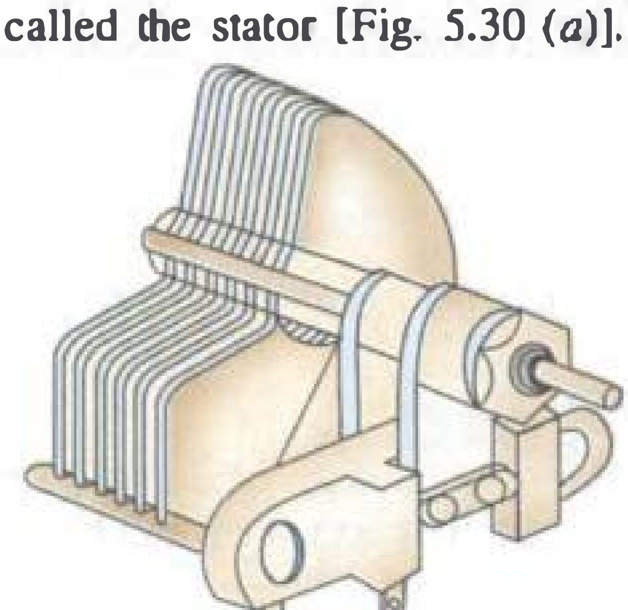
The miniature and high-voltage aluminium foil electrolytic capacitors manufactured by Bharat Capacitors Limited (BCL), Hyderabad are characterised by low leakage current, low dissipation, close tolerance in capacitance value, excellent reliability and long life. They meet all performance characteristics as laid down in JIS–C–5141 or MIL–C–62 specifications.

The two disadvantages of electrolytic capacitors are that they

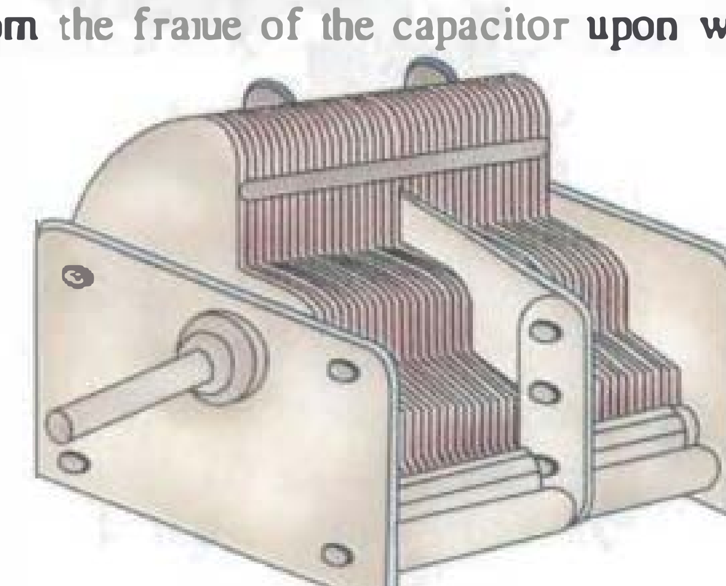
1. are polarity sensitive,
2. have low leakage resistance because the oxide film is not a perfect insulator. In other words, they have high leakage current which can become troublesome.

5.41. Variable Capacitors

A variable capacitor is one whose capacitance can be varied usually by rotating a shaft. It consists of two sets of metal plates separated from each other by air. One set of plates is stationary and is called the stator [Fig. 5.30 (*a*)]. It is insulated from the frame of the capacitor upon which



(*a*) Single section



(*b*) Two-gang

Fig. 5.30

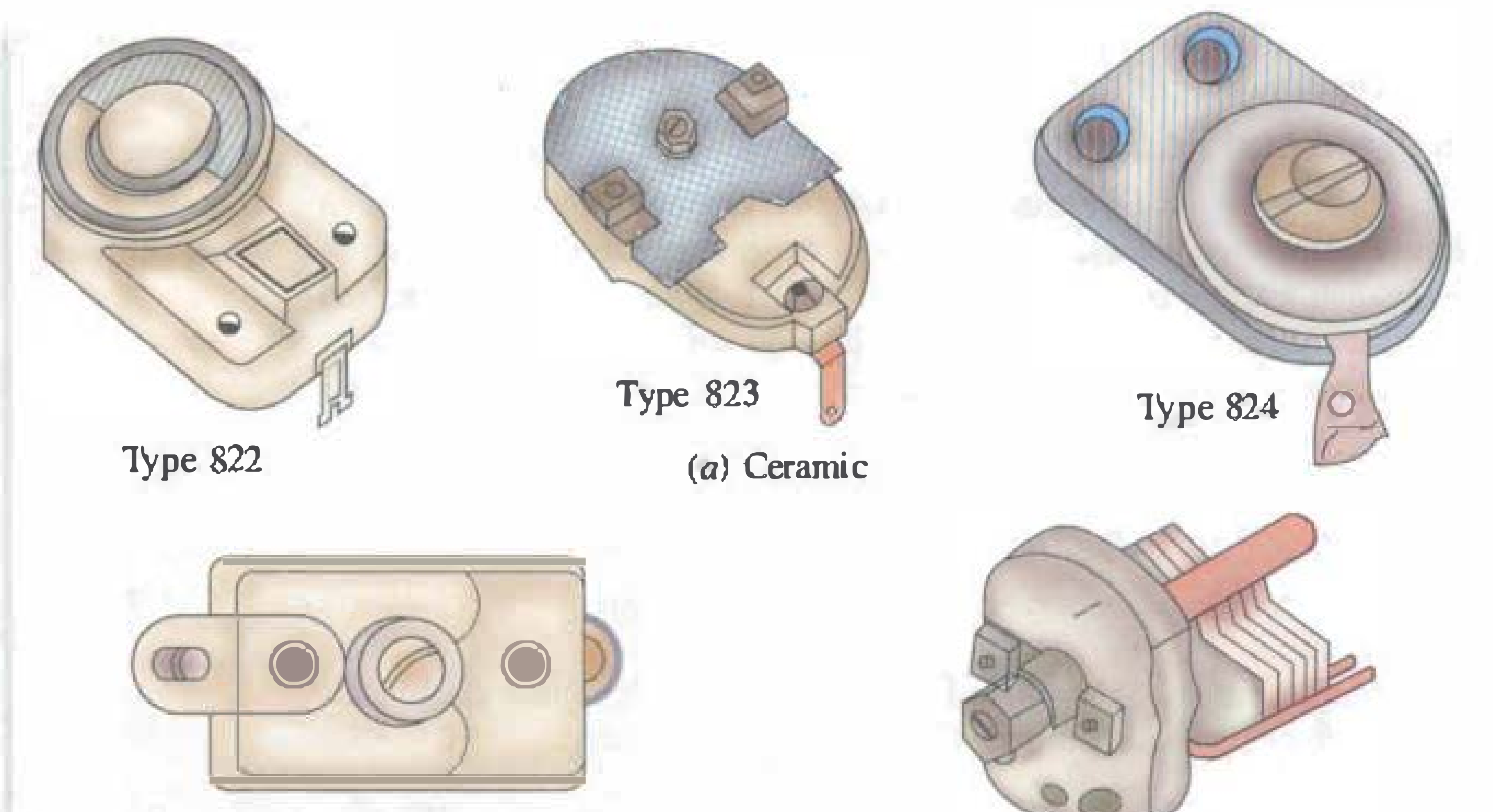
it is mounted. The other set of plates is connected to the shaft and can be rotated. That is why it is called the rotor. By rotating the rotor with the help of a suitable knob, rotor plates can be made to move in or out of the stator plates. Capacitance is maximum when rotor plates are fully 'in' and minimum when 'out.'

If n is the total number of plates and d is the separation between any two adjacent plates, then capacitance for air dielectric is

$$= \frac{(n-1)\,\varepsilon_0\,A}{d}$$

When two or more such capacitors are operated by a single shaft, it is known as a *ganged* capacitor. Fig. 5.30 (b) shows a 2-gang capacitor *i.e.*, one having two separate variable capacitors in one unit rotated by a single control. Commercial receivers and those used by short-wave listeners often have a variable capacitor with three gangs.

Another type of small variable capacitor which is often used in parallel with the main variable capacitor is sometimes known as trimmer and sometimes as padder. It is used primarily for making fine adjustments on the total capacitance of the device.



(a) Ceramic

(b) Mica

Fig. 5.31

(c) Air dielectric

A trimmer (Fig. 5.31) consists of two small flexible metal plates separated by air or mica or ceramic slab as the dielectric. The spacing between the plates can be changed by means of a screw adjustment. As the screw is turned inward, plates are compressed and its capacitance is increased.

Trimmers and padders are usually similar in appearance except that a padder may be somewhat larger or may have more plates. Capacitance of trimmers can be changed from 5 pF to a maximum value of 30 pF. Corresponding values for padder are 10 pF to 500 pF.

Variable capacitors are used primarily as tuning capacitors in radio receivers. When we tune two different stations, we actually vary the capacitance by moving the rotor plates in or out of the stator plates. Combined with an inductance, the variable capacitance tunes the receiver to a different resonant frequency for each transmitting station.

5.42. Voltage Ratings of Capacitors

Voltage rating of a capacitor is given by the maximum potential difference that can be applied across its plates without puncturing its dielectric. Such ratings are given for temperatures up to 60°C.

Higher temperatures result in lower voltage ratings. For general purpose paper, mica and ceramic capacitors, voltage ratings are typically 200-500 V dc. Ceramic capacitors with voltage ratings of 1 to 12 kV are also available. Electrolytic capacitors are commonly used in 25, 150 and 450 V ratings. Additionally, miniature electrolytics with 6 V and 10 V ratings are often used in transistor circuits. These ratings are for dc voltages. Those for ac voltages are less because of internal heat produced by continuous charge and discharge.

Voltage across a capacitor should not be allowed to exceed its rating. However, a capacitor with a higher voltage rating can be used in a low voltage circuit. For example, a 200 V, 0.05 μF capacitor can be replaced by a 400 V, 0.05 μF capacitor but not *vice-versa*.

5.43. Stray Circuit Capacitance

In an electronic circuit, the wiring and other components have capacitance to the metal chassis which acts as negative or grounded plate. Typical values of such stray capacitance are from 5 to 10 pF. Though at ordinary frequencies this value is quite small as compared to concentrated or lumped values of capacitance, it becomes important at high radio frequencies when one is forced to use small values of capacitance. The stray capacitance can be minimised by keeping connecting wires short and by placing leads and components as high off the chassis as possible. Sometimes, for very high frequencies, stray capacitance is included as part of the circuit design itself.

5.44. Leakage Resistance

A perfect or ideal capacitor is one which given the charge once will keep it forever. However, in practice, all capacitors get discharged in the long run due to small leakage current through their dielectric. Since leakage current is very small, leakage resistance is very high being almost 1000 MΩ for paper and mica capacitors and about 0.5 MΩ for electrolytic ones. An actual capacitor can be represented by an ideal capacitor having leakage resistance connected in parallel with it as shown in Fig. 5.32.

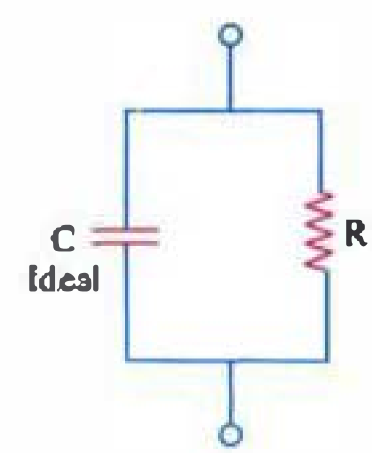


Fig. 5.32

5.45. Capacitors in Series

Connecting capacitors in series is equivalent to *increasing the thickness of the dielectric*.

Hence, combined capacitance is less than the *smallest* individual values.

Following points about series combination of capacitors should be noted :

1. charge on each capacitor is the *same* irrespective of its capacitance,
2. p.d. across each capacitor is *different* being inversely proportional to its capacitance,
3. sum of voltages across the capacitors equals the applied voltage.
   As seen from Fig. 5.33,
   $V = V_1 + V_2 + V_3$
4. combined capacitance is given by the reciprocal formula.
   In Fig. 5.33,

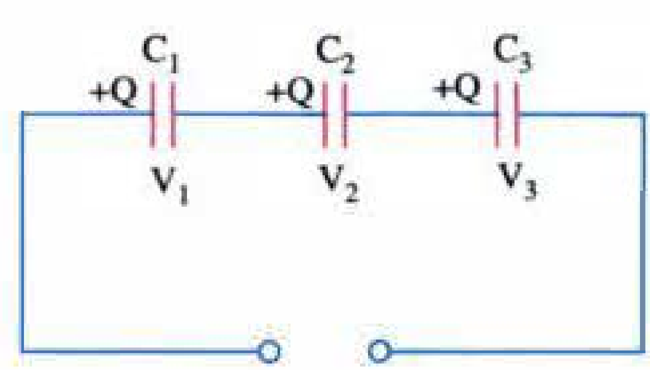


Fig. 5.33

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad \text{or} \quad C = \frac{1}{1/C_1 + 1/C_2 + 1/C_3}$$

Capacitors are used in series to provide a higher voltage breakdown rating for the combination. For example, combined voltage rating of three equal 200 V capacitors becomes 600 V when connected in series (even though overall capacitance is reduced).

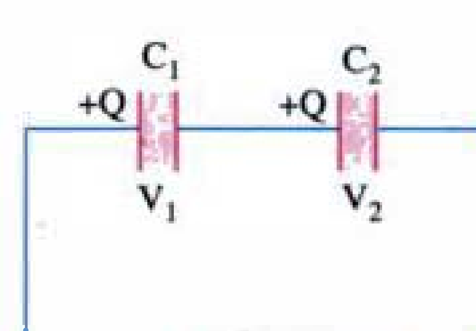


Fig. 5.34

5.46. Two Capacitors in Series

As seen from Fig. 5.34, charge on each capacitor is the same though voltages are different.

1. $$C = \frac{C_1 C_2}{C_1 + C_2}$$

2. $$V_1 = V \frac{C_2}{C_1 + C_2}$$

3. $$V_2 = V \frac{C_1}{C_1 + C_2}$$

5.47. Capacitors in Parallel

Connecting capacitors in parallel is equivalent to *adding their plate areas*. Hence, combined capacitance equals the sum of individual capacitances.

Following facts about parallel combination of capacitors (Fig. 5.35) should be noted :

1. charge across each capacitor is different, being directly proportional to its capacitance
   ($\because \quad Q = CV$)
2. p.d. across each capacitor is the same *i.e.*, the applied voltage V,
3. the sum of the individual charges is equal to the total charge supplied by the power source
   $$Q = Q_1 + Q_2 + Q_3$$
4. combined capacitance is equal to the sum of individual capacitances
   $$C = C_1 + C_2 + C_3$$

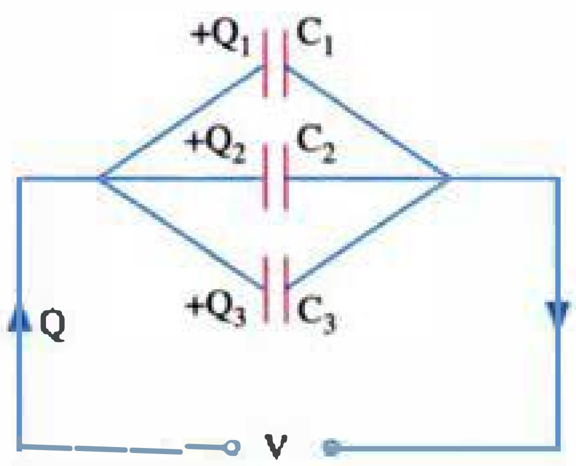


Fig. 5.35

5.48. Two Capacitors in Parallel

Consider the case when only two unequal capacitors are connected in parallel as shown in Fig. 5.36. In this case

1. since V is the same across both capacitors
   $$\because \qquad V = \frac{Q_1}{C_1} = \frac{Q_2}{C_2}$$
   $$\therefore \qquad \frac{Q_1}{C_1} = \frac{Q_2}{C_2} \text{ or } \frac{Q_1}{Q_2} = \frac{C_1}{C_2}$$
2. the two capacitor charges can be expressed in terms of the total charge Q taken from the power source.
   $$Q_1 = Q\frac{C_1}{C_1 + C_2}; \; Q_2 = Q\frac{C_2}{C_1 + C_2}$$

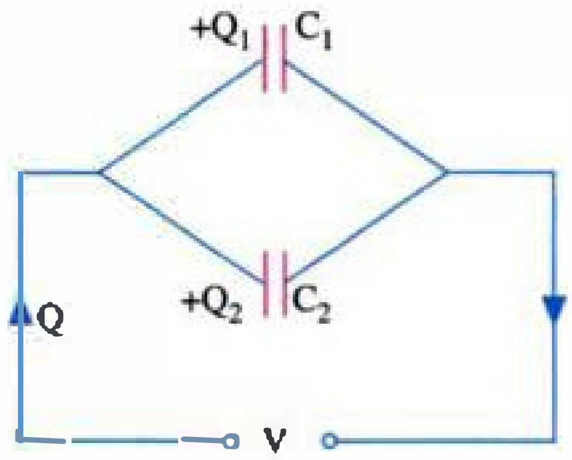


Fig. 5.36

5.49. Energy Stored in a Capacitor

Energy is required to charge a capacitor and is supplied by the charging agency *i.e.*, a battery or any other voltage source. This energy is stored in the electric field set up in the dielectric medium. On discharging the capacitor, the field collapses and the stored energy is released.

$$\text{Stored energy} = \frac{1}{2}CV^2 \text{ joules}$$

This stored energy is the reason why a charged capacitor can produce an electric shock when you touch its two leads. Stored energy of more than 1 joule can be dangerous with a capacitor charged to a voltage high enough (> 90 V) to produce electric shock.

The energy for each "flash" comes from the electrical energy stored in a capacitor.

Example 5.6. *A multiplate capacitor is made up of ten plates 4 cm × 5 cm separated by mica sheets having thickness of 1 mm and a relative permittivity of $\varepsilon_r = 6$. Find its capacitance.*

Solution. $$C = \frac{(n-1)\,\varepsilon_0\,\varepsilon_r\,A}{d}$$

Here, $n = 10,\ \varepsilon_r = 6,\ A = 4 \times 5 = 20\ \text{cm}^2 = 2 \times 10^{-3}$

m^2

$$d = 1\ \text{mm} = 10^{-3}\ \text{m},\ \varepsilon_0 = 8.854 \times 10^{-12}\ \text{F/m}$$

$$C = \frac{(10-1) \times 8.854 \times 10^{-12} \times 6 \times 2 \times 10^{-3}}{10^{-3}}$$

$$= 956 \times 10^{-12}\ \text{F} = \mathbf{956\ pF}$$

Example 5.7. *Two capacitors of 4 μF and 12 μF capacitance and each of working-voltage rating of 24 V are connected in series across a 24 V battery. Calculate*

1. *charge across each,* 2. *voltage across each,* 3. *combined voltage rating.*

Solution. 1. $$C = \frac{C_1 C_2}{C_1 + C_2} = \frac{4 \times 12}{4 + 12} = 3\,\mu\text{C}$$

$$Q = CV = 3 \times 24 = 72\,\mu\text{C}$$

Each of the two series-connected capacitors will have the same charge.

2. $$V_1 = V\frac{C_2}{C_1 + C_2} = 24 \times \frac{12}{16} = \mathbf{18\ V}$$

$$V_2 = V\frac{C_1}{C_1 + C_2} = 24 \times \frac{4}{16} = \mathbf{6\ V}$$

Alternatively, since charge across each capacitor is 72 μC and their capacitances are known, values of V_1 and V_2 can be easily found from this data.

$$V_1 = Q/C_1 = 72/4 = 18\ \text{V};\quad V_2 = Q/C_2 = 72/12 = 6\ \text{V}$$

3. Combined voltage rating is = 24 + 24 = **48 V**

Example 5.8. *Two capacitors of 0.0003 μF and 0.0006 μF are connected in series. Find their combined capacitance.*

If they are connected in parallel, what will be the new value of total capacitance?

Solution. $$C = \frac{C_1 C_2}{C_1 + C_2} = \frac{0.0003 \times 0.0006}{0.0003 + 0.0006} = \mathbf{0.0002\,\mu F}$$

Note. In the case of such fractional capacitances, an easier method is to multiply both capacitance values by a figure that will provide a whole number. Then, when the result has been obtained, it should be divided by the same number. In the present case, we will multiply both capacitances by 10,000. Hence,

$$C = \frac{3 \times 6}{3 + 6} = 2$$

Dividing this result by 10,000, we get

$$C = 2/10{,}000 = 0.0002\,\mu\text{F}$$ — as before

When connected in parallel

$$C = 3 + 6 = 9/10{,}000 = 0.0009\ \mu F$$

Example 5.9. *Find the charges on capacitors shown in Fig. 5.37 and the P.Ds. across them.*

Solution. Equivalent capacitance between points A and B is

$$C_{AB} = C_2 + C_3 = 5 + 3 = 8\ \mu F$$

This capacitance is in series with the 2 μF capacitor.

Hence, combined capacitance is

$$C = \frac{2 \times 8}{2 + 8} = 1.6 \mu C$$

Charge taken from the battery is

$$Q = CV = 1.6 \times 100 = 160\ \mu C$$

Same would be the charge on 2 μF capacitor.

$\therefore \quad Q_1 = 160\ \mu C$

$\therefore \quad V_1 = Q_1 / C_1 = 160/2 = \mathbf{80\ V}$

Now, $\quad V = V_1 + V_2 \quad$ or $\ 100 = 80 + V_2$

$\therefore \quad V_2 = 20\ V$

$\therefore \quad Q_2 = C_2V_2 = 3 \times 20 = \mathbf{60 \mu C}$

$\quad Q_3 = C_3V_3 = 5 \times 20 = \mathbf{100\ \mu C}$

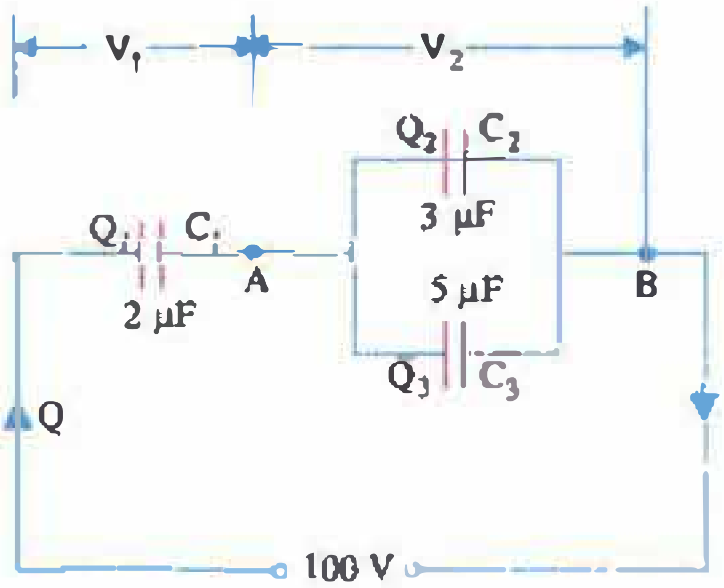


Fig. 5.37

5.50. Troubles in Capacitors

Two common problems with capacitors are (*i*) **open** and (*ii*) **short**. In either case, the capacitor is useless because it cannot store energy. A good capacitor has very high dielectric resistance in the range of 500 to 1000 MΩ for paper and ceramic capacitors and about 0.5 MΩ for electrolytic capacitors. A short-circuited capacitor has *zero* resistance *i.e.,* it shows continuity. A leaky capacitor has a resistance somewhat lower than its normal value.

5.51. Checking Capacitors with Ohmmeter

The procedure is as follows :

1. Discharge the capacitor before checking.
2. Make sure that ohmmeter voltage does not exceed the working voltage of the capacitor.
3. Disconnect one side of the capacitor from the circuit to eliminate any parallel resistance path that can lower the resistance reading.
4. Keep your fingers off the conductors because the body resistance (50 K or so) connected in parallel will lower the resistance.
5. Use highest-ohm scale.

The trouble in a capacitor is indicated by the following ohmmeter readings :

1. If meter pointer immediately goes to practically zero and stays there, the capacitor is short-circuited.
2. If the pointer first goes to low-resistance side (showing capacitor charging) and then comes up and shows a reading less than the normal, it is leaky.

3. If the pointer does not go to low-resistance side of the scale (*i.e.*, if capacitor shows no charging action) but just goes straight to infinity, the capacitor is open.
4. If the meter pointer first moves quickly towards the low-resistance side of the scale (showing capacitor charging) and then slowly goes to infinity, it shows a good capacitor which is supposed to have very large (almost infinite) resistance.

5.52. Charging of a Capacitor

As shown in Fig. 5.38 (*a*), when S is closed, the capacitor starts getting charged from the battery. The capacitor, however, requires a certain amount of time to get fully charged to the battery voltage V. The time taken depends on its capacitance (C) and the resistance (R) in the charging circuit.

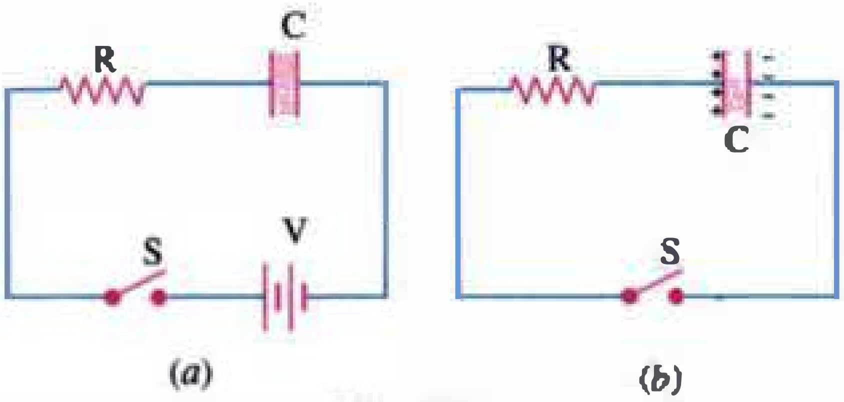


Fig. 5.38

The time required for the charge to attain 63.2% of its final value is called *time-constant* (T) of the circuit. Its value = CR and is in seconds if C is in farads and R in ohms.

A total time equal to 5 time-constants ($= 5T = 5CR$) is required for the capacitor to be considered fully charged as shown in Fig. 5.39.

In Fig. 5.38 (*b*), the fully-charged capacitor can be discharged through R by closing S. In one time-constant, the charge decreases to 36.8% of its fully-charged value. Again, in 5 time-constants, the capacitor is considered fully discharged.

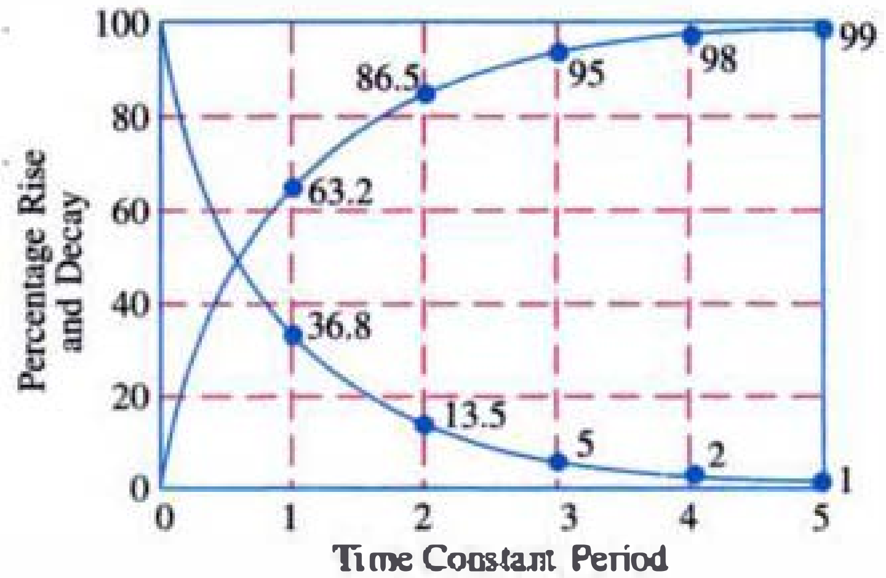


Fig. 5.39

The increase and decrease of charge across the capacitor can be found from the Universal Time Constant Chart of Fig. 5.39. It also represents rise and decay of charging and discharging current of the capacitor respectively.

Example 5.10. *A 50 μF capacitor is charged a 40 K resistor to a potential difference of 400V. Calculate*

1. *time constant of the circuit ;*
2. *value of full charge;*
3. *charge acquired in one time-constant ;*
4. *energy stored in the fully-charged capacitor.*

Solution.

1. $T = CR = 50 \times 10^{-6} \times 40 \times 10^3 = \textbf{2 seconds}$
2. Full charge, $Q = CV = 50 \times 20^{-6} \times 400 = \textbf{0.02 C}$
3. Charge acquired by the capacitor in one time-constant *i.e.*, in 2 seconds

$$= 63.2\% \text{ of full charge}$$
$$= 0.632 \times 0.02 = \textbf{0.0126 C}$$

4. Energy stored $= \frac{1}{2} CV^2 = \frac{1}{2} \times (50 \times 10^{-6}) \times 400^2 = \textbf{2 joules}$

5.53. Capacitor Connected Across an AC Source

Suppose a capacitor is connected across an ac voltage supply as shown in Fig. 5.40. It is found that the capacitor is charged first in one direction during the positive half-cycle of the applied voltage

[Fig. 5.40 (*a*)] and then in the opposite direction during the negative half-cycle [Fig. 5.40 (*b*)]. Since, it is an alternating voltage, the capacitor keeps getting charged and discharged continuously. If a lamp is included in the circuit, it will continue to glow. The reason is as follows :

During the positive half-cycle of the applied voltage, charging current flows from plate N to M through the *external* circuit containing the lamp. It cannot flow 'through' the dielectric. During the negative half-cycle, current direction is reversed but it again passes through the lamp thereby keeping it alight. It hardly makes any difference to the lamp whether current through it passes from left to right or right to left. It will be appreciated that no current whether dc or ac can pass *through* a capacitor.

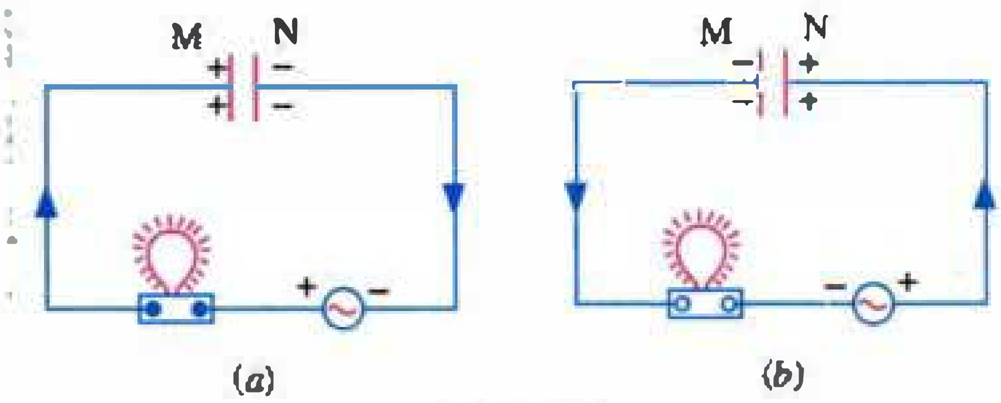


Fig. 5.40

5.54. Capacitive Reactance

A good capacitor completely blocks the passage of direct current 'through' it. However, it allows alternating current to pass 'through' it in the sense discussed above. In fact, what it actually does is that it allows current to flow through the *external* circuit first in one direction and then in the opposite direction at a frequency equal to the frequency of the applied voltage. Even then, it offers opposition to the flow of this alternating current. This opposition is called capacitive reactance (X_C) and is given by

$$X_C = \frac{1}{2\pi f C} = \frac{0.159}{f\,C}$$

Its unit is ohm.

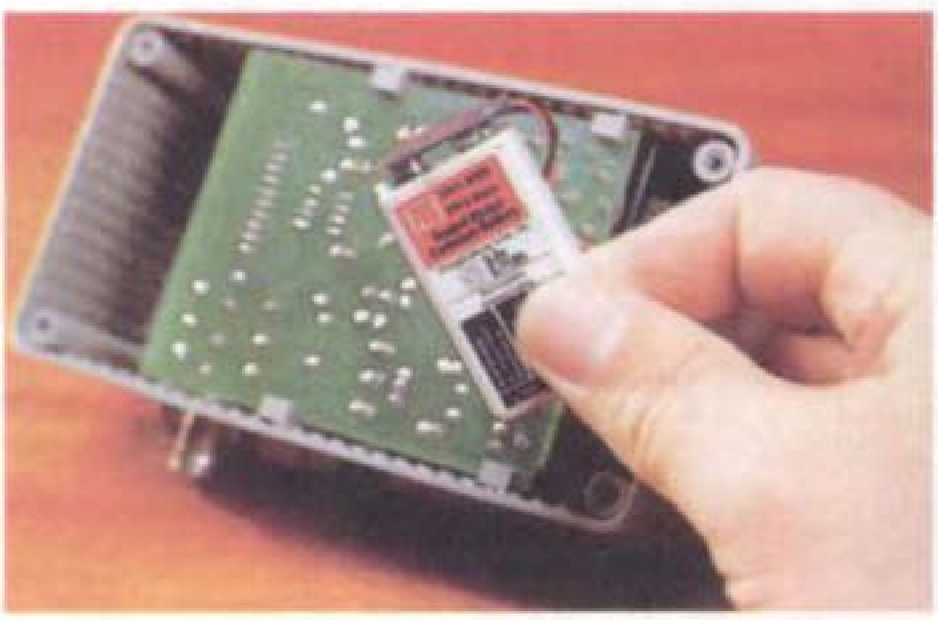
Capacitive reactance varies *inversely* as the frequency of the applied ac voltage. Higher the frequency, lesser the reactance and *vice-versa*. For dc voltage $f = 0$, hence $X_C = 1/0 = \infty$. That is why a capacitor blocks direct current and voltage.

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word(s) or numerical value (s).

1. Wire-wound resistors show troublesome .... effects at high frequencies.
2. The amount by which the actual resistance of a resistor may vary form its nominal value is known as the ....of the resistor.
3. A potentiometer is used for changing the value of voltage whereas a rheostat is used for changing............ .
4. The first .... colour bands of a resistor indicates the resistance value of a resistor whereas fourth one indicates its resistance ....
5. Iron cores are laminated in order to minimise .... loss.
6. Inductor cores which have the least core loss even at high frequencies are made of ....
7. Unwanted inductance in a circuit is known as inductance.
8. Opposition offered by a coil having both reactance and resistance is called ....
9. Higher the Q-value of a tuned circuit, greater its ....
10. As separation between the two plates of a capacitor is increased, its capacitance is............
11. For the same size, a ceramic capacitor has .... capacitance than a mica capacitor.
12. Ceramic capacitors are preferable for use at .... frequencies.
13. Electrolytic capacitors are called .... capacitors.
14. Variable capacitors are frequently used in ....circuits of radio receivers.
15. Higher the applied frequency, ...the reactance offered by a capacitor.

Energy Sources

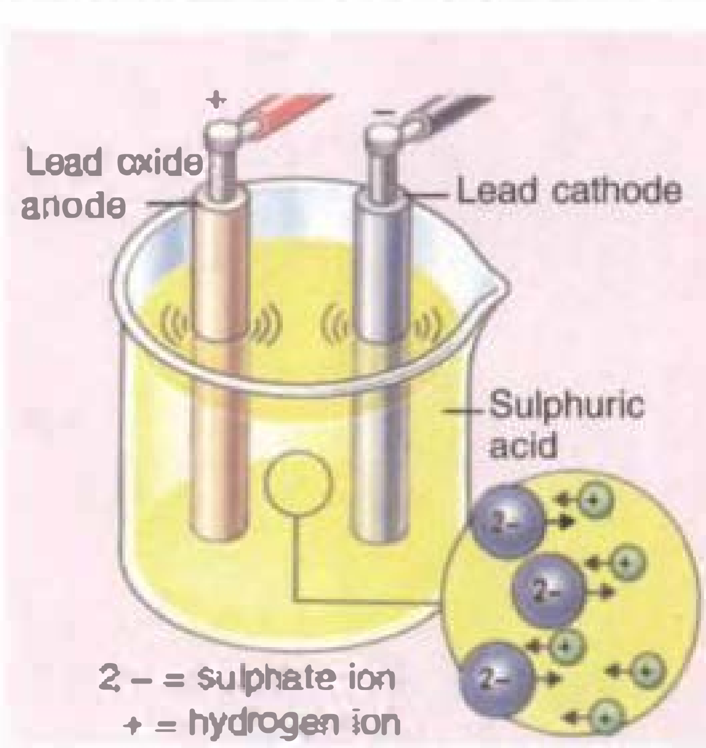


6.1. Primary and Secondary Cells

A voltaic chemical cell is a combination of materials which produce direct-current (dc) electrical energy from its *internal* chemical reactions. These cells can be sub-divided into the following two classes :

(*a*) **Primary Cell.** In this cell, chemical reactions are irreversible. During the generation of electric energy, it consumes materials which cannot be replenished by recharging. Hence, such cells cannot be recharged back to their original condition after being discharged.

(*b*) **Secondary Cell or Storage Cell or Accumulator.** In these cells, chemical reactions are reversible. After discharge, such a cell can be restored to its original condition by passing an electric current through it in a direction opposite to that of the discharge current.



Secondary cell.

Further points of comparison between the two classes are tabulated given on next page.

	Primary Cells	Secondary Cells
1.	low cost	expensive
2.	small size	reasonably small
3.	short life	comparatively long life
4.	useless when discharged	rechargeable
5.	light weight	heavier

6.2. Cell and Battery

A battery consists of two or more cells connected either in series or parallel or both. Often, many people call a flashlight cell a flash light battery which is technically incorrect.

6.3. Voltage and Current of a Cell

The voltage rating of a cell is given by its open-circuit voltage *i.e.*, voltage it can produce when not connected to a load circuit. This voltage depends on the types of materials used and not on the physical size of the cell.

The capacity of a cell is given by the amount of current it can supply to an external load circuit. It depends on the condition and quantity of electrolyte and physical size of the electrodes. Everything else being the same, a larger cell can deliver more current for a longer period of time than a smaller one.

6.4. Cell Life

It is given by the period of time during which the cell can be stored on a shelf without losing more than approximately 10% of its original capacity. The loss of capacity occurs even when cell is not in use and is primarily due to partial drying up of paste electrolyte and to other chemical actions which change the materials within the cell. Since heat helps both these processes, it is advisable to keep a cell in a cool place in order to extend its life.

6.5. Different Types of Dry Cells

We will consider the following primary and secondary cells :

(*a*) carbon-zinc cell

(*b*) alkaline cell

1. manganese-alkaline cell
2. nickel-cadmium cell
3. mercury cell
4. silver-oxide cell
5. lead-acid cell

6.6. Carbon Zinc Cell

It is the oldest and most widely used commercial dry cell (Fig. 6.1).

(*a*) Construction

1. The zinc can functions both as a container to hold the electrolyte and as the negative electrode.
2. The positive electrode is a carbon rod down the centre but not low enough to touch the zinc bottom.
3. The electrolyte is a paste of ammonium chloride and manganese dioxide.

(*b*) Size and Voltage

Such cells are available in several sizes and have open-circuit voltage from 1.4 to 1.6 V, regardless of size. Larger cells with more zinc, electrolyte and depolarizer have a higher current rating upto 0.25 A or 250 mA. The flashlight cell has a current rating of 50 mA for nearly 60 hours of service. The cell has a height of about 57 mm and a diameter of about 32 mm.

Carbon-zinc batteries are made in many types having voltages of 3, 4, 5, 6, 9, 13.5, 22.5 and 45 V (all multiples of 1.5 V). In some batteries, cells are cylindrical in shape and in others they are flat.

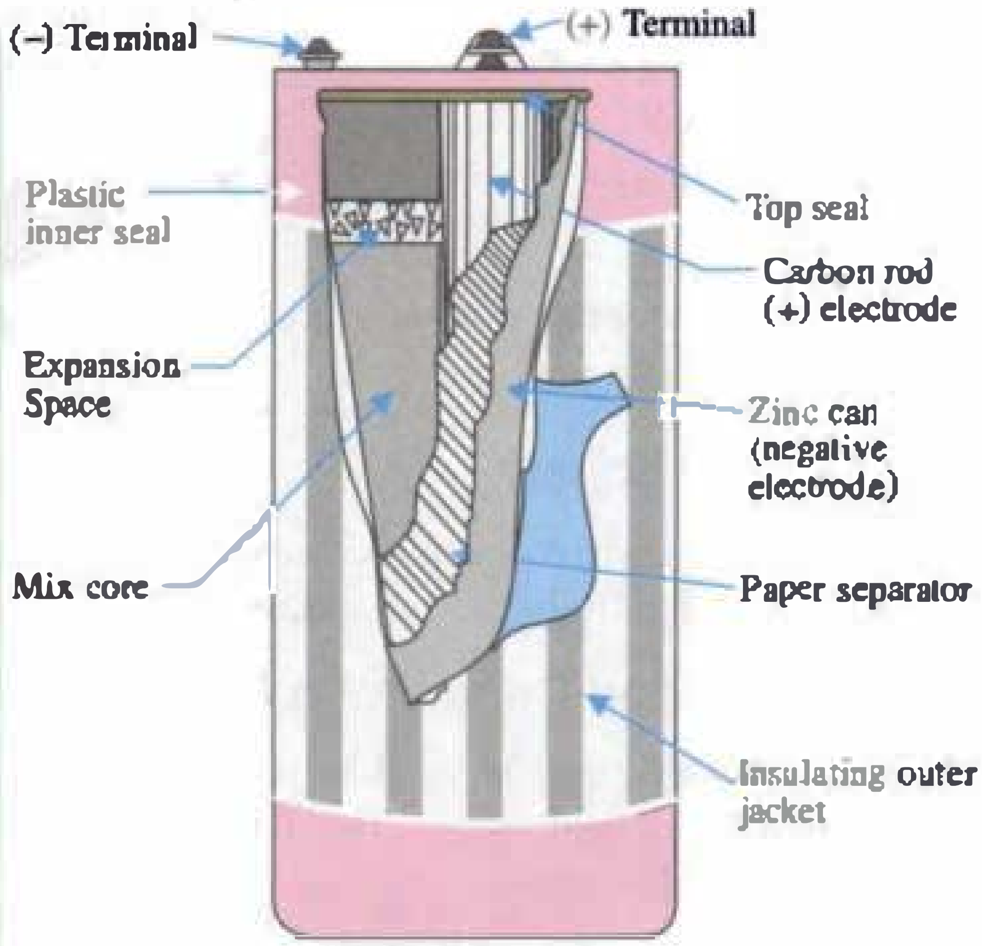


Fig. 6.1

(c) Operating Efficiency

Carbon-zinc cells and batteries render efficient service provided they are used *intermittently* for short periods at a time at relatively low currents. Such operation helps to keep them sufficiently depolarised.

(d) Recharging

The dry cell can be recharged if certain precautions are taken :

1. voltage should not be below 1 V when removed for service,
2. charging rate should be kept low and spread over 10 to 15 hours,
3. recharged cells should be used at one in view of their limited shelf life.

This walkman is powered by batteries of the primary cell type. Typically, they have to be replaced every two or three months.

6.7. Alkaline Cells

All those cells which use a caustic electrolyte are called alkaline cells. We will consider

1. manganese-alkaline cell
2. nickel-cadmium cell
3. mercury cell and
4. silver-oxide cell.

Fig. 6.2

6.8. Manganese Alkaline Cell

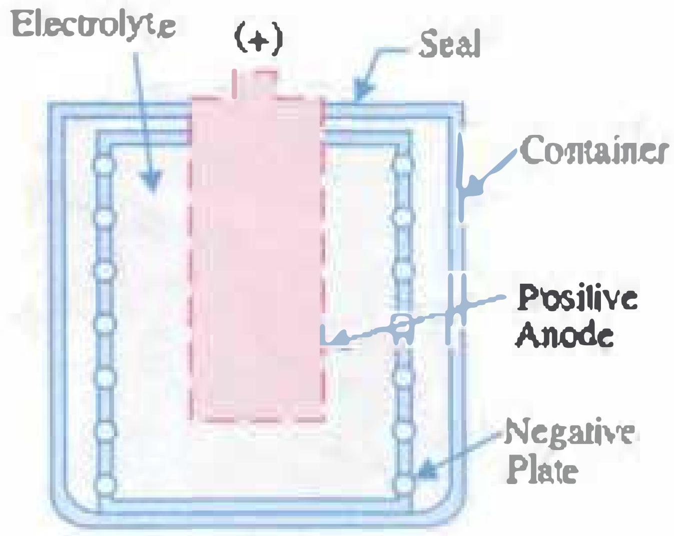
It is a *primary* cell having zinc as anode and manganese dioxide as cathode in a leak-proof steel can (Fig. 6.2). The electrolyte is potassium hydroxide (KOH) or sodium hydroxide (NaOH). Because of the high conductivity of the electrolyte, this cell has higher current rating than a carbon-zinc cell. It provides an output voltage of 1.5 V. Some alkaline batteries can be recharged a few times and have voltages of 4.5, 7.5, 13.5 and 15 V.

6.9. Nickel Cadmium Cell

It is a *dry* cell but is *rechargeable*. In present-day electronics, it has superseded both lead-acid cell and nickel-iron (NiFe) alkaline cell.

(a) Construction

The action material cadmium (a metal akin to zinc), in powder form, is pressed (*i.e.*, sintered) into perforated steel plates which then form the negative electrode of the cell (Fig. 6.3). The positive anode is a steel mesh coated with solid nickel hydroxide (NiOH). The electrolyte is potassium hydroxide (caustic potash) usually in jelly form. The container is a steel can which is sealed after the cell is placed in it. These cells are also available in flat button shape.



(a)

(b)

Fig. 6.3

(b) Voltage and Current

The open-circuit voltage of such cells is from 1.25 to 1.5 V. They have much longer life when they are rapidly discharged at intervals. In fact, long periods of inactivity can cause the cells to fail. Such cells need to be charged at constant current and can be recharged upto 1000 times or more.

These cells have very low internal resistance and can deliver high currents without much loss of terminal voltage. The most common nickel-cadmium batteries have voltages of 6, 9.6 and 12 V.

Their chemical reaction is given by the following equation :

$$Cd + 2\,NiOH + 2\,KOH = Cd\,(OH)_2 + 2\,Ni + 2\,KOH$$

Fig. 6.4 shows the range of rectangular nickel-cadmium (Nicad) cells and batteries. These Nicad cells have a normal no-load voltage of 1.2 V, are capable of high current loads and 1000 cycles of discharge, can tolerate overcharge and general electrical abuse like short circuit.

Fig. 6.4

(c) Uses

Since such cells can easily supply high current, they are widely used as sources of energy in radios, TV sets, tape recorders, cameras and cordless type home appliance such as electric toothbrush or electric carving knife etc. They give good service under extreme conditions of shock, vibration and temperature.

6.10. Mercury Cell

It is a *primary* cell and is widely used in miniaturised electronic gadgetry.

(a) Construction

The cathode is made of compressed mercuric oxide and graphite whereas anode is made of highly purified zinc powder.

The two are separated by a porous material. The electrolyte is a paste mixture of potassium hydroxide and zinc oxide. The flat pallet construction of a mercury cell is shown in Fig. 6.5.

(b) Size and Voltage

Such cells are available in wide range of shapes and sizes—the smallest being about 3 mm thick and 12.5 mm in diameter. Open-circuit voltage at room temperature varies from 1.35 to 1.4 V depending on the electrolyte mixture. With pure mercuric oxide for cathode, voltage output is extremely stable at 1.35 V. Mercury batteries are available in a variety of voltage ratings.

(c) Uses

Mercury cells enjoy a long shelf life without deterioration and are extremely rugged.

Since they can provide almost constant voltage under varying load conditions, mercury cells and batteries are widely used in electronic watches, hearing aids and test instruments etc.

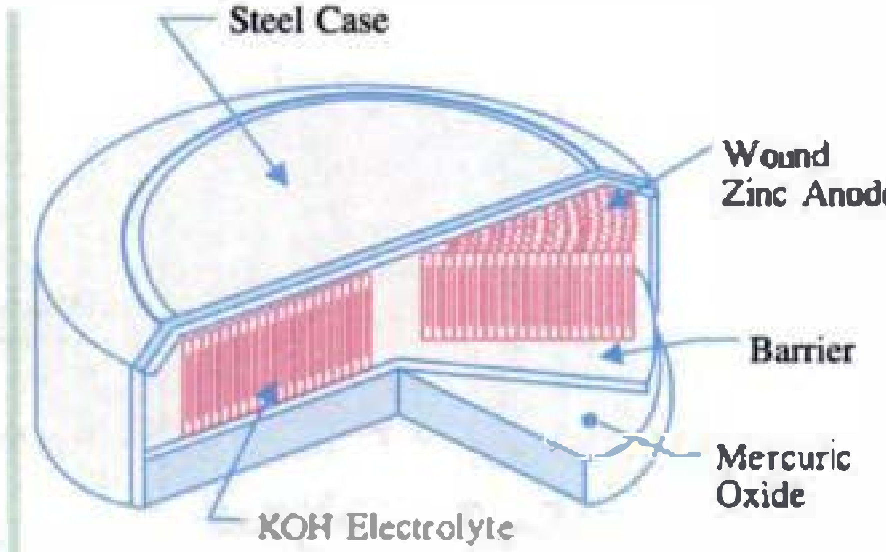


Fig. 6.5

6.11. Silver Oxide Cell

It is a *primary* cell with an open-circuit voltage of 1.5 V. It has a cathode of silver oxide and an anode of zinc in an alkaline electrolyte. As shown in Fig. 6.6, it is generally made in button size for use in cameras, hearing aids and electronic watches.

6.12. Lead Acid Cell

It is a *wet* secondary cell mostly used for making automobile batteries.

(a) Construction

Its anode plate (brown coloured) is a grid made of a lead-antimony alloy into which is pressed the active material : lead peroxide (PbO_2). The cathode is a similar plate having pure porous (sponge like) lead as active material. The two plates are immersed in a solution of dilute sulphuric acid of specific gravity 1.21 or so.

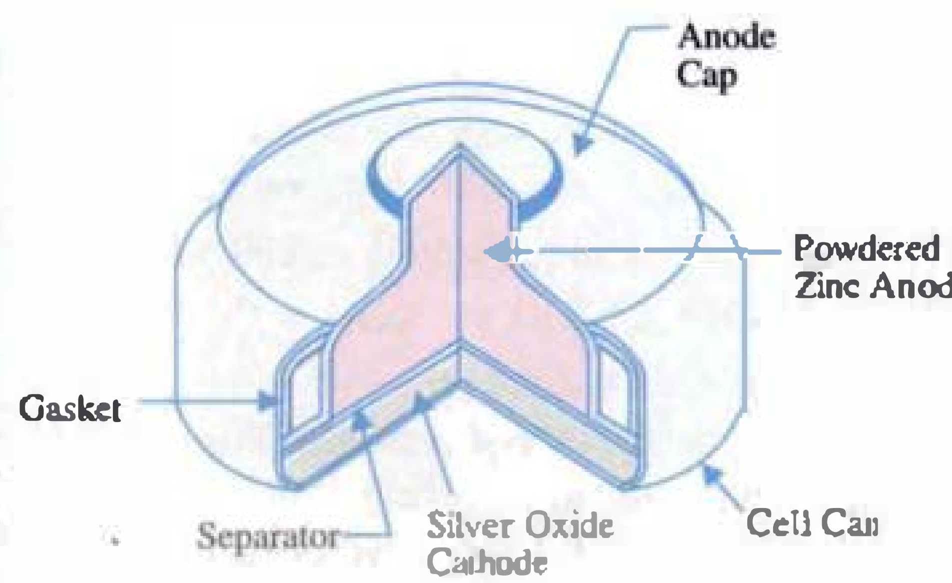
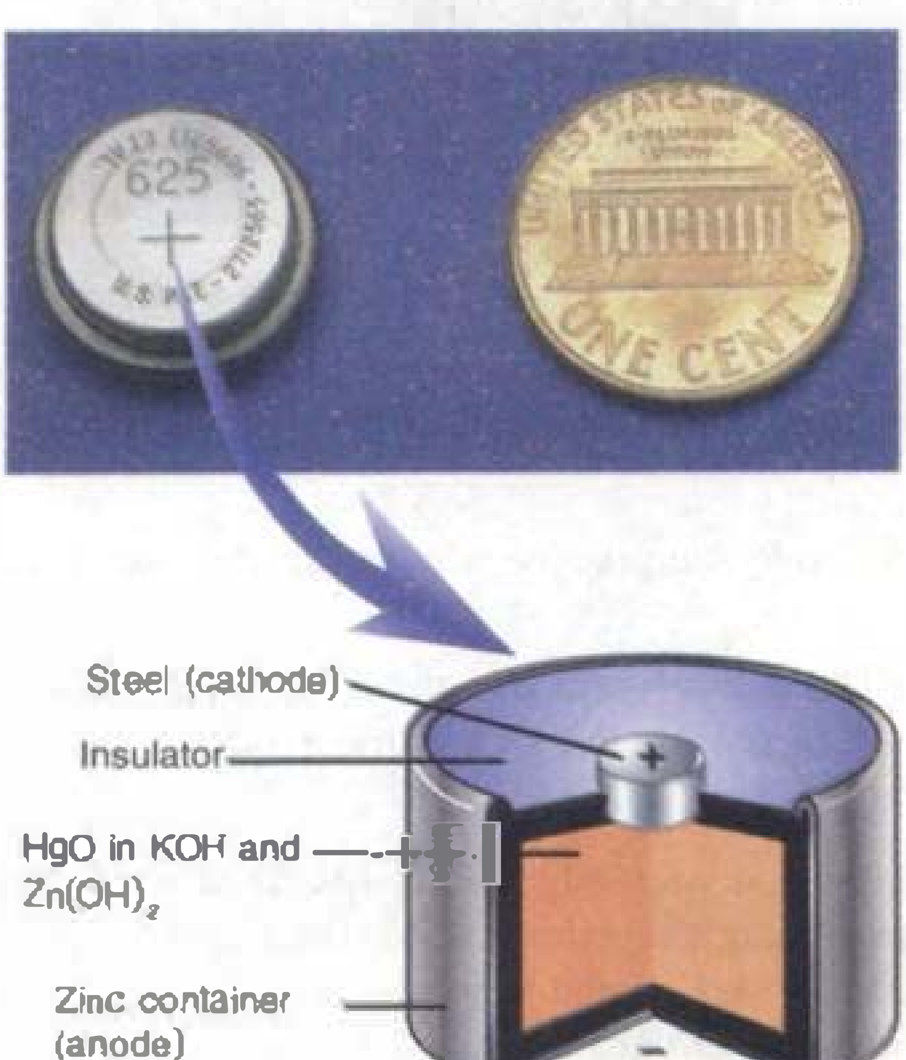


Fig. 6.6

(b) Voltage

It has an open-circuit voltage of 2 to 2.2 V when fresh. It should not be used after its voltage has fallen to 1.85 V when it should be put on charge. It has much larger current capacity as compared to dry cells, considered earlier.



A mercury cell in section.

(c) Use

Principal use of these cells is in the manufacture of portable lead-acid batteries used in automobiles (car and motor vehicles). For car battery, 6 cells are connected in series to give a total voltage of 12 V or more. For traction batteries, the voltages vary from 12 V (6 cells) to 64 V (32 cells) for industrial trucks and from 30V (15 cells) to 72 V (56 cells) for dairy and bakery road vehicles.

6.13. Battery Rating

Lead-acid batteries are rated in terms of discharge current, they can supply continuously for a specified period of time. It is usually expressed in ampere-hours (Ah). The capacity is always given at a specified rate of discharge usually 20 hour rate. It means that a battery which is rated at 100 Ah should deliver 5 A of current continuously for 20 hours and maintain at least 1.75 V per cell. Of course, battery can supply less current for longer time or more current for a shorter time.

6.14. Testing Dry Cells

The condition of a dry cell or battery can be checked by the terminal voltage developed *when it is connected to a load*. If this voltage is less than 80% of the open-circuit voltage, it should be rejected. The basic reason is that a bad cell has high internal resistance which will become detectable when cell is tested *on load*. Due to normal current flow, there would be a large internal drop and hence terminal voltage would drop by a considerable amount. Such would not be the case when cell is tested on no-load.

6.15. Photoelectric Devices

As the name shows, these devices convert light energy directly into electric energy. We will consider the following semiconductor devices only because they are self-generating.

1. photovoltaic cell
2. solar cell

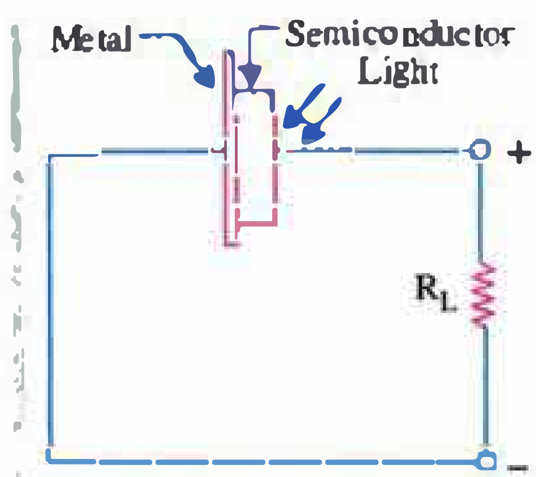
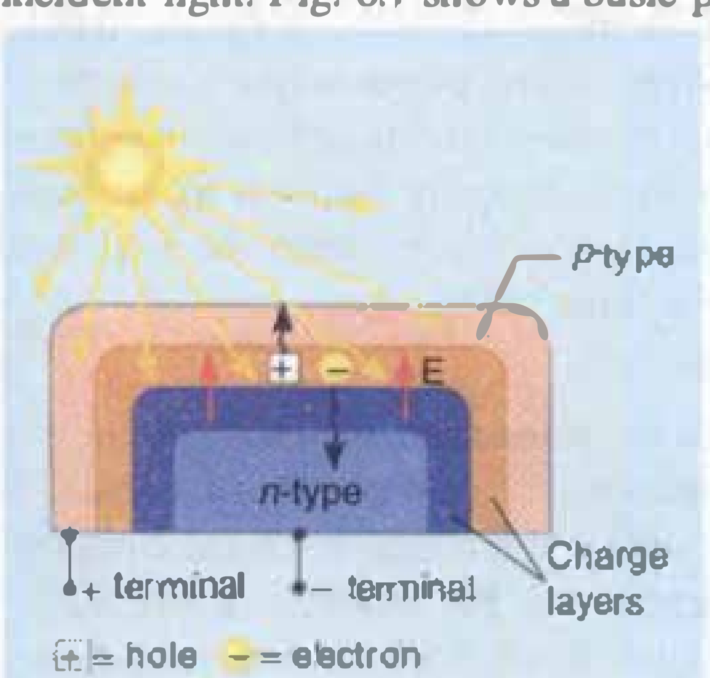


Fig. 6.7

6.16. Photovoltaic Cell

In this cell, light energy is used to create a potential difference which is directly proportional to the frequency and intensity of the incident light. Fig. 6.7 shows a basic photovoltaic cell.



A solar cell formed from a p-n junction. When sunlight strikes the solar cell it acts like a battery, with positive and negative terminals.

It consists of a piece of semiconductor material such as selenium (Se), silicon (Si) or germanium (Ge) which is bonded to a metal plate.

When light falls on the semiconductor, valence electrons and holes are liberated from its crystal structure. These electrons flow out of the semiconductor into the metals whereas holes flow in the opposite direction. It creates a potential difference between the semiconductor and the metal which is sufficient to cause current flow through a load resistor as shown in Fig. 6.7.

These cells are used in devices like portable exposure meters and direct-reading illumination meters.

6.17. Solar Cell

It is also called solar energy converter and is basically a P-N junction device which converts solar energy into electric energy.

(a) Construction and Working

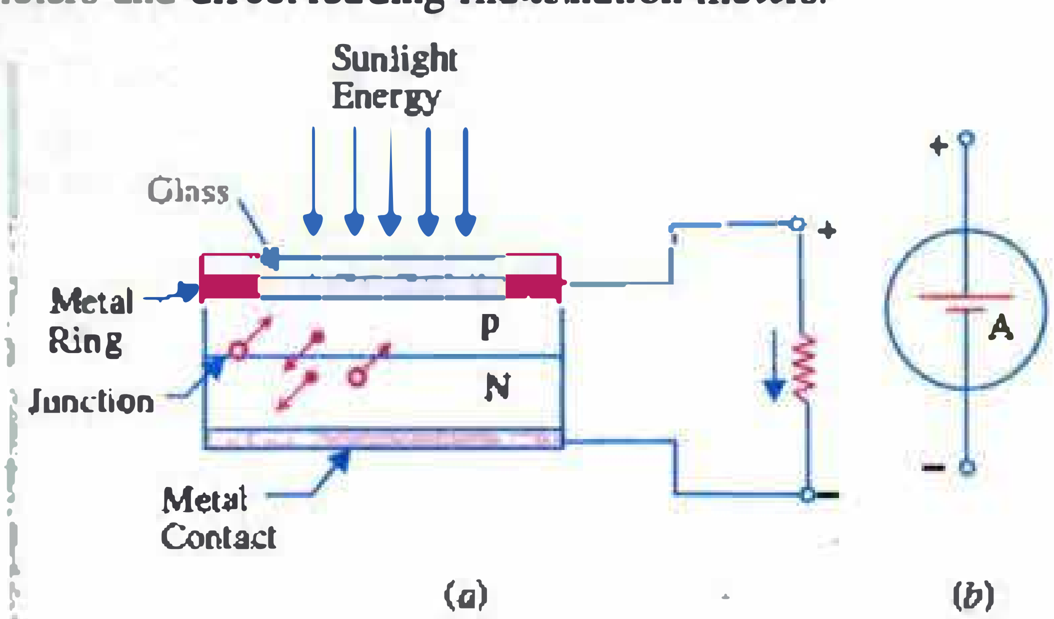


Fig. 6.8

As shown in Fig. 6.8 (*a*), it essentially consists of a silicon P-N junction diode generally packaged in TO-type can with a glass window on top. Surface layer of P-material is made extremely thin so that incident light photons may easily reach the P-N junction.

When these photons collide with valence electrons, they impart them sufficient energy as to leave their parent atoms. In this way, free electons and holes are generated on both sides of the junction and their flow constitutes the minority current. This current is directly proportional to the illumination (lumen/metre^2 or mW/cm^2) and also depends on the size of the surface area being illuminated. The open-circuit voltage V_{oc} is a function of illumination. Consequently, power output of a solar cell depends on the level of sunlight illumination. Power cells are also available in flat strip form so as to cover sufficiently large surface area.

This calculator makes use of solar energy.

The nickel-plated ring around the P-layer acts as the positive output terminal (*i.e.*, anode) and the metal contact at the bottom serves as the negative output terminal (*i.e.*, cathode). The symbol is shown in Fig. 6.8 (*b*). Si and Ge are the most widely used semiconductor materials for solar cell although gallium arsenide (GaAs), indium arsenide (In As) and cadmium arsenide (Cd As) are also being used now-a-days.

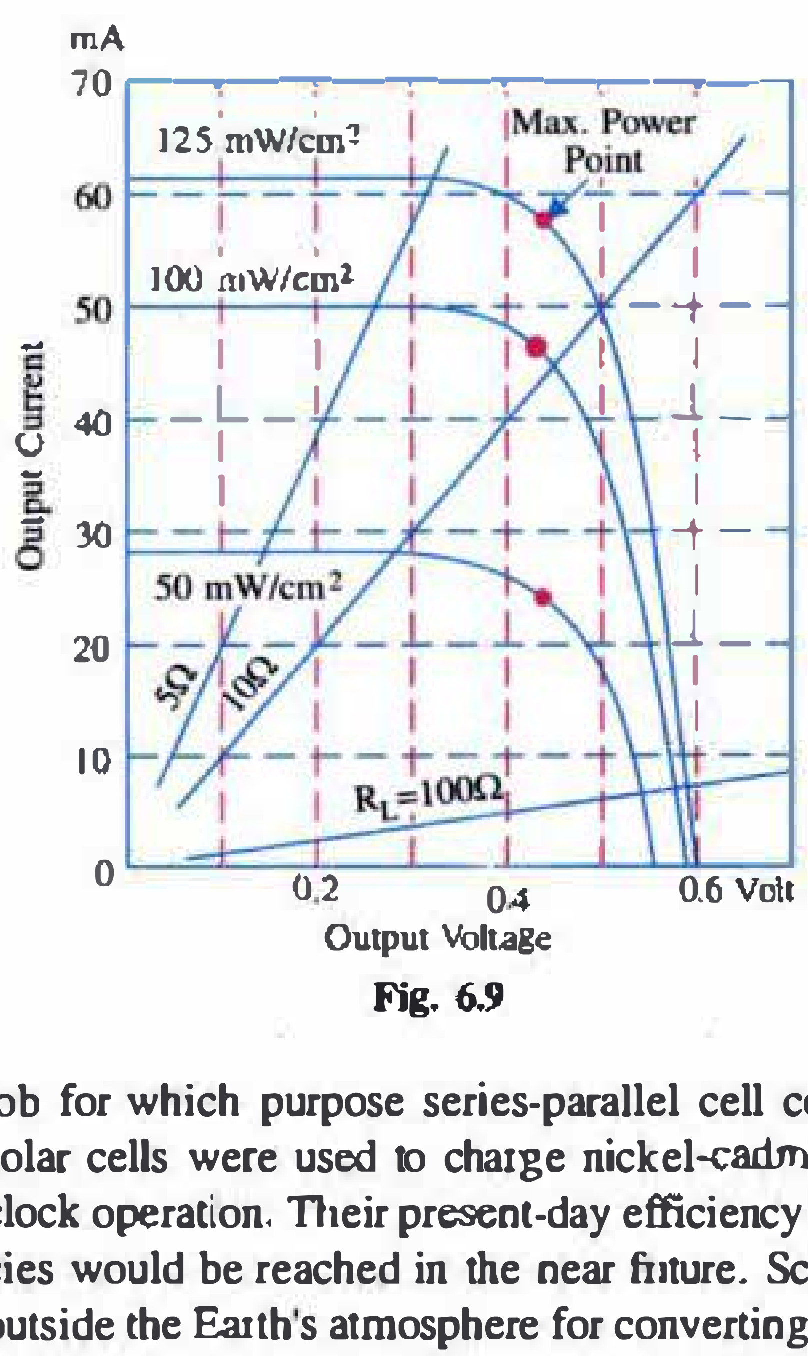


Fig. 6.9

(*b*) Characteristics

Typical V-I characteristics of a solar cell corresponding to different levels of illumination are shown in Fig. 6.9.

Consider the characteristic for incident illumination of 100 mW/cm^2 in Fig. 6.9. If we short-circuit the cell, current is maximum and equals 50 mA. Since output voltage is zero, power output is also zero. On open-circuit, current is zero though output voltage is nearly 0.57 V. Hence, power output is again zero. For obtaining maximum power output, the cell must be operated at the 'knee' of the curve.

(*c*) Uses

Solar cells are being used on board satellites to recharge their batteries. Since their sizes are small, a large number of cells are required to do the charging job for which purpose series-parallel cell combinations are employed. For example, about 9,000 solar cells were used to charge nickel-cadmium batteries of Tiros weather satellite for around the clock operation. Their present-day efficiency level is around 15% but it is hoped that higher efficiencies would be reached in the near future. Scientists are planning to orbit large banks of solar cells outside the Earth's atmosphere for converting solar energy into electricity. This energy would then be sent to Earth in the form of a powerful microwave beam which would be reconverted into electricity for terrestrial use.

Example 6.1. *An Earth satellite has 12 V nickel-cadmium batteries which supply a continuous current of 0.5 A throughout the day. Solar cells having V-I characteristics of Fig. 6.9 are employed to keep the batteries fully charged. If illumination from the Sun for 12 hours in every 24 hours is 125 mW/cm^2, determine the approximate number of solar cells required.*

Solution. The circuit for the solar cell battery charger is shown in Fig. 6.10. Let there be n cells connected in series to provide higher voltage and let m such series-groups be connected in parallel to provide the necessary current. Total number of cells required = $m \times n$.

As seen from the V-I characteristics of Fig. 6.9, each cell supplies 56 mA at 0.45 V. If we allow a drop of 1.5 V for series resistor etc., we need (12 + 1.5) = 13.5 V from each series group.

$\therefore \quad n \times 0.45 = 13.5$ Ah

or $\quad n = 13.5/0.45 = 30$

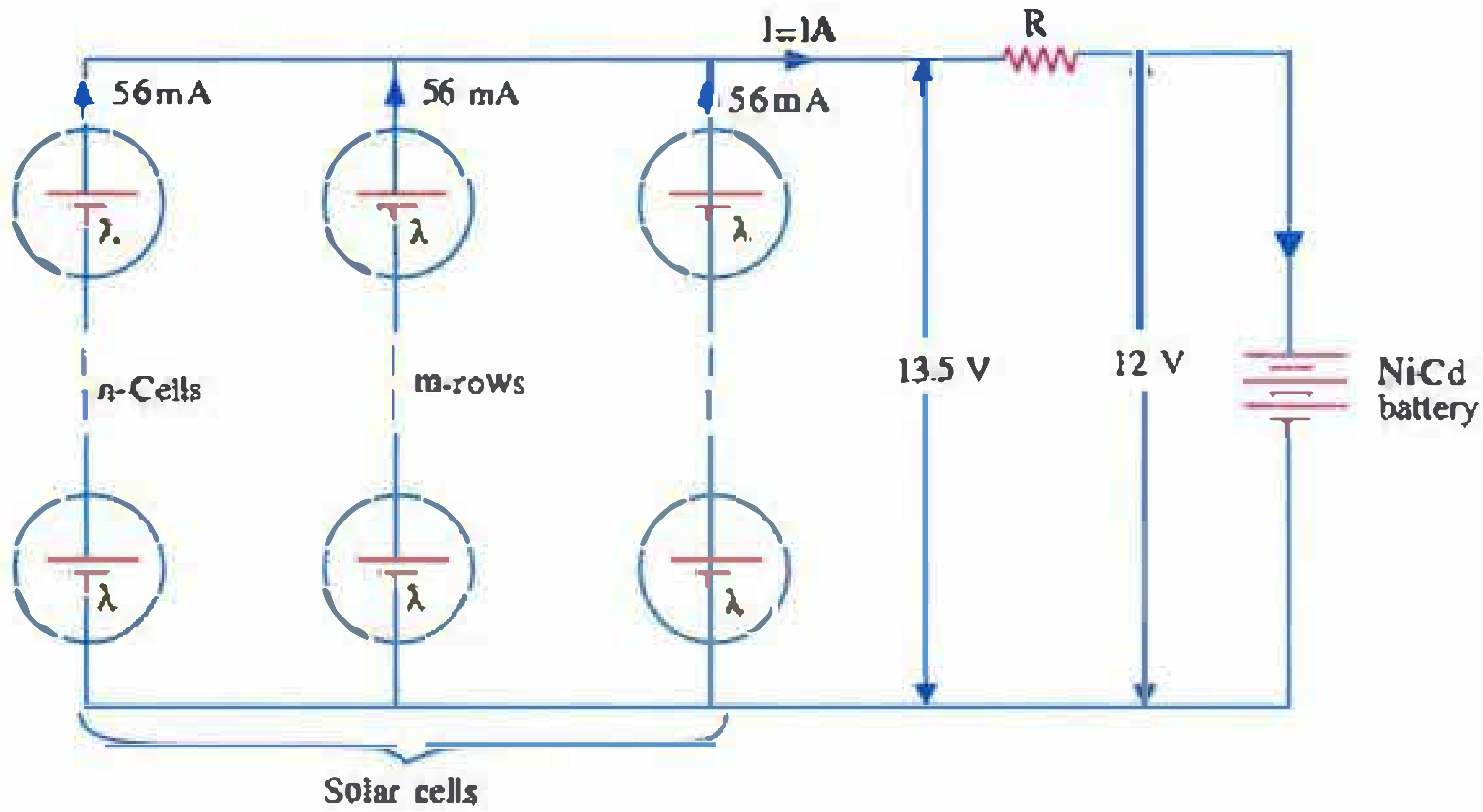


Fig. 6.10

Obviously, this much charge must be put back into the battery by the solar battery charger. Since solar battery itself is illuminated for only 12 hours per day, it must provide a charging current of 12 Ah/12 h = 1 A. Since each row can supply only 56 mA = 0.056 A.

$\therefore \quad m \times 0.056 = 1 \quad$ or $\quad m = 1/0.056 = 18$

Hence, total number of solar cells needed to make up the required solar battery charger is

$$= m \times n = 18 \times 30 = \mathbf{540}$$

CONVENTIONAL PROBLEMS

1. A 1.5 V carbon-zinc dry cell is connected across a load of 1000 Ω. Calculate the current and power supplied by it. **[1.5 mA ; 2.25 mW]**
2. A 6 V lead-acid has an internal resistance of 0.01 Ω. What would be the short-circuit current of the cell ? Will you be able to get it in practice ? **[600 A, No]**
3. A lead-acid battery discharges at the rate of 5 A for 20 hours. (*a*) How much charge must be put back into the battery to restore its original charge assuming 100% efficiency ? (*b*) How long will this charging take place if charging current is 2.5 A ? **[(*a*) 100 Ah or 36 × 10^4 (*b*) 40 h]**
4. The output voltage of a Ni-Cd battery drops from 12 V at zero load to 11.95 V with a load current of 5 A. What is the internal resistance of the battery ? **[0.01 Ω]**

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word (s) or numerical value (s).

1. Devices which convert light energy directly into electric energy are called .... devices.
2. A .... cell is one that cannot be recharged.
3. A battery consists of a number of ....
4. For increasing the shelf life of a cell, it is advisable to keep it in a .... place.
5. Nickel-cadmium cell is a dry cell but is ....
6. Lead-acid cell is a wet ....cell because it can be recharged.
7. The working of a photovoltaic cell depends on contact between a................ and a metal.
8. A solar cell is essentially a P-N ....

B. Answer True or False

1. Chemical reactions in a secondary cell are reversible.
2. The capacity of a cell depends on the physical size of its electrodes.

3. A larger cell can deliver more current for a longer period of time than a smaller one.
4. Nickel-cadmium cell is the example of a dry but rechargeable cell.
5. Mercury cell provides almost constant voltage under varying load conditions.
6. Silver oxide cells are generally made in the button size.
7. Battery rating is generally expressed in Ah.
8. It is best to test dry cells on no-load.
9. Photoelectric devices convert light energy directly into electric energy.
10. Solar cell converts Sun's heat energy directly into electric energy.
11. The current produced by a solar cell depends only on the solar illumination.
13. Silicon and germanium are the most widely-used semiconductor materials for a solar cell.

C. Multiple Choice Items

1. The output voltage of a lead-acid cell is about .... volt.
   (*a*) 1.5 (*b*) 2.2
   (c) 1.25 (*d*) 6
2. The current delivering capacity of a cell depends on
   (*a*) condition of the electrolyte
   (*b*) quality of the electrolyte
   (*c*) physical size of the electrode
   (*d*) all the above
3. Which of the following is a dry but rechargeable cell ?
   (*a*) nickel-cadmium cell
   (*b*) mercury cell
   (*c*) lead-acid cell
   (*d*) solar cell
4. Rating of a battery is usually expressed in
   (*a*) watt-hour (*b*) joule
   (c) ampere-hour (*d*) amperes
5. Constructionally, a solar cell consists of
   (*a*) a semiconductor bonded to a metal
   (*b*) a piece of silicon
   (*c*) P-N junction
   (*d*) photoemissive material
6. For obtaining maximum power from a solar cell, it should be operated on
   (*a*) level part (*b*) knee
   (*c*) falling portion
   (*d*) any part of its V-I characteristic.

ANSWERS

A. Fill in the blanks

1. photoelectric 2. primary 3. cells 4. cool
5. rechargeable 6. secondary 7. semiconductor 8. junction

B. True or False

1. T 2. T 3. T 4. T 5. T 6. T 7. T
8. F 9. T 10. T 11. F 12. F 13. T

C. Multiple Choice Items

1. *b* 2. *d* 3. *a* 4. c 5. *c* 6. *b*.

CHAPTER 7

Magnetism and Electro-magnetism

7.1. Magnetic Materials

Different materials can be classified as either magnetic materials or non-magnetic materials (air, glass, wood, paper, porcelain, plastic and rubber etc.). However, it should be noted that even though these non-magnetic materials cannot be magnetised, they allow the magnetic flux to pass through them. Magnetic materials may be further subdivided into following three groups as regards their magnetic properties :

1. Ferromagnetic Materials

These are the most important magnetic materials used in Electricity and Electronics. They are easily and strongly magnetised in the *same* direction as the field. They have high value of relative permeability from 50 to 5000 *i.e.*, they conduct magnetic flux 50 to 5000 times more easily than air. Most commonly used ferromagnetic materials are : iron, steel, nickel, cobalt and commercial alloys such as alnico, permalloy and supermalloy.

Alnico is a trade name for an alloy of aluminium, nickel, iron and cobalt. Permanent magnets made of alnico are commonly used in motors, generators, loudspeakers, microphones and meters etc. Permalloy (nickel and iron or cobalt, nickel and iron) has a relative permeability of the order of 100,000. Similarly, supermalloy is an alloy of nickel, iron, molybdenum and manganese.

2. Paramagnetic Materials

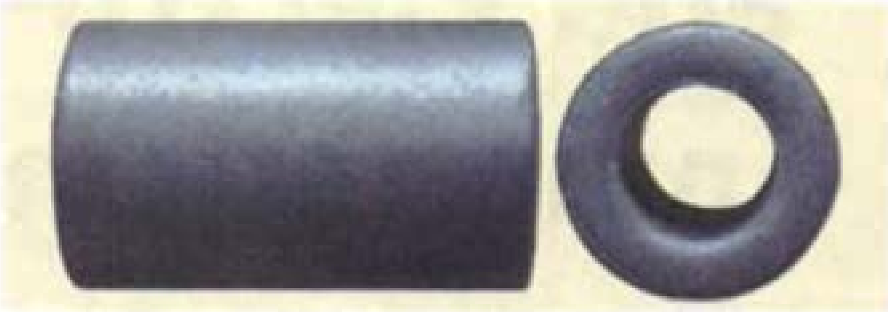
They become only slightly- or weakly-magnetised in a strong magnetic field in the *same* direction as the field. They conduct magnetic flux only slightly better than vacuum (or air). This group includes aluminium, chromium, platinum and manganese etc. Their relative permeability is slightly greater than one.

3. Diamagnetic Materials

These include bismuth, antimony, copper, zinc, mercury, gold and silver which have a relative permeability of less than one *i.e.*, they conduct magnetic flux less readily than air. They are also slightly magnetised but in a direction opposite to that of the magnetising field.

7.2. Ferrites

It is the name given to the recently-discovered ceramic materials that have the ferromagnetic properties of iron. Ferrites are made first by grinding a combination of iron oxide and an alkaline-earth material such as barium into a fine powder. This powder is then pressed into the desired shape and baked at a high temperature. It produces magnetic material which is highly magnetic having a relative permeability in the range 50 to 3000. However, unlike iron, it is an insulator so far as electric conduction is concerned. Like alloy magnets, ceramic magnets can also be shaped into any desired shape. Permanent ceramic magnets are used as gasket latches on refrigerator doors. Ferrite cores (usually adjustable) are used for RF transformers upto 20 MHz frequencies. Another application is ferrite beads. A bare wire is passed through one or more ferrite beads (Fig. 7.1). When current is passed through the wire, a magnetic field is produced. This field is concentrated by the beads into the wire which serves as a simple and economical RF choke.



Ferrite cores are used for RF transformers upto 20 MHz frequencies.

7.3. Types of Magnets

All magnets may be divided into (*i*) permanent magnets and (*ii*) electromagnets.

Fig. 7.1

1. Permanent Magnets (PM)

Once magnetised, they maintain their magnetic strength almost indefinitely. They are made of hard magnetic materials such as cobalt steel which is magnetised by induction in the manufacturing process. A very strong field is needed for this purpose. When magnetising field is removed, cobalt steel retains most of its induced magnetism due to its very high retentivity. Other high-retentivity materials are alnico and permalloy etc., which are used in PM loudspeakers. As the name indicates, permanent magnets will last indefinitely if not subjected to high temperature, to physical shock or to a strong demagnetising field. Moreover, they do not get exhausted with use.

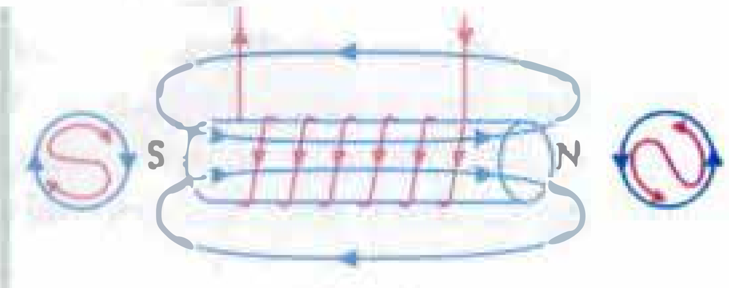


Fig. 7.2

2. Electromagnets

They consist of a coil of wire wound over a soft iron core. When current is passed through the coil, it produces a magnetic field which magnetises the core into a bar magnet with polarities as shown in Fig. 7.2. More current and more turns produce a stronger magnetic field which results in a stronger electromagnet. When current is switched off, field disappears

A buzzer uses copper wires in its electromagnets.

and the iron core is no longer a magnet. This ability of an electromagnet to provide a strong magnetic force of attraction that can be turned OFF and ON has found many applications in lifting magnets, buzzers, bells, horns, relays and magnetic circuit breakers etc. A relay is just a switch with contacts which are opened or closed by an electromagnet. Another application of electromagnets is in the magnetic tape recording.

7.4. Demagnetising or Degaussing

Though magnetism is useful, still there are times when need arises to remove magnetism from certain objects. For example, wrist watches made of magnetic material will not keep correct time if they become magnetised. Similarly, metal cutting tools such as drills and reamers become magnetised due to Earth's magnetic field and start attracting metal chips and filings. This causes them to become dull in due course of time.

Such objects can be demagnetised by using a demagnetiser which consists of a multi-turn coil carrying alternating current. When the object to be demagnetised is placed inside the coil, the alignment of its molecular magnets is destroyed by the alternating magnetic field of the demagnetiser.

A permanent magnet may be demagnetised by heating it to a high temperature or by hammering it.

7.5. Magnetic Shielding

There is no known shield against magnetism *i.e.*, there is no material which does not allow magnetic flux to pass through it. In other words, there is no magnetic insulator. However, some materials have greater permeability than others. For example, iron allows magnetic flux to pass through more easily than air. This fact is made use of in protecting a certain object against the disturbing magnetic field of a nearby component. Suppose we want to protect or shield a meter from the unwanted magnetic field of a neighbouring magnet or Earth's magnetic field. It can be done by surrounding the meter by a ring of soft iron or any other ferromagnetic material as shown in Fig. 7.3. The magnetic flux finds it easier to pass through the ring than air thereby causing no disturbance to the working of the meter. This action is called *shielding*.

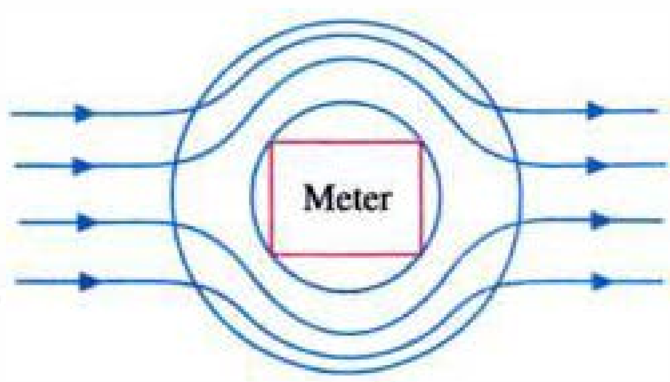


Fig. 7.3

7.6. Magnetic Terms and Units

Following terms are commonly used while discussing the subject of magnetism and electromagnetism.

1. Magnetic Flux (Φ)

The entire group of magnetic lines of force coming out of the N-pole of a magnet is called magnetic flux (Fig. 7.4).

Unit. Unit of magnetic flux is weber (Wb).

2. Flux Density (B)

It is given by the flux incident normally on a unit area. As shown in Fig. 7.5, if a magnetic flux of Φ webers falls perpendicularly on an area of A m², then flux density is given by

$$B = \frac{\Phi}{A}$$

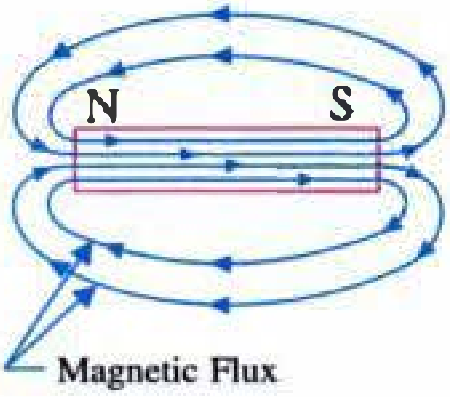


Fig. 7.4

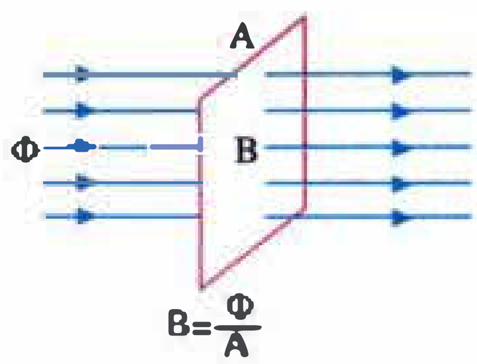


Fig. 7.5

Unit. Obviously, the unit for flux density is weber/metre^2 (Wb/m^2) which is also called Tesla (T).

3. Magnetic Field Strength (H)

It is also called intensity of magnetic field or (more commonly) magnetising force. As we know, each magnet has its own magnetic field consisting of lines of force which start from its *N*-pole, pass through the surrounding medium, re-enter the *S*-pole and complete their path from *S* to *N*-pole through the body of the magnet. When a magnetic material is placed in the magnetic field, it becomes magnetised whereas non-magnetic materials remain unaffected.

The strength of a magnetic field at any point is measured by the force experienced by a *N*-pole of 1 Wb placed there. A uniform magnetic field is one whose strength remains the same everywhere (Fig. 7.7). It is represented by equally-spaced straight lines of flux.

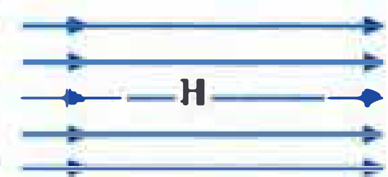


Fig. 7.6

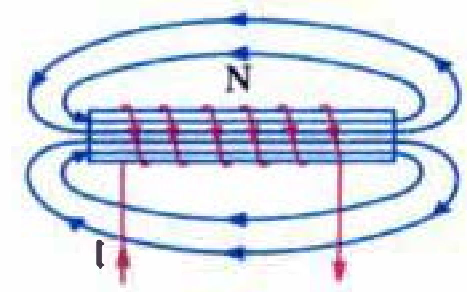


Fig. 7.7

Unit. The unit of H is newton/weber (N/Wb). It is the same thing as an ampere/meter (A/T) which is sometimes written as ampere-turn/meter (AT/m).

4. Magnetising Force of a Solenoid

As shown in Fig. 7.7, if *L* is the length of the iron core, the value of magnetising force produced by the electromagnetic is

$$H = \frac{NI}{l} \text{ A/m or AT/m}$$

5. Permeability

It is the ability of a magnetic material to conduct magnetic flux through it. If it allows the flux to pass through more easily or readily, it is said to have greater permeability. The permeability of a substance is measured both in absolute terms and in relative terms with respect to vacuum (or approximately, air).

(*a*) Absolute Permeability (μ)

Suppose there is a uniform magnetic field of strength *H* established in air as shown in Fig. 7.8. Further, suppose that a bar of a magnetic material, say, iron is placed in it as shown in Fig. 7.9. The iron bar gets magnetised by *induction*. Suppose, it develops a *polarity* of *m* weber. Then, induced flux developed by it is also *m* weber. The lines of induction flux emanate from its *N*-pole, go around and re-enter its *S*-pole and then continue from *S*- to *N*-pole within the magnet as shown in Fig. 7.9.

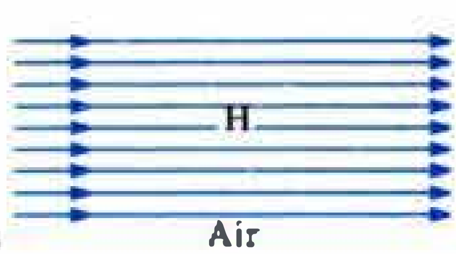


Fig. 7.8

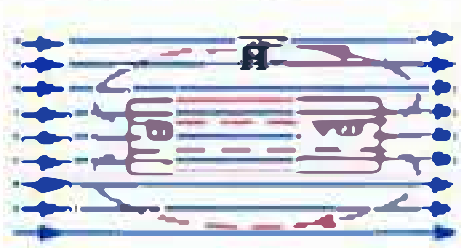


Fig. 7.9

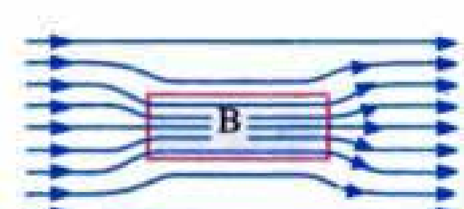


Fig. 7.10

These lines are seen to be in opposition to the lines of force of the main field *H outside* the magnet but in the same direction *within* it. The resultant field is shown in Fig. 7.10. If Φ is the *total* flux* passing through the bar and *A* is its pole area, then flux density within the bar is

$$B = \frac{\Phi}{A} \text{ tesla or Wb/m}^2$$

The absolute permeability of the bar is given by

$$\mu = \frac{B}{H} = \frac{\text{flux density}}{\text{magnetising force}}$$

* There are two fluxes : one due to *H* and the other due to induced magnetism.

Its unit is henry/metre (H/m).

Also, $B = \mu H$ tesla

(*b*) Relative Permeability (μ_r)

The absolute permeability of vacuum is denoted by μ_0 and has been allotted the value of $4\pi \times 10^{-7}$ H/m. Permeabilities of all other magnetic materials are expressed in terms of the absolute permeability of vacuum which has been selected (by mutual agreement) as the reference medium.

Suppose a certain medium has an absolute permeability of μ. Then, its relative permeability (μ_r) *i.e.*, permeability as compared to vacuum is given by

$$\mu_r = \frac{\mu}{\mu_0} = \frac{\text{absolute permeability of medium}}{\text{absolute permeability of vacuum}}$$

Being a mere ratio of two similar quantities, it has no unit.

Also $\mu = \mu_0 \mu_r$

As an example, suppose mild steel has a relative permeability $\mu_r = 400$. Then, its absolute permeability is given by

$$\mu = \mu_0 \mu_r = 4\pi \times 10^{-7} \times 400 \text{ H/m}$$
$$= 16\pi \times 10^{-5} \text{ H/m}$$

It is universal practice to give relative permeabilities of various media since μ can always be found by multiplying μ_r with μ_0 which is a universal constant.

6. Retentivity

It is the ability of a material to hold its magnetism after the magnetising force has been removed. Materials having high retentivity make good permanent magnets.

7. Hysteresis

Suppose the exciting coil of an electromagnet is energised by a source of alternating current (Fig. 7.11). As the current reverses its direction of flow through the coil, the flux also reverses its direction. Hence, the core also undergoes reversal of magnetisation. But it is found that magnetisation of the core does not reverse as quickly as the reversal of flux *i.e.*, the two are not in step with each other. This phenomenon is called hysteresis and is due to the retentivity of the magnetic material of the core.

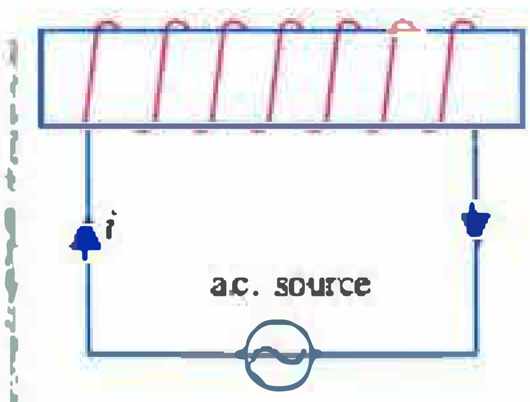


Fig. 7.11

Hysteresis leads to net loss of energy which is called hysteresis loss. This loss depends directly on

(*i*) maximum flux density B_{max} established in the core

(*ii*) frequency of reversal of magnetisation.

8. Permeance

It is the reciprocal of reluctance and resembles electrical conductance. Its unit is henry.

9. Reluctivity

It is specific reluctance and corresponds to electrical resistivity which is 'specific resistance'.

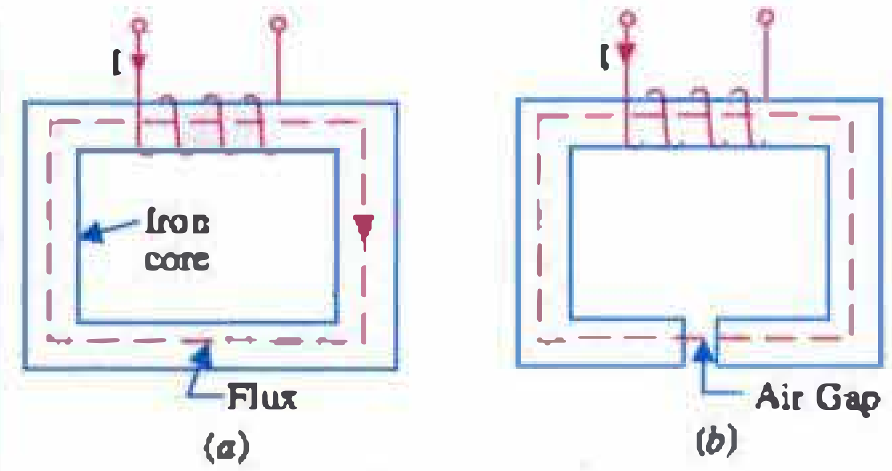
7.7. Ohm's Law for Magnetic Circuit

In Fig. 7.12 (*a*) is shown a magnetic circuit having iron path only, whereas in Fig. 7.12 (*b*) there is a small air gap in the circuit. Like electric circuit, a magnetic circuit also has three quantities interconnected by a law similar to Ohm's law.

The three quantities are :

1. **Magnetomotive force (MMF)**

It resembles voltage or *electromotive force* (*EMF*) in an electric circuit and is responsible for producing magnetic flux in a magnetic circuit. Its value is given by the product of current through the coil and its number of turns *i.e.*, NI. Its unit is ampere-turn*.



(*a*) (*b*)

Fig. 7.12

2. **Magnetic flux (Φ)**

It resembles *current* in an electric circuit. It consists of magnetic lines of force and its unit is weber.

3. **Reluctance (S)**

It resembles *resistance* in an electric circuit. It represents the opposition which a core offers to the production of flux through it. Its value is

$$S = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A}$$

Its unit is 'reciprocal' henry *i.e.*, per henry.

Ohm's law for magnetic circuit is

$$\text{flux} = \frac{\text{mmf}}{\text{reluctance}} = \frac{NI}{S}\text{ weber}$$

$$= \frac{NI}{l/\mu A}\text{ weber} = \frac{\mu N A I}{l}\text{ weber} = \frac{\mu_0 \mu_r N A I}{l}\text{ weber}$$

Example 7.1. *A mild-steel ring having a cross-sectional area of 5 cm² and a mean circumference of 40 cm has a coil of 200 turns wound uniformly around it. Calculate*

(i) reluctance of the ring

(ii) current required to produce a flux of 800 μ Wb in the ring.

Take relative permeability of mild-steel as 380.

Solution. (*i*) $\frac{l}{\mu_0 \mu_r A} = \frac{0.4}{4\pi \times 10^{-7} \times 380 \times (5 \times 10^{-4})} = \mathbf{1.675 \times 10^6 \text{ henry}^{-1}}$

(*ii*) Now, $\Phi = \frac{NI}{S}$ $\quad\therefore\quad 800 \times 10^{-6} = \frac{200 \times I}{1.675 \times 10^6}$ $\quad\therefore\quad \mathbf{I = 6.7\ A}$

7.8. Transformer

It is a static (or stationary) piece of apparatus that

1. transfers electric power from one circuit to another having mutual inductance with it.
2. Does so without change of frequency.
3. Does it by electromagnetic induction.

Constructionally, transformers may be either isolation transformers (with electrically-insulated primary and secondary windings) or autotransformers (with electrically-connected primary and secondary windings). The two are shown in Figs. 7.13 and 7.14 respectively.

Autotransformer

* Strictly speaking, it should be ampere only because turn has no units.

The two-winding isolation transformer may be further subdivided into

(*i*) core type transformer .... in which the windings surround a considerable part of the core (Fig. 7.15).

(*ii*) shell type transformer .... in which the core surrounds a considerable part of the windings (Fig. 7.16).

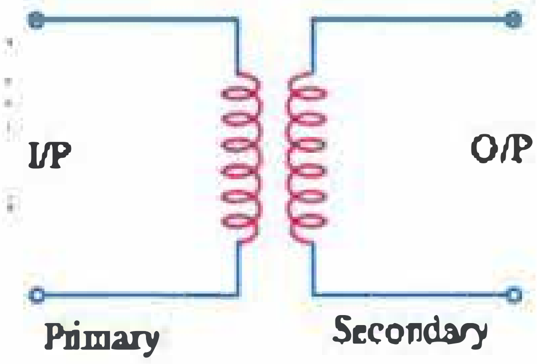


Fig. 7.13

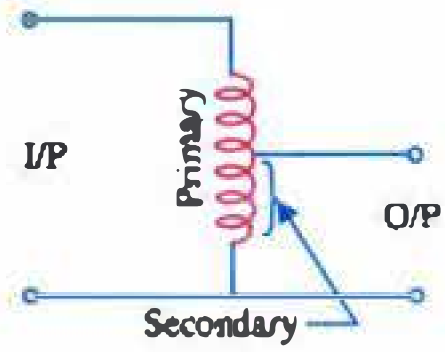
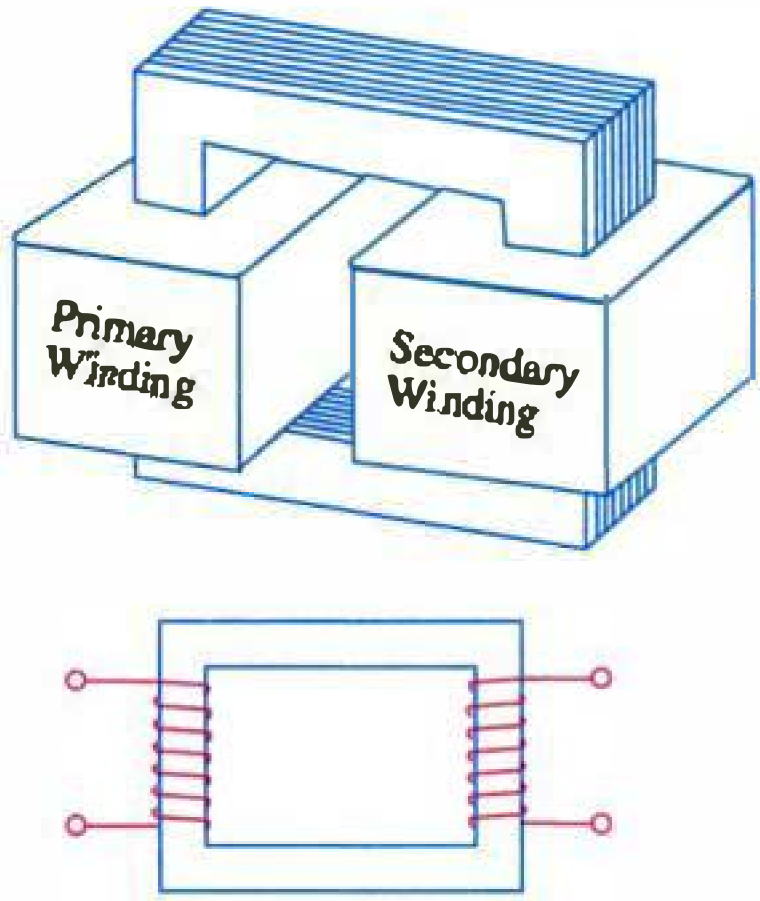
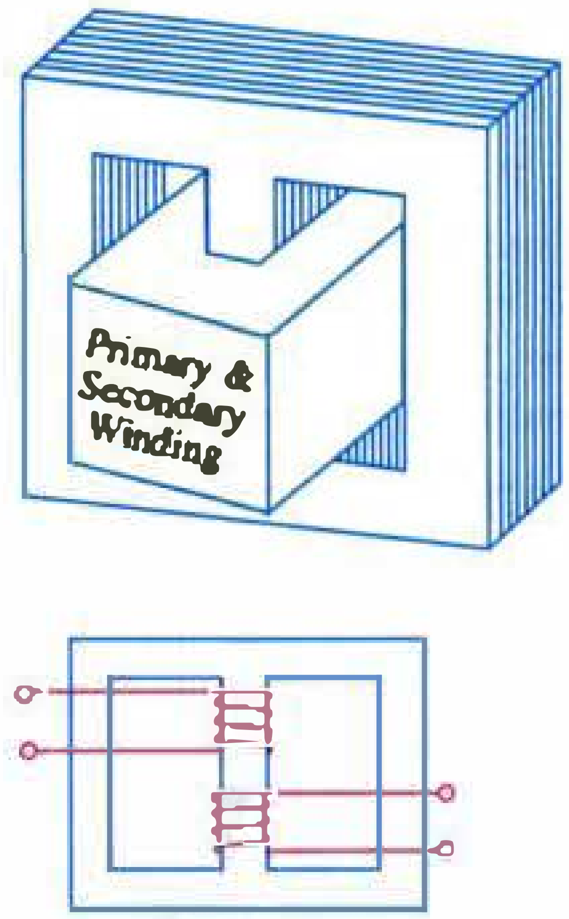


Fig. 7.14

As seen, core-type transformer is made up of a package of thin rectangular silicon steel laminations. Each lamination is coated with an insulating varnish and the total core pressed together. The primary and secondary windings are placed on each side of the common core (Fig. 7.15).



Core Type
Fig. 7.15



Shell Type
Fig. 7.16

The shell type constuction also consists of similar laminations. The two windings are wound in layers and fit over the centre section of the core as shown in Fig. 7.16.

Functionally, the transformers used in electronic circuits can be classified according to the frequency range over which they operate such as :

1. Audio Frequency (AF) Transformers

They are designed to operate over the audio frequency (AF) range of 20 Hz to 20 kHz, have laminated core and are usually smaller than power transformers. They are primarily used for impedance matching and, in some cases, for voltage amplification. Two such typical transformers are shown in Fig. 7.17. Such transformers are usually designated according to their applications as input or output transformer, microphone transformer, modulation transformer and interstage transformer etc. Usually, they are rated by their primary and secondary impedances and current-carrying capability.

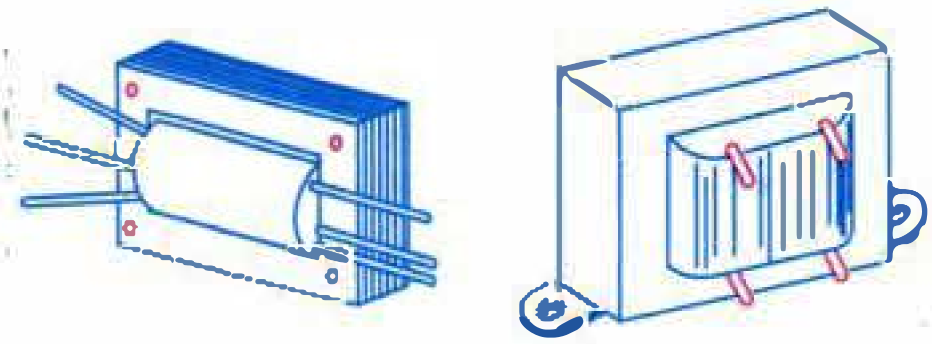


Fig. 7.17

2. Radio Freqdency (RF) Transformers

They are designed to operate at high frequencies (above audio range) and are referred to either as intermediate frequency (IF) transformers or radio frequency transformers. They may have air core or ferrite core (mostly adjustable). Most of the RF transformers have either one or both of the windings tuned *i.e.*, in conjunction with capacitor, they form a resonant circuit which works best at one particular frequency.

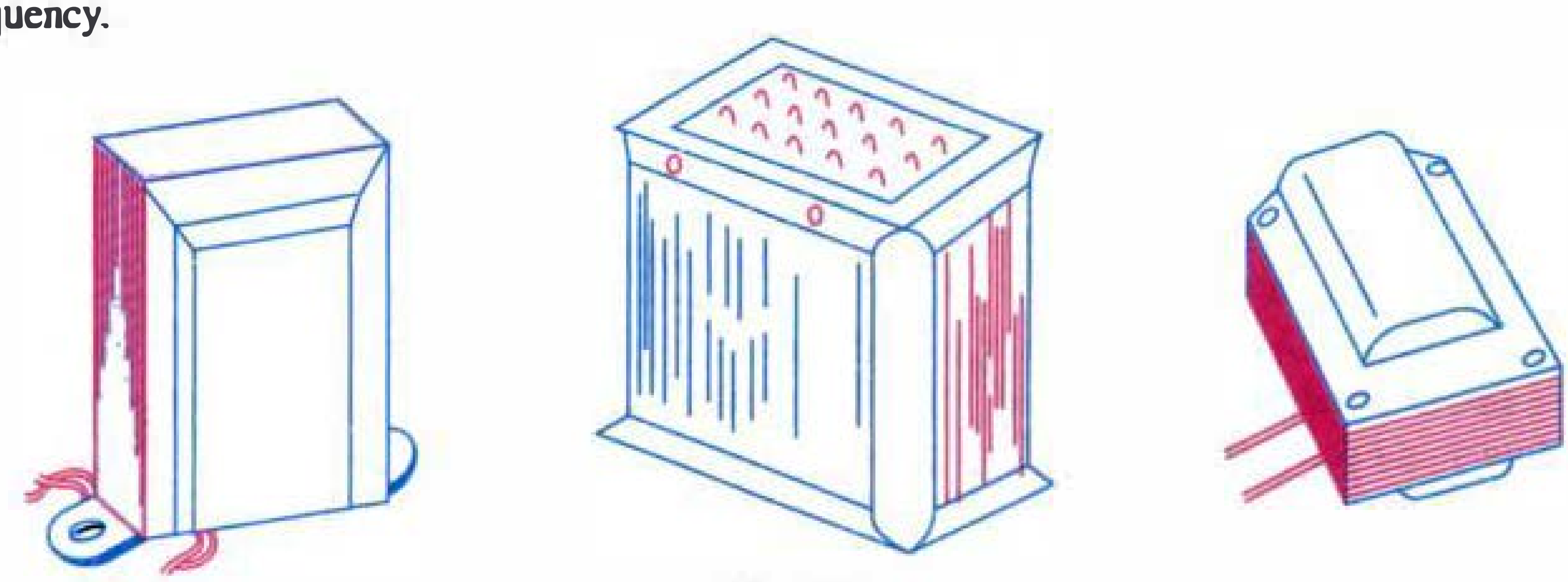


Fig. 7.18

3. Power Transformers

Usually, they have laminated core and have one primary winding but several secondary windings insulated from each other (Fig. 7.18). They are commonly used in the power supply of electronic equipment and provide various ac voltage necessary for the production of dc voltages. Typical transformers of this type are shown in Fig. 7.18.

7.9. Transformer Working

Consider the core-type transformer shown in Fig. 7.19. It consists of two highly inductive coils which are electrically separate but magnetically linked through an iron core of low reluctance. The two coils possess high mutual inductance. If one coil is connected to source of alternating voltage, an alternating flux is set up in the laminated core most of which is linked with the other coil. Hence, mutually-induced voltage is produced in the second coil. If the second coil circuit is closed, a current flows in its and so electric energy is transfered (entirely magnetically) from the first coil to the second coil. The first coil in which electric energy is fed is called *primary* winding and the other from which energy is drawn out is called *secondary* winding. Whether secondary voltage V_2 is more or less than primary voltage V_1 depends on the turn ratio of the transformer. It is found that

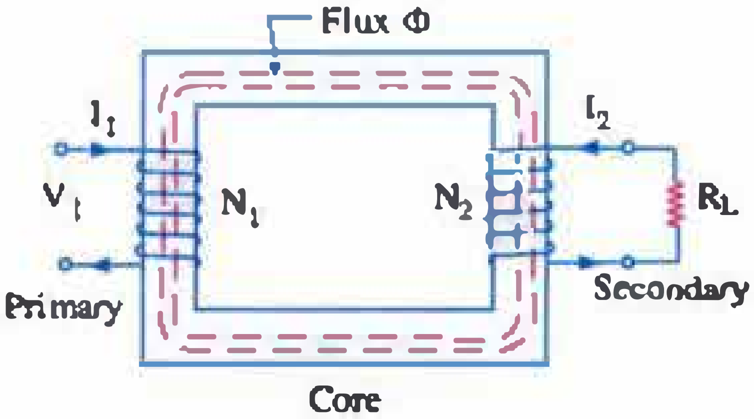


Fig. 7.19

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

If $N_2 > N_1$, then $V_2 > V_1$ and the transformer is called *step-up* transformer, since it steps up the input primary voltage. If $N_2 < N_1$, then $V_2 < V_1$ and the transformer is called *step down* transformer.

Voltage transformation ratio (K) of a transformer is given by V_2/V_1.

$$\therefore \qquad K = \frac{V_2}{V_1} = \frac{N_2}{N_1} \qquad \text{or} \qquad V_2 = KV_1$$

As seen, voltage transformation ratio equals the turn ratio.

Assuming an ideal transformer and equal power factor for both windings,

input power = output power

$$V_1 I_1 = V_2 I_2 \qquad \therefore \quad I_2 = I_1 / K$$

$$\therefore \qquad \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

It is obviously from the above that a transformer which is *step-up for voltage is step-down for current.* If voltage is increased five times, current becomes one-fifth because output power has to equal the input power (in an ideal case). It means that current ratio is reciprocal of voltage ratio.

Suppose, we have transformer with $N_1 = 100$ and $N_2 = 600$. Let $V_1 = 200$ V and $I_1 = 3$ A. Then,

$$K = \frac{N_2}{N_1} = \frac{600}{100} = 6; \qquad V_2 = KV_1 = 6 \times 200 = 1200 \text{ V}$$

$$I_2 = I_1/K = 3/6 = 0.5 \text{ A}$$

It is seen that secondary voltage is 6 times the primary voltage but, at the same time, secondary current is one-sixth of the primary current.

$$P_1 = 200 \times 3 = 600 \text{ W}; \qquad P_2 = 1200 \times 0.5 = 600 \text{ W}$$

As seen, the two powers are equal.

It is worth noting that whatever the actual value of primary and secondary volts, *the voltage/turn is the same in both windings.* In the above case

Primary volts/turn = 200/100 = 2 V; Secondary volts/turn = 1200/600 = 2 V

The two values are equal even though V_1 and V_2 are themselves unequal.

7.10. Transformer Impedance

Each transformer winding has its own resistance, inductive reactance and hence impedance. As shown in Fig. 7.20,

Primary impedance, $Z_1 = \sqrt{R_1^2 + X_1^2}$; Secondary impedance, $Z_2 = \sqrt{R_2^2 + X_2^2}$

Another very interesting thing about these impedances is that they assume different values when *viewed from the other winding.* For example, when Z_2 is viewed from primary winding, it assumes a value $Z_2' = Z_2 / K^2$. But, when Z_1 is viewed from secondary, it appears to have a value of $Z_1' = K^2 Z_1$. This fact is made use of in the working of an impedance-matching transformer (Art. 7.14).

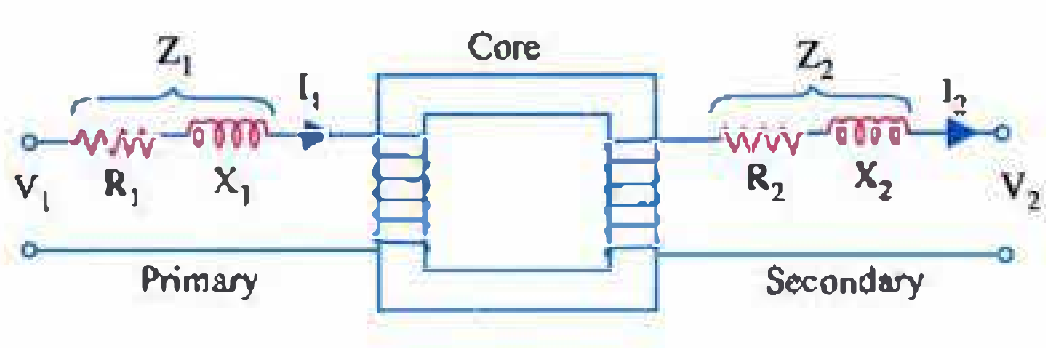


Fig. 7.20

Example 7.2. *A power transformer has 100 primary turns and 600 secondary turns. If primary voltage is 120 V and full-load primary current is 12 A, find secondary*

(i) voltage V_2 and (ii) current I_2.

Solution. Here $K = N_2/N_1 = 600/100 = 6$

(i) $V_2 = KV_1 = 6 \times 120 = 720$ V; (ii) $I_2 = I_1/K = 12/6 = 2$ A

Example 7.3. *A low-voltage soldering rod taking 40 A at 12 V is to be operated from the secondary of a 240 V transformer. Calculate*

(i) turn ratio of the transformer and (ii) primary current.

Solution. (i) $\frac{V_2}{V_1} = \frac{12}{240} = \frac{1}{20} \qquad \therefore \quad \frac{N_2}{N_1} = \frac{1}{20}$

Obviously, it is a step-down transformer having $K = 1/20$

(ii) $I_1 = KI_2 = \frac{1}{20} \times 40 = 2$**A**

7.11. Can a Transformer Operate on DC ?

A transformer cannot operate on a steady or unchanging dc voltage such as that of a battery. It requires a voltage which rises and falls. Since an ac voltage not only changes its magnitude but its direction as well (Fig. 7.21), it is used to operate the transformers.

However, a transformer will operate from dc voltage if this voltage also undergoes changes. Transformers used for audio amplifiers work on pulsating dc voltage (Fig. 7.22). Main thing which causes the transformer to work is the *change* in voltage. It is immaterial whether the voltage changes from positive to negative values as in Fig. 7.21 or from positive to zero values as in Fig. 7.22 (it could, in fact, be from minus to zero values as well).

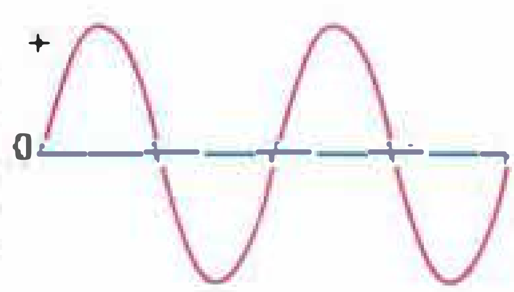


Fig. 7.21

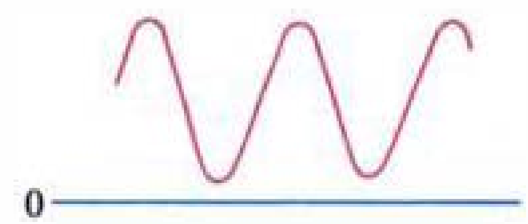


Fig. 7.22

7.12. RF Shielding

Coils are often encased in a metal cover, usually of copper or aluminium, in order to protect them from external varying flux of RF currents. Otherwise, unwanted eddy currents would be induced in them. Purpose of RF shielding is different from magnetic shielding (Art. 7.5) which protects against steady flux only. The shield cover not only isolates the coil from external varying magnetic fields but also minimizes the effect of coil's own RF currents on other external circuits.

7.13. Autotransformer

It is a transformer with one winding only, part of it being common to both primary and secondary. Here, primary and secondary are not electrically isolated from each other as is the case in a 2-winding transformer. However, its theory and operation are similar to that of a 2-winding transformer. Because of one winding, it is compact, efficient and cheaper.

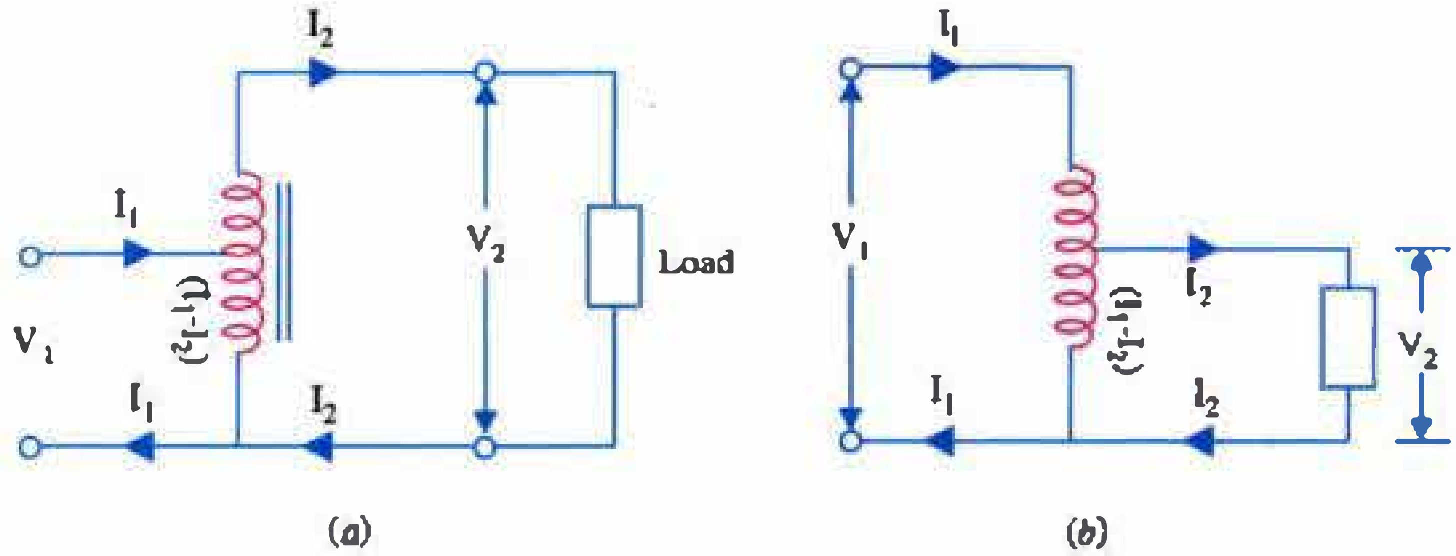


Fig. 7.23

Fig. 7.23 (*a*) shows a step-up autotransformer whereas Fig. 7.23 (*b*) shows a step-down type. As with other transformers, this step-up or step-down ratio depends on the turn ratio between the primary and secondary. Fig. 7.24 shows an audio output stage of an automobile radio that uses a step-down autotransformer.

Such a transformer is also used as an adjustable transformer for both stepping up or stepping down the input voltage (Fig. 7.25). It is often used for a light dimmer or for adjusting power to a radio transmitter.

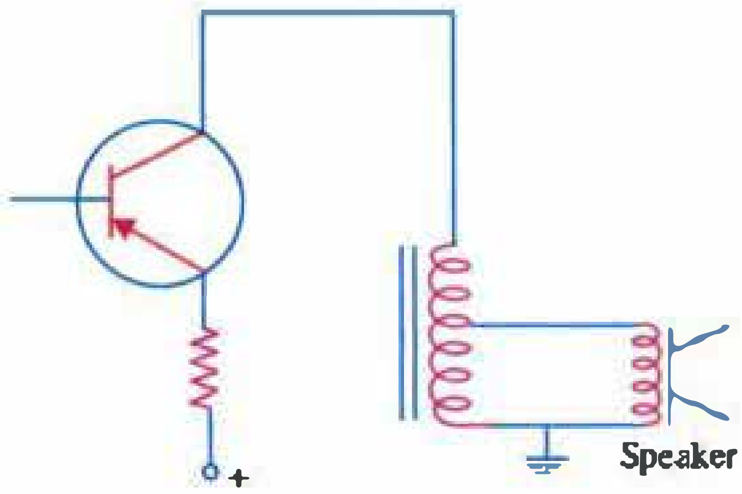


Fig.7.24

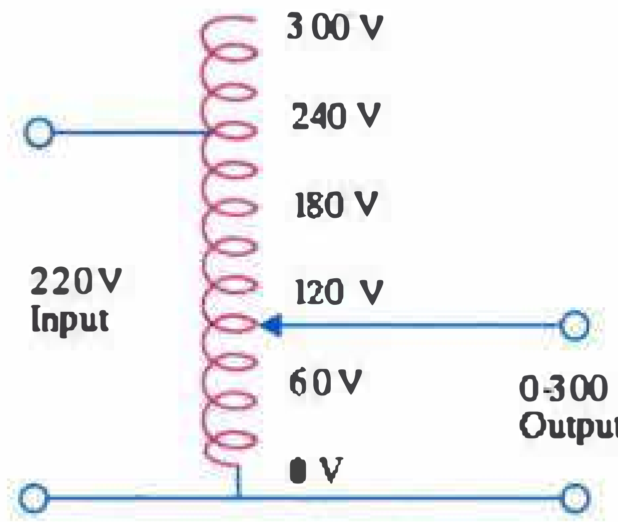
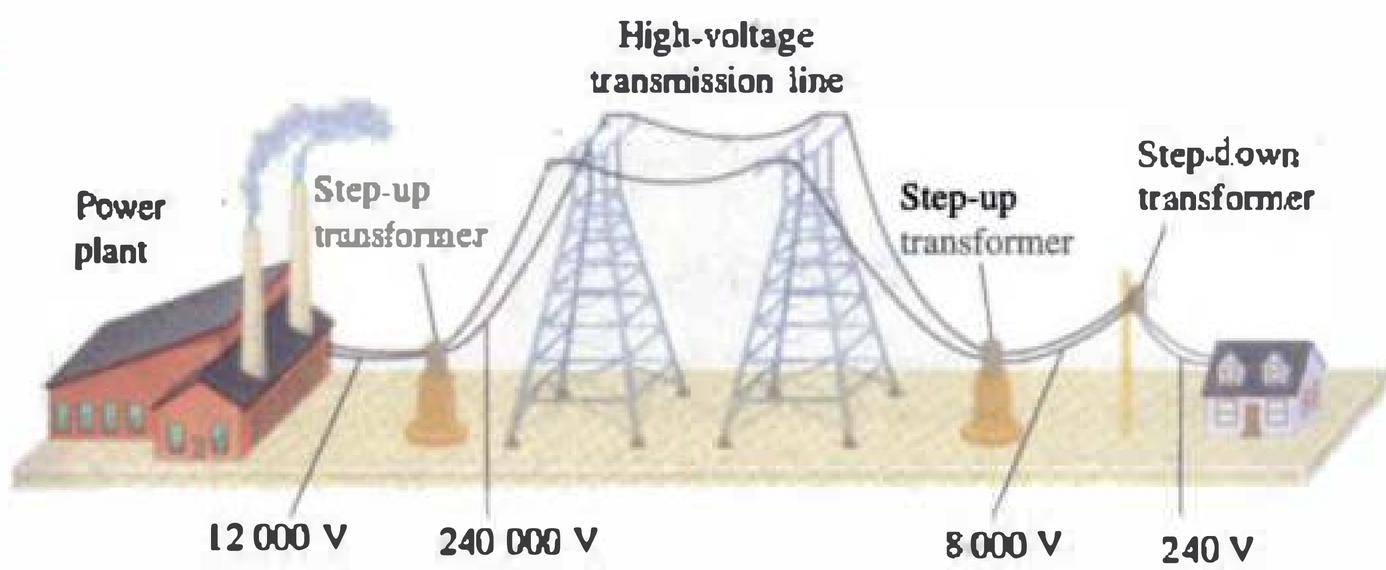


Fig. 7.25

Example 7.4. *The primary and secondary voltages of an autotransformer are 500 V and 400V respectively. Show on a diagram, the current distribution in the transformer if secondary current is 100 A.*



Transformers play an important role in the transmission of electric power.

Solution. $K = V_2/V_1$

$= 400/500 = 0.8$

Here, $I_2 = 100$ A --given

$I_1 = KI_2$

$= 0.8 \times 100 = 80$ A

As seen, current in the common portion of the winding is 20 A. Circuit diagram is shown in Fig. 7.26.

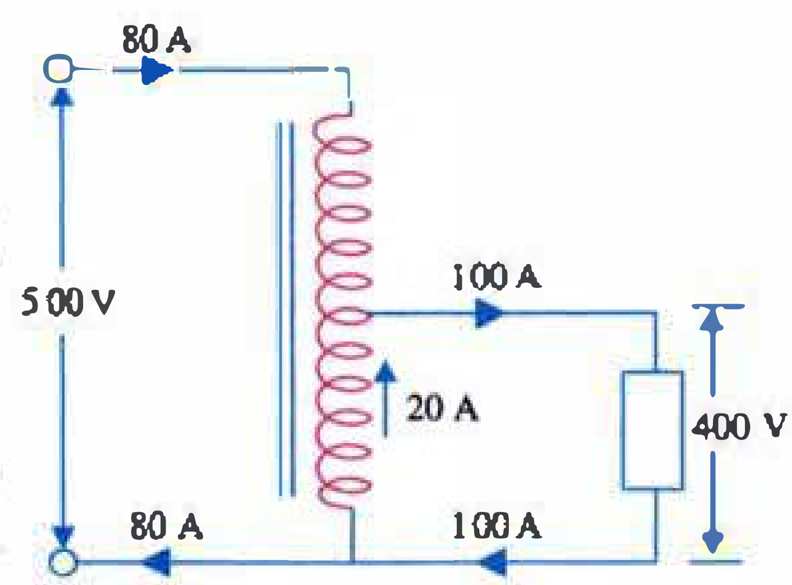


Fig. 7.26

7.14. Impedance Matching

For maximum transfer of power from one circuit to another the two should have equal impedances (Art. 4.9). If they do not have equal impedances, a transformer with suitable turn ratio can be used to achieve this impedance match. In electronic circuitry, it often becomes necessary to connect a circuit of high output impedance to one of low input impedance*. What it really means is that a certain circuit working at a high voltage but low current (hence high impedance) has sometime to be coupled to another circuit which requires lower voltages but higher current (hence low impedance). If two such circuits are coupled directly, energy transfer will not be maximum. In such cases, a transformer is used as an impedance-matching device because it can do the job of increasing or decreasing the voltages and currents very efficiently.

Suppose a circuit of *output* impedance 300 Ω is to be coupled to a circuit of *input* impedance 3 Ω. The turn-ratio (N_2/N_1) of the transformer should be such that when 3 Ω impedance in its secondary

* Usually, a higher-voltage low-current circuit is called a high impedance circuit, while a low-voltage higher-current one is referred to as low-impedance circuit.

is viewed by its primary, it should appear as 300 Ω. Now, when viewed from primary side, a 3 Ω resistance is seen as equal to $3/KC^2$ (Art. 7.9).

Hence, for equal matching $\frac{3}{K^2} = 300$

$$K = \sqrt{1/100} = 1/10 \qquad \therefore \frac{N_2}{N_1} = \frac{1}{10}$$

It means that secondary turns should be one-tenth the primary turns. Often, autotransformers are also used for impedance matching purpose.

Example 7.5. *A transformer is required to match the 400 Ω output impedance of a transistor power amplifier to a 4 Ω speaker coil. What should be the turn ratio?*

Solution. Obviously, the transformer primary would be fed from the amplifier whereas the secondary would be connected to the speaker.

$$K = \sqrt{Z_2/Z_1} = \sqrt{4/400} = 1/10 \qquad \therefore N_2/N_1 = 1/10$$

CONVENTIONAL PROBLEMS

1. A coil of 500 turns and resistance 20 Ω is wound uniformly on an iron ring of mean circumference 50 cm and cross-sectional area 4 cm². It is connected to a 24 V dc supply. Under these conditions, the relative permeability of iron is 800. Calculate the values of
   (*a*) mmf of the coil
   (*b*) magnetising force
   (*c*) total flux in iron core
   (*d*) reluctance of the iron ring
   [(*a*) 6000 AT (*b*) 1200 AT/m (*c*) 0.483 mWb (*d*) 1.24 × 10^6 H^{-1}]
2. A magnetic circuit consists of an iron ring of mean circumference 80 cm with cross-sectional area 12 cm² throughout. A current of 2 A in the magnetising coil of 200 turns produces a total flux of 1.2 mWb in the iron. Calculate
   (*i*) flux density in iron
   (*ii*) absolute and relative permeability of iron
   (*iii*) reluctance of the circuit **[(*a*) 1 T or Wb/m² (*b*) 0.002, 1590 (c) 3.33 × 10^5 henry^{-1}]**
3. A step-down transformer with a voltage step-down ratio of 20 has 6 V across 0.3 Ω secondary. Calculate (*i*) secondary current and (*ii*) primary current. **[(*i*) 20 A (*ii*) 1 A]**
4. A step-down transformer with 10 : 1 turn ratio is connected to 220 V, 50 Hz ac supply mains
   (*a*) What is the frequency of secondary voltage ?
   (*b*) How much is secondary voltage ?
   (*c*) If secondary load is 100 Ω, what is the secondary current and primary current ? Assume 100 per cent efficiency. **[(*a*) 50 Hz (*b*) 22 V (*c*) 0.22 A ; 0.022 A]**

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word (s) or numerical value (s).

1. Even though wood is a non-magnetic material, it allows magnetic .... to pass through.
2. Ferromagnetic materials have high value of relative ....
3. Alnico is used for making permanent magnets because it has high ....
4. Ceramic material which has ferromagnetic properties of iron is called ....
5. Unit of magnetic flux density is ....
6. Ratio of *B* and *H* is called .... permeability.
7. Unit of magneto-motive force is ....
8. .... is reciprocal of reluctance.
9. An autotransformer has only .... winding.
10. An impedance-matching transformer couples two circuits of unequal ....

B. Answer True or False

1. Cobalt is a ferromagnetic material.
2. Gold is diamagnetic whereas silver is paramagnetic.
3. Ferrites have permeability of less than one.
4. Cobalt steel is ideal for making electromagnets.
5. Demagnetising means the same thing as degaussing.
6. All transformers work on the principle of mutual inductance.
7. In autotransformers, electric energy is transferred to secondary only by induction.
8. Transformers can be used for coupling a high-output impedance circuit to a low-input impedance circuit but not *vice-versa*.

C. Multiple Choice Items

1. A permanent magnet will not attract
   (*a*) steel (*b*) nickel
   (*c*) aluminium (*d*) copper
2. Magnets made of low-retentivity but high permeability iron are called
   (*a*) electromagnets
   (*b*) permanent magnets
   (*c*) weak magnets
   (*d*) one-pole magnets
3. The unit of magnetising force is
   (*a*) ampere/metre (*b*) newton
   (*c*) tesla (*d*) ampere
4. Working of a transformer essentially depends on
   (*a*) self-inductance
   (*b*) mutual inductance
   (*c*) magnetic circuit (*d*) magnetic flux
5. Radio frequency transformers often employ air-core coils in order to
   (*a*) eliminate core loss
   (*b*) reduce coil weight
   (*c*) cut initial cost
   (*d*) eliminate winding labour
6. A transformer has 1000 primary turns and 500 secondary turns. If primary voltage is 200 V, secondary voltage would be .... volt.
   (*a*) 400 (*b*) 100
   (*c*) 800 (*d*) 50
7. If a 5 : 1 step-down audio transformer has a primary current of 20 mA, the secondary current would be .... mA.
   (*a*) 4 (*b*) 500
   (*c*) 100 (*d*) 0.8
8. Basic requirement for the operation of a transformer is that its input primary voltage must be
   (*a*) alternating (*b*) sinusoidal
   (*c*) changing (*d*) pulsating
9. If a circuit of output impedance 400 Ω is to be coupled to a circuit of input impedance 4 Ω, its primary to secondary turn ratio should be
   (*a*) 1/10 (*b*) 10
   (*c*) 100 (*d*) 1/100
10. RF shielding of a coil is primarily meant to protect it from external
    (*a*) electric fields (*b*) magnetic fields
    (*c*) varying magnetic fields
    (*d*) dust and heat
11. An autotransformer consists of 200-turn winding connected to 200 V ac supply mains. For getting 24 V output, the winding should be tapped at turn number
    (*a*) 24 (*b*) 12
    (*c*) 100 (*d*) 72
12. The main purpose of laminating a transformer core is to decrease its
    (*a*) electrical resistance
    (*b*) reluctance
    (*c*) eddy current loss
    (*d*) hysteresis loss

ANSWERS

A. Fill in the blanks

1. flux 2. permeability 3. retentivity 4. ferrite 5. tesla
6. absolute 7. ampere 8. permeance 9. one 10. impedances

B. True or False

1. T 2. F 3. F 4. F 5. T 6. T 7. F 8. F

C. Multiple Choice Items

1. *d* 2. *a* 3. *a* 4. *b* 5. *a* 6. *b* 7. *c* 8. *c* 9. *b* 10. *c*
11. *a* 12. *c*

8 CHAPTER

A.C. Fundamentals

8.1. Introduction

So far we have considered direct current (dc) which is produced by a voltage source whose terminals have fixed polarity *i.e.*, whose poles do not change their polarity with time. Hence, they provide a current whose direction flow does not change with time. However, this direct current may be steady (constant in value as in Fig. 8.1 (*a*) or fluctuating (pulsating as in Fig. 8.1 (*b*) or may be interrupted into short pulses as shown in Fig. 8.1 (*c*). Main point is that its direction of flow remains the same *i.e.*, from the positive terminal of the voltage source to its negative terminal. Examples of voltage sources are : electric cell, battery and d.c. generators etc.

Alternating current (a.c.) is produced by a voltage source whose terminal polarity keeps alternating (or reversing) with time. What was the positive terminal at one instant [Fig. 8.2 (*a*)] becomes negative terminal some time later and what was negative terminal at one instant [Fig. 8.2 (*b*)] becomes positive terminal at some other instant?

As a result of constantly-reversing polarity of voltage source, the direction of current flow in the circuit also keeps reversing as shown in Fig. 8.2. In addition to reversing its direction, current keeps changing in value with time–from zero to maximum in one direction and back to zero and then from zero to maximum in the opposite direction and again

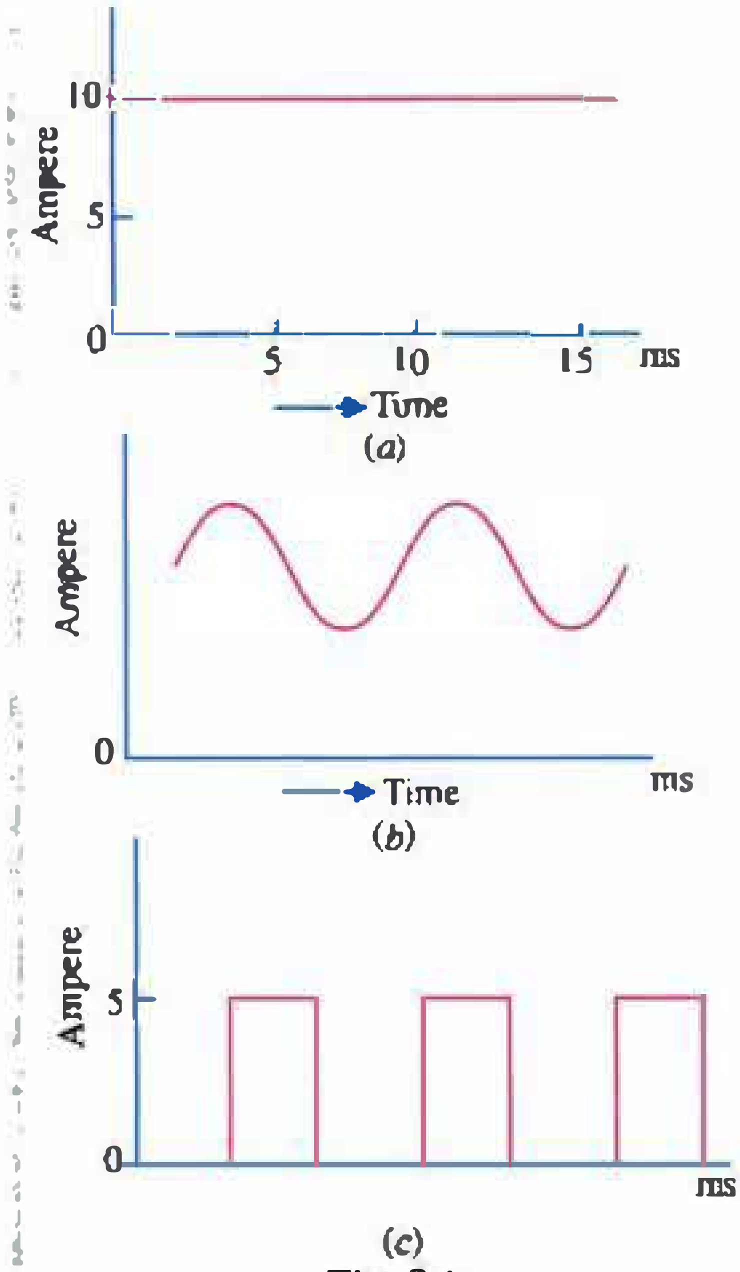


Fig. 8.1

back to zero. It is obvious that an alternating voltage source will cause an alternating current.

It may be noted in passing that 'a.c.' electricity is not 'better' than 'd.c.' electricity as some people feel. Alternating voltages and currents have their own fields of application which d.c. does not have and *vice-versa*. Any way, it is important to keep in mind that *a.c. does not replace d.c.* A.C. is commonly used in electronic circuits most of which are, however, controlled by d.c. voltages.

The most common source of alternating voltage is the alternator or a.c. generator.

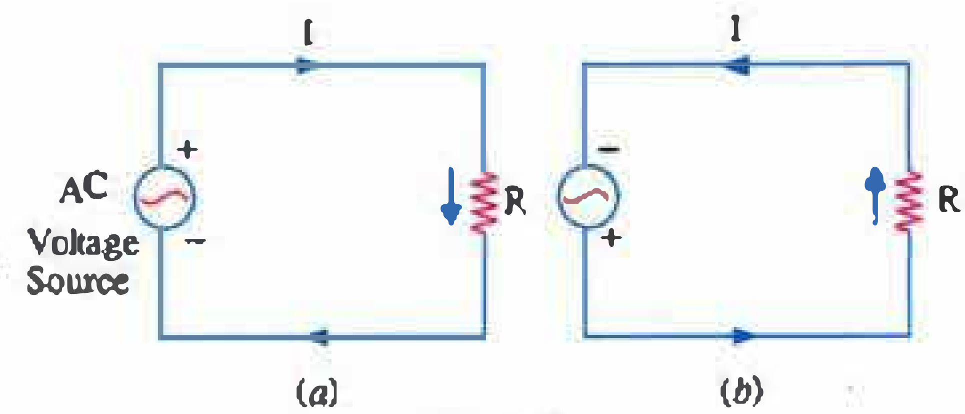


Fig. 8.2

8.2. Types of Alternating Waveforms

The alternating voltages and currents can have different waveforms or wave-shapes as shown in Fig. 8.3. These waveforms are obtained by plotting the instantaneous values of voltage or current as ordinate against time as abscissa.

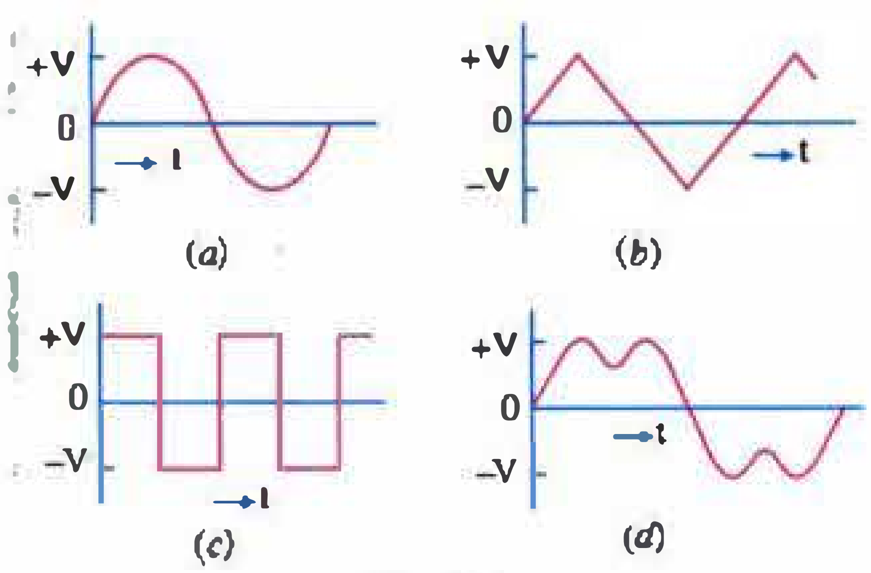


Fig. 8.3

Fig. 8.3 (*a*) shows a sine wave because it is obtained by plotting a sine function. Fig. 8.3 (*b*) depicts a triangular waveform whereas Fig. 8.3 (*c*) shows a square waveform and Fig. 8.3 (*d*) illustrates a complex waveform. Another point worth noting is that alternating quantities may or may not be symmetrical *i.e.*, their positive and negative, halves may or may not be identical. All the waveforms shown in Fig. 8.3 represent different types of alternating voltages which are symmetrical.

Since sinusoidal a.c. *i.e.*, an a.c. having sine waveform is most important, we will discuss it in some detail. But it should be noted that a waveform may be sinusoidal but not symmetrical and *vice-versa*. Fig. 8.3 (*a*) shows a waveform which is both sinusoidal and symmetrical. However, the waveforms shown in Fig. 8.4 are sinusoidal but non-symmetrical. In Fig. 8.4 (*a*), negative half is different from the positive half and in Fig. 8.4 (*b*), the negative half has been completely suppressed. Such an a.c. is called half-wave rectified a.c. (Art. 16.6).

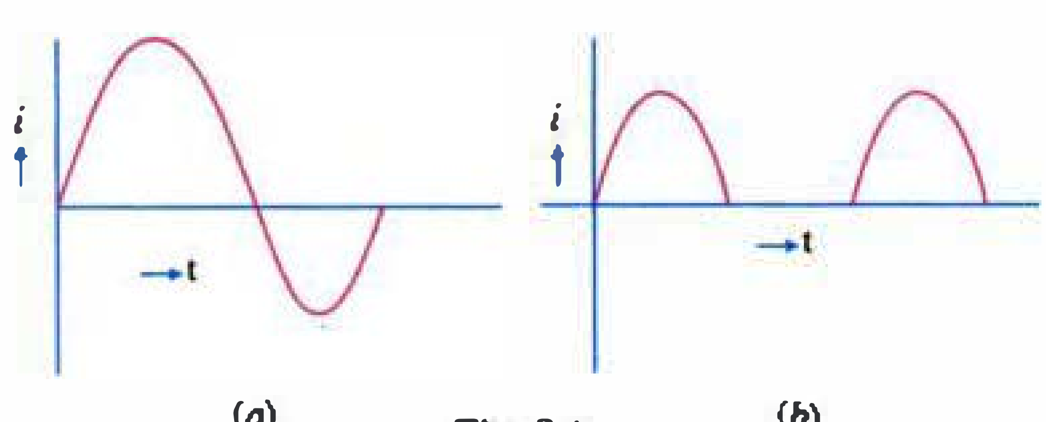


Fig. 8.4

8.3. The Basic AC Generator

Such a rotary generator is schematically shown in Fig. 8.5. It consists of a pivoted loop armature having two coil sides *A-B* and *C-D* which rotate with uniform velocity through a uniform stationary magnetic field of horse-shoe magnet. As the armature coils cut the magnetic flux, an alternating voltage is induced in them according to Faraday's Laws of Electromagnetic Induction. The magnitude of this voltage depends (among other factor) on the *rate* at which flux is cut by the coil sides. This a.c. voltage is taken out from the armature coil via sliprings and brushes (not shown in the figure) for driving current through an external load.

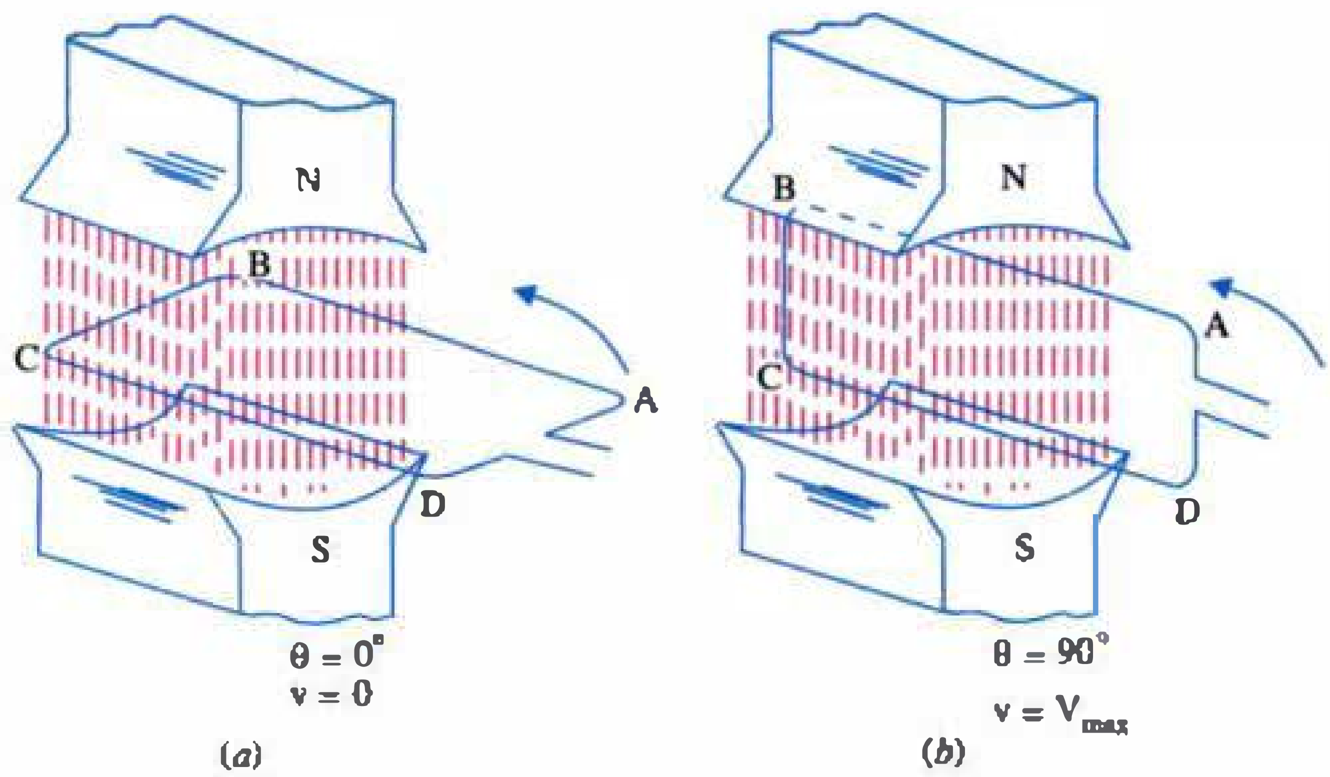
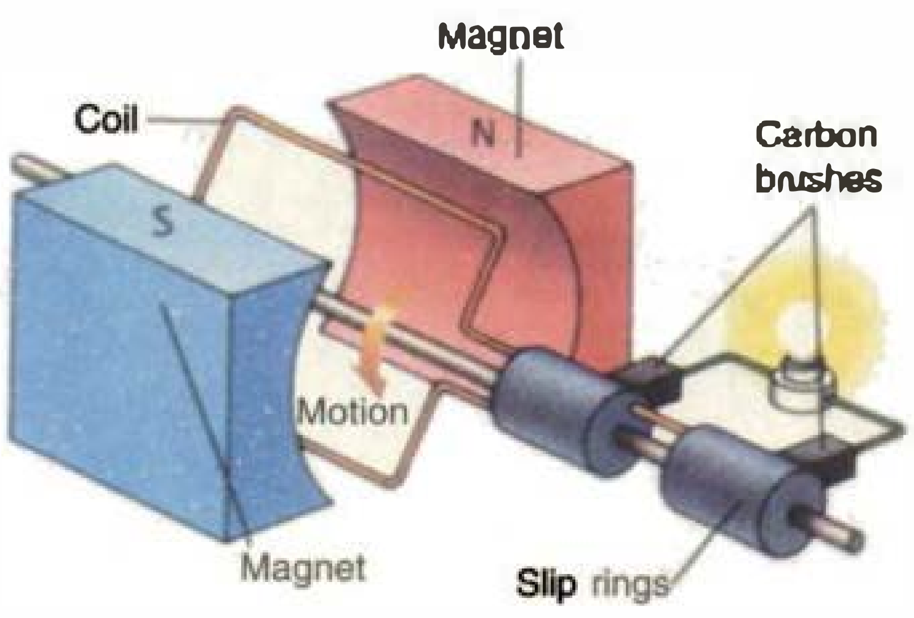


Fig. 8.5

The coil has been assumed to rotate in the anticlockwise direction in Fig. 8.5.



A basic AC generator.

1. When the armature coil lies in the horizontal plane, maximum flux with it but its *rate* of flux cutting (*i.e.*, $d\Phi/dt$) is zero. It is so because as the two sides *A-B* and *C-D* just start moving *upwards* and *downwards* respectively, they *slide* along or move parallel to the flux lines. They, in fact, just rub along the lines of flux without cutting them. Hence, induced voltage *v* at that instant is zero. We will take this horizontal position of the coil as the $\theta = 0$ position [Fig. 8.5 (*a*)].

2. As the coil rotates further up, rate of flux cutting increases till it becomes maximum when $\theta = 90°$ as shown in Fig. 8.5 (*b*). Hence, the induced voltage at $\theta = 90°$ has maximum value of V_{max}.

3. As the coil rotates further, *v* starts decreasing sinusoidally till it again becomes zero when $\theta = 180°$. At this stage, coil has turned through half the circle and the induced voltage has gone through half the cycle.

4. As the coil turns through the remaining half circle *i.e.*, from 180° to 360°, the induced voltages undergoes similar changes in magnitude except that its polarity is reversed. The voltage *v* has a maximum value of V_{max} at 270° and zero at 360°. In this way, the coil completes one full turn which corresponds to 360° of rotation and is the equivalent of one cycle of the output voltage.

The process of voltage generation is more clearly shown in Fig. 8.6. Since voltage generated in the two sides of the coil are equal (though opposite in polarity), we may consider only one coil side say, *A-B*, to explain the above process. Initially, coil side *A-B* is assumed to be positioned at point *E*.

(ii) $I_n = 141.4$ A $\quad\therefore\quad I = \dfrac{I_m}{\sqrt{2}} = \dfrac{141.4}{\sqrt{2}} = \mathbf{100\ A}$

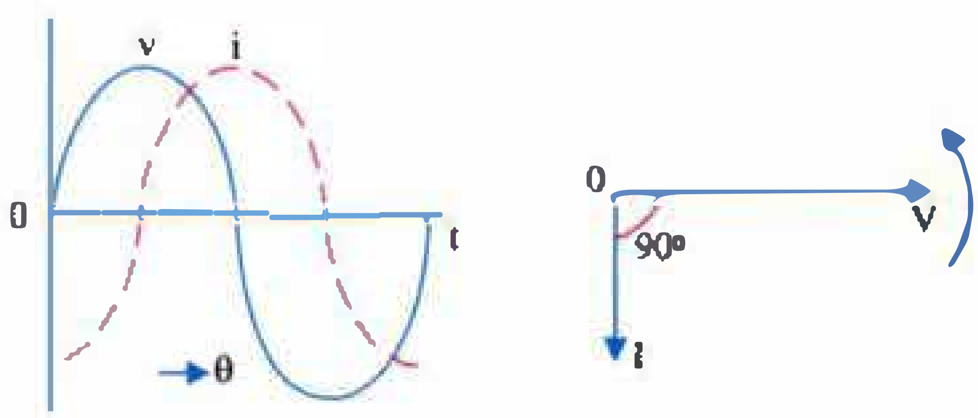
(iii) $I_{av} = 0.637 \quad I_m = 0.637 \times 141.4 = \mathbf{90\ A}$

8.10. Vector Representation of an Alternating Quantity

A sinusoidally alternating voltage or current can be graphically represented by counter-clockwise rotating vector provided it satisfies the following conditions :

1. its length is equal to the peak value (even rms value will do) of the alternating quantity,
2. it is in the horizontal position at the same instant when the alternating quantity is zero and is increasing positively,
3. its angular velocity is such that it completes one revolution in the same time as taken by the alternating quantity to complete one cycle.

In Fig. 8.16 (*a*) is shown a sinusoidal current wave lagging behind the alternating voltage wave by 90°. The same fact has been shown vectorially in Fig. 8.16 (*b*). Here, vector *OV* represents rms value of the voltage which is taken as the reference quantity. Similarly, vector *OI* represents rms. value of the alternating current which lags behind the voltage by 90°. Both vectors are supposed to be rotating in the counter-clockwise direction at the same angular velocity ω as that of the two alternating quantities.



(*a*) (*b*)

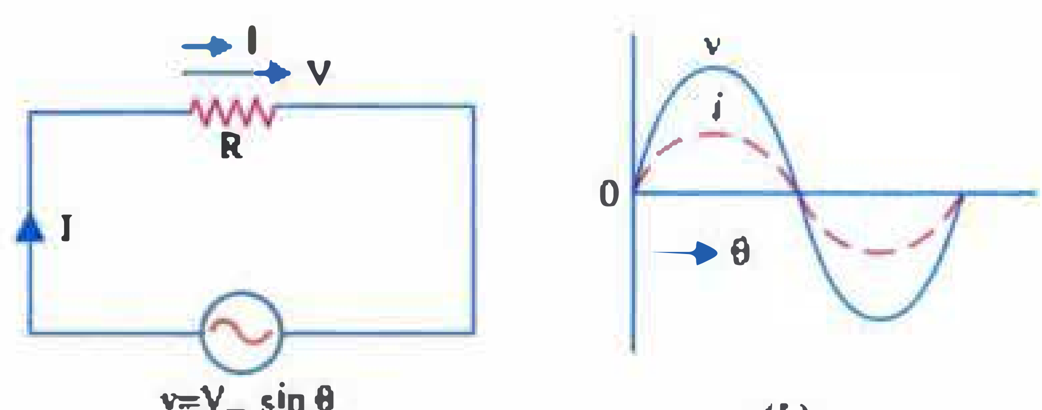
Fig. 8.16

8.11. AC through Pure Resistance Only

It is found that when a sinusoidal voltage is applied across a pure ohmic resistance, it produces a sinusoidal current

(i) which is in phase with the voltage as shown in Fig. 8.17, both graphically and vectorially;

(ii) whose rms value is given by $I = V/R$.



(*a*) **Fig. 8.17** (*b*)

If the equation of the applied voltage is $v = V_m \sin \theta$, then equation of the current is $i = I_m \sin \theta$.

The power wasted in the circuit in the form of heat is $P = I^2R$ where I is the r.m.s. value of the current.

In general, it should be noted that potential drop $v(t)$ across a resistor R is directly proportional to the current $i(t)$ in it. Hence, as shown in Fig. 8.18,

$$v(t) = R \cdot i(t) \qquad \therefore \qquad i(t) = \frac{v(t)}{R}$$

and power $\qquad p(t) = v(t) \cdot i(t)$

Here, $v(t)$ and $i(t)$ indicate the instantaneous values of time-varying voltage and current respectively which may have any wave form.

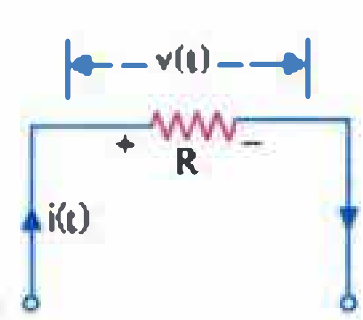


Fig. 8.18

8.12. AC through Pure Inductance Only

When a sinusoidally alternating voltage is applied across a pure inductive coil of inductance L, it produces a sinusoidal current (*i*) whose rms value is

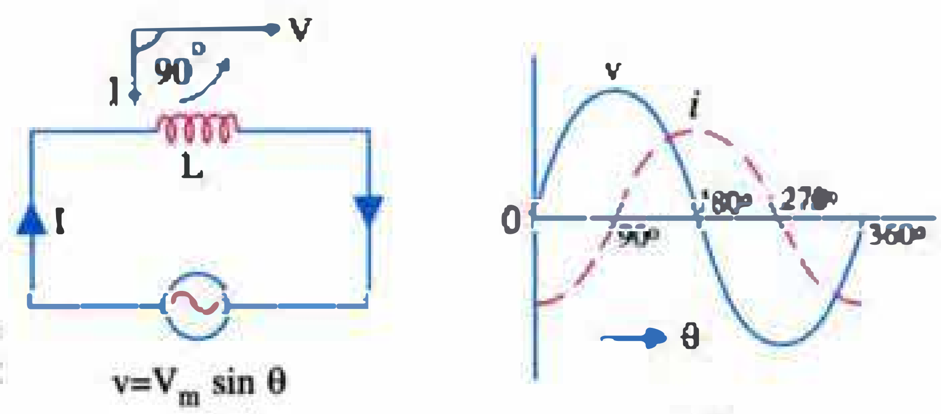
$$I = \frac{V}{X_L} = \frac{V}{2\pi f L}$$

(*ii*) which lags behind the applied voltage by 90° as shown in Fig. 8.19.

If $\quad v = V_m \sin\theta$

then $\quad i = I_m \sin(\theta - \pi/2)$

It is found that power absorbed by this coil is zero. It may be noted that when current in a coil changes, the magnetic flux linked with it also changes thereby producing an induced voltage $v(t)$ in it (Fig. 8.20). This voltage is proportional to the *rate of change of current* if permeability of the coil core is constant. The constant of proportionality is called the inductance of the coil.



(*a*) Fig. 8.19 (*b*)

8.13. AC through Pure Capacitance Only

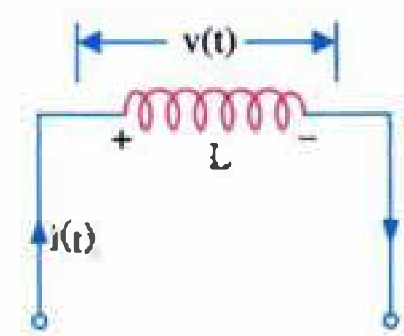


Fig. 8.20

When a sinusoidal voltage is applied across a pure capacitor,it produces a sinusoidal current

(*i*) whose magnitude is given by

$$I = \frac{V}{X_C} = \frac{V}{1/\omega C} = \omega VC$$

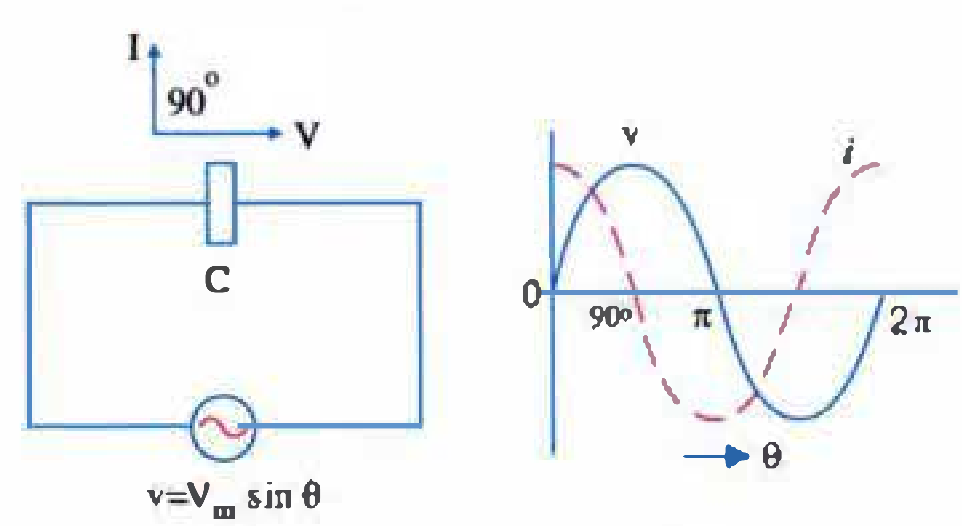
(*ii*) which leads the applied voltage by 90° as shown in Fig. 8.21.

Hence, if $v = V_m \sin\theta$, then current is given by

$$i = I_m \sin(\theta + \pi/2)$$

Power absorbed by such a capacitor is zero.

It may be noted that potential difference v between the terminals of a capacitor is directly proportional to the charge q on it. The constant of proportionality is the capacitance of the capacitor. As seen from Fig. 8.22,



(*a*) Fig. 8.21 (*b*)

$$q(t) = C.v(t)\ ; \qquad i(t) = \frac{dq}{dt} = C\frac{dv}{dt}$$

$$\therefore \quad v(t) = \frac{1}{C}\int i\,.dt; \qquad p(t) = vi = Cv\frac{dv}{dt}$$

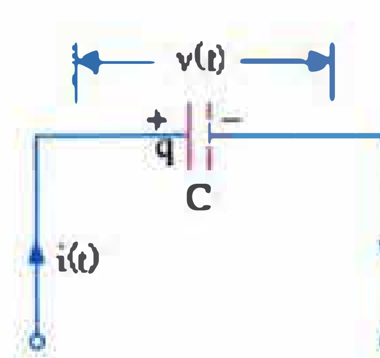


Fig. 8.22

Example 8.4. *Two capacitors of 60 μF and 30 μF are connected in series. Find the circuit current when this combination is connected across 50 Hz, 200 V supply mains.*

Solution. The equivalent capacitance of the combination is

$$C = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{30 \times 60}{30 + 60} = 20\,\mu\text{F}$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 50 \times 20 \times 10^{-6}} = 159\ \Omega$$

$\therefore \qquad I = 200 / 159 = \mathbf{1.26\ A}$

Example 8.5. *A voltage given by v(t) = 100 sin ωt is applied across a resistor of 20 Ω. Find (a) current i(t) (b) power p(t) and (c) average power. Draw the sketches.*

Solution.

(*a*) $$i(t) = \frac{v(t)}{R} = \frac{100 \sin \omega t}{20} = \mathbf{5 \sin \omega t}$$

(*b*) Instantaneous power is given by

$$p(t) = v(t).i(t) = (100 \sin \omega t)(5 \sin \omega t) = \mathbf{500 \sin^2 \omega t}$$

(*c*) The average power is = 500/2 = **250 W.**

The sketches are shown in Fig. 8.23.

Example 8.6. *A sinusoidal voltage v (t) = 200 sin 1000 t is applied across a pure inductive coil of inductance L = 0.02 H. Determine current i(t) (b) instant power p(t) and (c) average power consumed by the coil. Also draw their waveforms.*

Solution.

(*a*) $$i(t) = \frac{1}{L}\int v\,dt = \frac{1}{0.02}\int 200 \sin 1000\,t\,dt$$

$$= \frac{200}{0.02}\left(-\frac{\cos 1000\,t}{1000}\right) = \mathbf{-10 \cos 1000\,t}$$

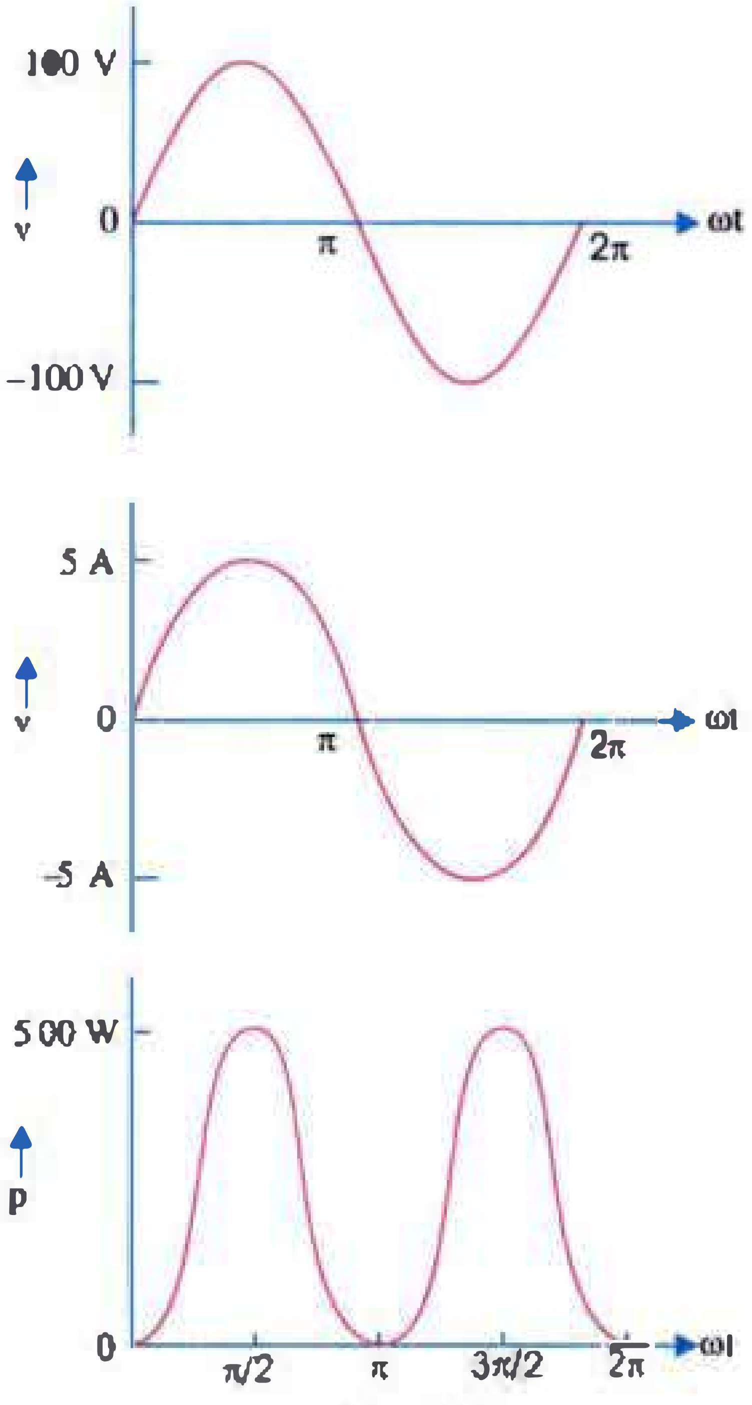


Fig. 8.23

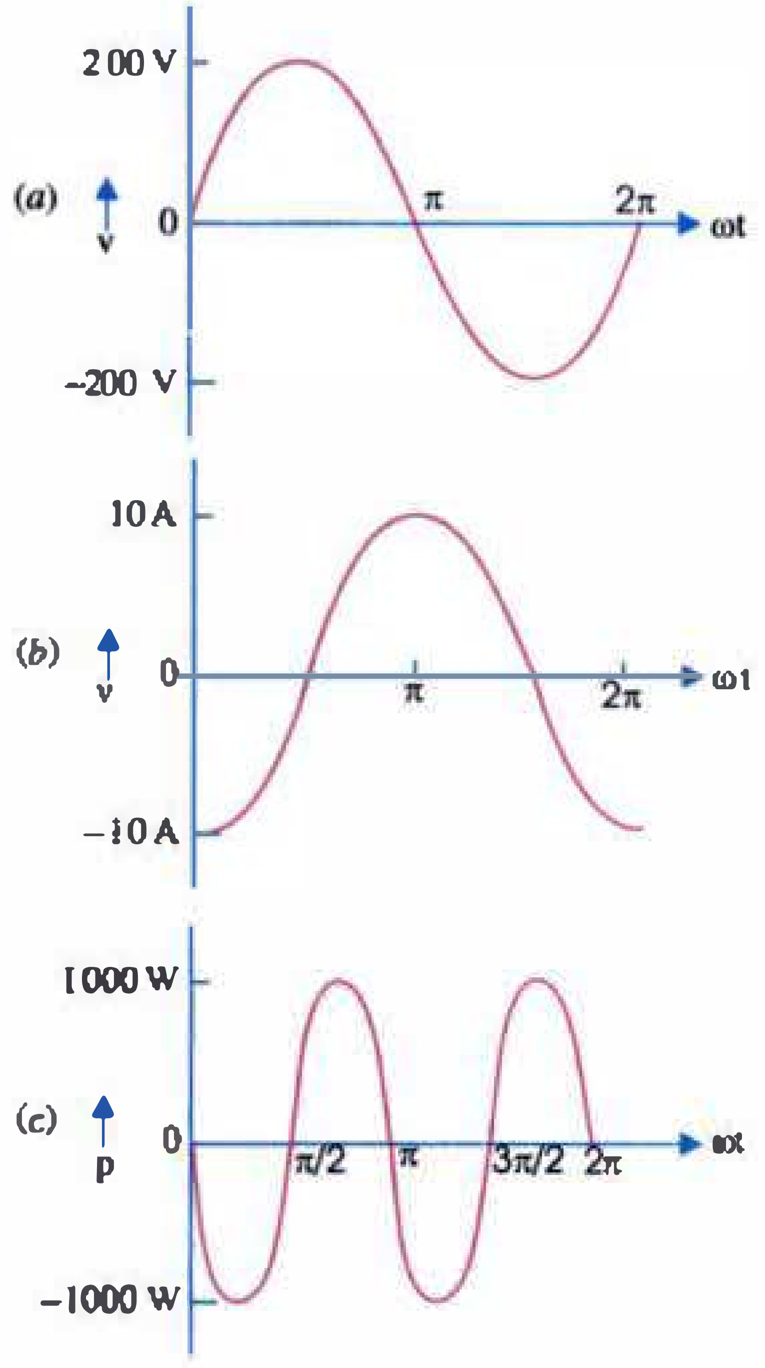


Fig. 8.24

Its wave form is shown in Fig. 8.24 (*b*).

(*b*) $p(t) = v(t).\, i(t)$

$$= (200 \sin 1000\, t) \times (-10 \cos 1000\, t)$$

$$= -200 \sin 1000\, t . \cos 1000\, t$$

$$= -2000 \times \frac{1}{2} \sin 2000\, t = \mathbf{-1000 \sin 2000\, t}$$

As seen from Fig. 8.24 (*c*), average power is zero.

Note. $\sin x \cos x = 1/2 \sin 2x$.

Example 8.7. *A sinusoidal voltage $v(t) = 200 \sin 1000\, t$ is applied across a pure capacitor of 100 μF. Find (a) current i (t) (b) charge q (t) and (c) power p(t). Draw their sketches.*

Solution.

(*a*) $i(t) = C \dfrac{dv}{dt} = C \dfrac{d}{dt}(200 \sin 1000\, t)$

$$= 100 \times 10^{-6} (200 \times 1000 \cos 1000\, t) = \mathbf{20 \cos 1000\, t \text{ amperes}}$$

The sketch is shown in Fig. 8.25 (*b*).

(*b*) $q(t) = C.v(t) = 100 \times 10^{-6} \times 200 \sin 1000\, t = \mathbf{0.02 \sin 1000\, t}$ **coulomb.**

It is sketched in Fig. 8.25 (*c*).

(*c*) $p(t) = vi = 200 \sin 1000\, t \times 20 \cos 1000\, t$

$$= 200 \times 20 \times \frac{1}{2} \sin 2000\, t = \mathbf{2000 \sin 2000 t \text{ watt.}}$$

It is shown in Fig. 8.25 (*d*). It is obvious that net power consumed by the capacitor over one cycle is zero.

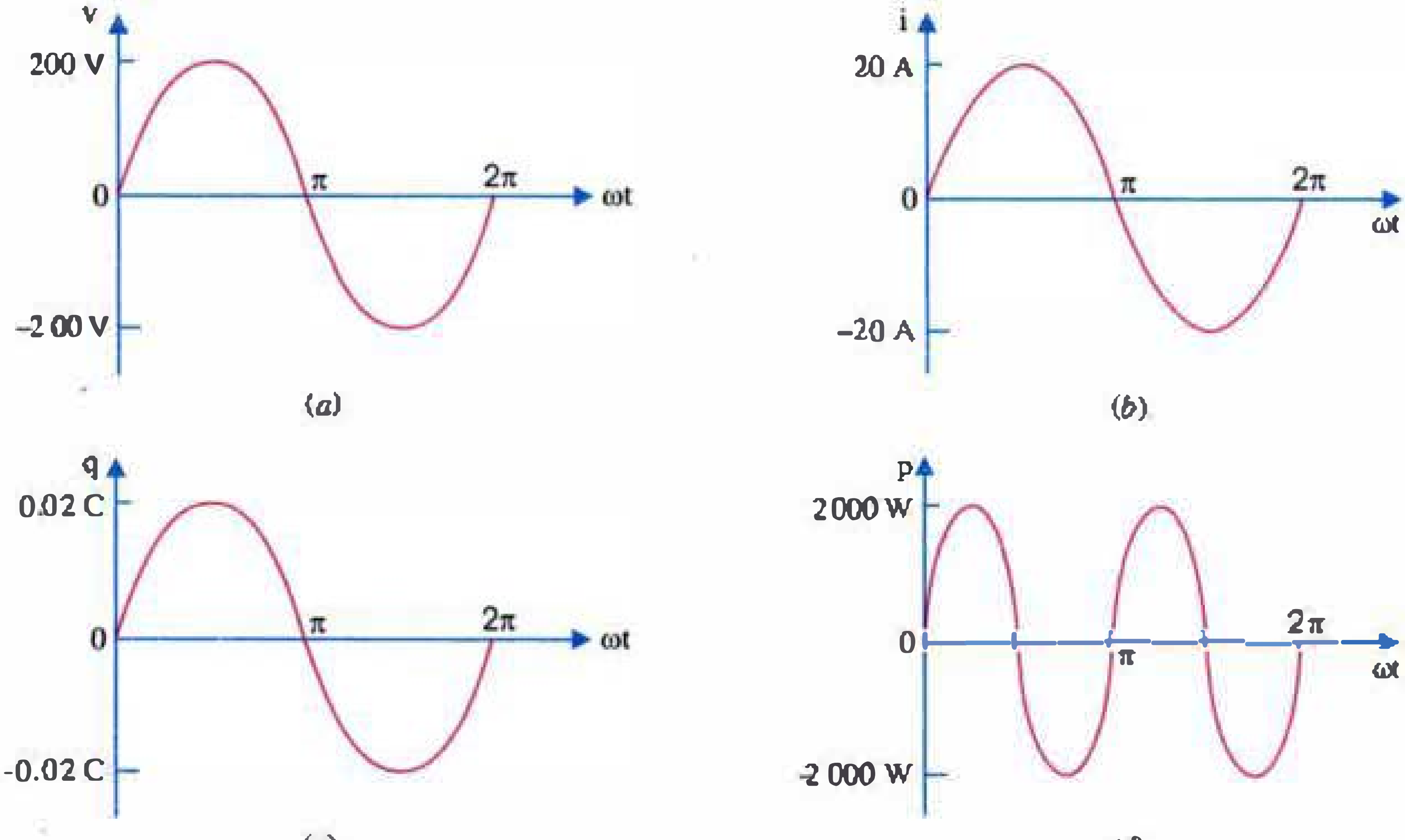


Fig. 8.25

8.14. Non-Sinusoidal Waveforms

The sine wave is considered the basic waveform because it is the one produced by alternators and electronic oscillators. Moreover, it is the only waveform which will produce a single frequency current from a single-frequency voltage when applied to resistive, inductive or capacitive load. The waves deviating from the standard sine or cosine wave are treated as *distorted* waves, they are called non-sinusoidal waveforms like the triangular and square waveforms shown in Fig. 8.3 (*b*) and (*c*) respectively and find many applications in electronic circuits. In the case of non- sinusoidal waveforms,

1. it is common practice to designate peak-to-peak value instead of peak value only because they generally have unsymmetrical peaks;
2. usually no angles are shown along the horizontal axis as is usually done in the case of sine waves. Instead, only time period is indicated;
3. the two half cycles may be non-symmetrical either in amplitude or time or both.

Non-sinusoidal waveforms are also called *complex* waveforms. A non-sinusoidal voltage may produce a current waveform similar to its own when load is resistive but it will not do so if load is either capacitive or inductive.

Example 8.8. *A non-sinusoidal current having the waveform shown in Fig. 8.26 is passed through a pure inductance of 5 mH. Sketch the voltage waveform v(t).*

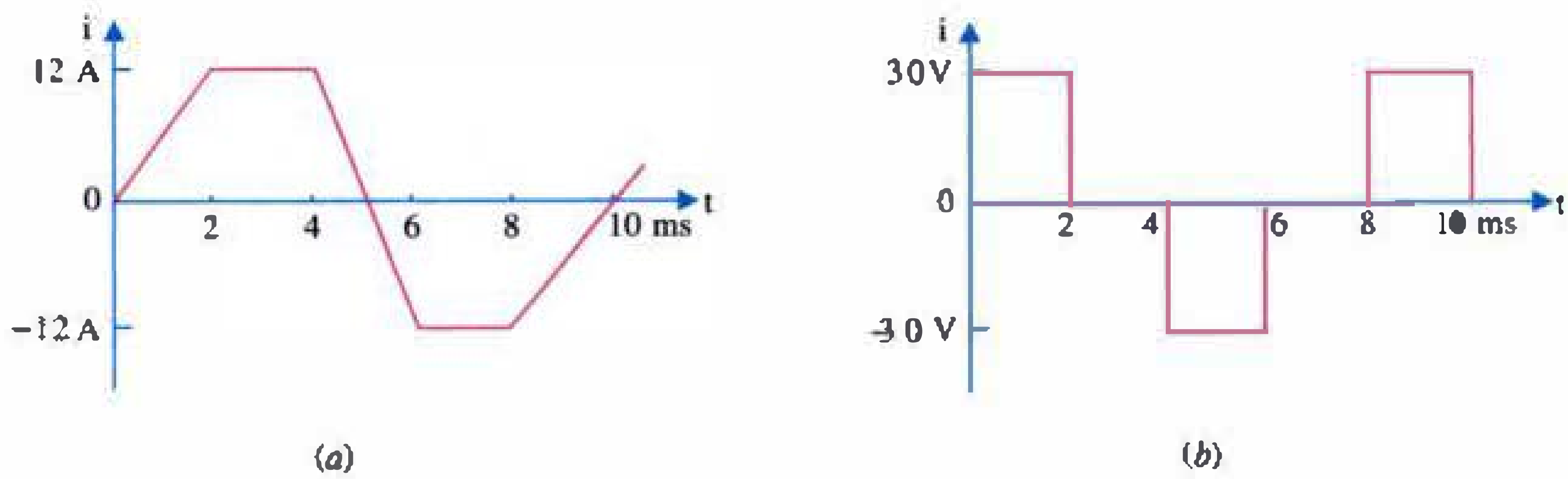


Fig. 8.26

Solution. For finding values of $v(t)$ at different instants, we will use the equation

$$v(t) = L\frac{di}{dt}$$

Let us first find the average value of di/dt during different time intervals.

(*a*) Between 0 and 2 ms

$$\text{average } \frac{di}{dt} = \frac{12-0}{2\times 10^{-3}} = 6\times 10^3 \text{ A/s}$$

(*b*) Between 2 and 4 ms

$$\text{average } \frac{di}{dt} = \frac{0}{2\times 10^{-3}} = 0$$

(*c*) Between 4 and 6 ms

$$\text{average } \frac{di}{dt} = \frac{-12-(12)}{2\times 10^{-3}} = -12\times 10^3 \text{ A/s}$$

(*d*) Between 6 and 8 ms

$$\text{average } \frac{di}{dt} = 0$$

(*e*) Between 8 and 10 ms

$$\text{average } \frac{di}{dt} = \frac{0-(-12)}{2\times 10^{-3}} = 6\times 10^3 \text{ A/s}$$

5. Two alternating currents are given by

$$i_1 = 50\sin\left(314t + \frac{\pi}{6}\right)$$

$$i_2 = 20\sin\left(314t - \frac{\pi}{4}\right)$$

Find their phase difference. Which of the two currents leads the other ? [(*a*) 75° (*b*) I_1]

SELF EXAMINATION QUESTIONS

A. Fill in the blanks by most appropriate word (s) or numerical value (s).

1. A train of sine waves which contains 50 positive peaks and 50 negative peaks per second has a frequency of .... Hz.
2. The polarity of an ac waveform reverses every .... cycle.
3. The time period of a sine wave of 1 kHz is .... millisecond.
4. For a sinusoidal ac voltage of peak value 100 V, the rms value is ....V.
5. For a sinusoidal ac voltage of rms value 70.7 V, the p-p value is ....V.
6. The ac current drawn by a capacitor .... the applied voltage by 90°.
7. Higher the frequency of the ac current .... the reactance offered by a capacitor.
8. Complex waveforms can be formed by adding.........to the fundamental frequency.
9. Frequencies which are .... multiple of the fundamental frequency are called harmonics.
10. Net power consumed by a pure inductive coil or pure capacitor is ....

B. Answer True or False

1. Sine wave has been adopted universally as a standard waveform because it is easy to produce.
2. A waveform can be sinusoidal but non-symmetrical and *vice-versa*.
3. One complete cycle of a waveform contains two alternations which may not be identical.
4. A frequency of 15 kHz lies in the audio-frequency range.
5. Average value of a sinusoidal ac is slightly greater than its rms value.
6. Greater the capacitance of a capacitor, higher the reactance it offers to an alternating voltage.
7. A non-sinusoidal waveform consists of a fundamental frequency plus its harmonics.
8. A square waveform can be built up from sinusoidal waveforms of different frequencies.
9. Only sinusoidal voltage produces a sinusoidal current in any type of load.
10. When harmonics of a fundamental sine wave are added to it, we get a complex wave.

C. Multiple Choice Items

1. An ac current given by $i = 14.14 \sin(\omega t + \pi/6)$ has an rms value of .... amperes
   (*a*) 10 (*b*) 14.14
   (*c*) 1.96 (*d*) 7.07
   and a phase of .... degrees.
   (*e*) 180 (*f*) 30
   (*g*) –30 (*h*) 210
2. The rms value of a sinusoidal ac current is equal to its value at an angle of .... degrees.
   (*a*) 60 (*b*) 45 (*c*) 30 (*d*) 90
3. Two sinusoidal currents are given by the equations : $i_1 = 10 \sin(\omega t + \pi/3)$ and $i_2 = 15 \sin(\omega t - \pi/4)$. The phase difference between them is .... degrees.
   (*a*) 105 (*b*) 75 (*c*) 15 (*d*) 60
4. An ac current is given by $i = 100 \sin 100\pi t$. It will achieve a value of 50 A after .... second.
   (*a*) 1/600 (*b*) 1/300
   (*c*) 1/1800 (*d*) 1/900
5. The average value of an ac current wave given by $i = 100 \sin 100\pi t$ is .... amperes.
   (*a*) 70.7 (*b*) 141.4 (*c*) 157 (*d*) 63.7

ANSWERS

A. Fill in the blanks

1. 50 2. half 3. one 4. 70.7 5. 200 6. leads
7. greater 8. harmonics 9. integral 10. zero

B. True or False

1. F 2. T 3. T 4. T 5. F 6. F 7. T 8. T 9. T 10. T

C. Multiple Choice Items

1. *a*, *f* 2. *b* 3. *a* 4. *a* 5. *d*

9

CHAPTER

Series A.C. Circuits

9.1. R-L Circuit

Suppose a *pure* coil of inductance L is connected in series with a *pure* resistance R* and is energised by a sinusoidal voltage of r.m.s. value V** as shown in Fig. 9.1 (*a*). If we take the current as the reference quantity, then it will give rise to a sinusoidal voltage drop v_R across R which will be in phase with it as shown in Fig. 9.1 (*c*). The voltage drop v_L across the coil will *lead* the current by 90° as shown in Fig. 9.1 (*d*). In other words, current through a coil lags behind the voltage across it. The resultant voltage is the *vector* (or phasor) sum of v_R and v_L and as shown in Fig. 9.1 (*e*), leads current by some angle ϕ. In other words, circuit current *lags behind* the applied voltage by an angle ϕ.

These facts have been shown in the phasor diagram of Fig. 9.2 (*a*) which is called voltage triangle. Here

V = r.m.s. value of applied voltage

I = r.m.s. value of circuit current

$V = IR$

= r.m.s. voltage drop across R (in phase with I)

$V = IX_L$

= r.m.s. voltage drop across L

(at right angles to I)

* This R could also be the internal resistance of an actual coil itself.

** The equation of the alternating voltage would be $v = \sqrt{2}\, V \sin \omega t$.

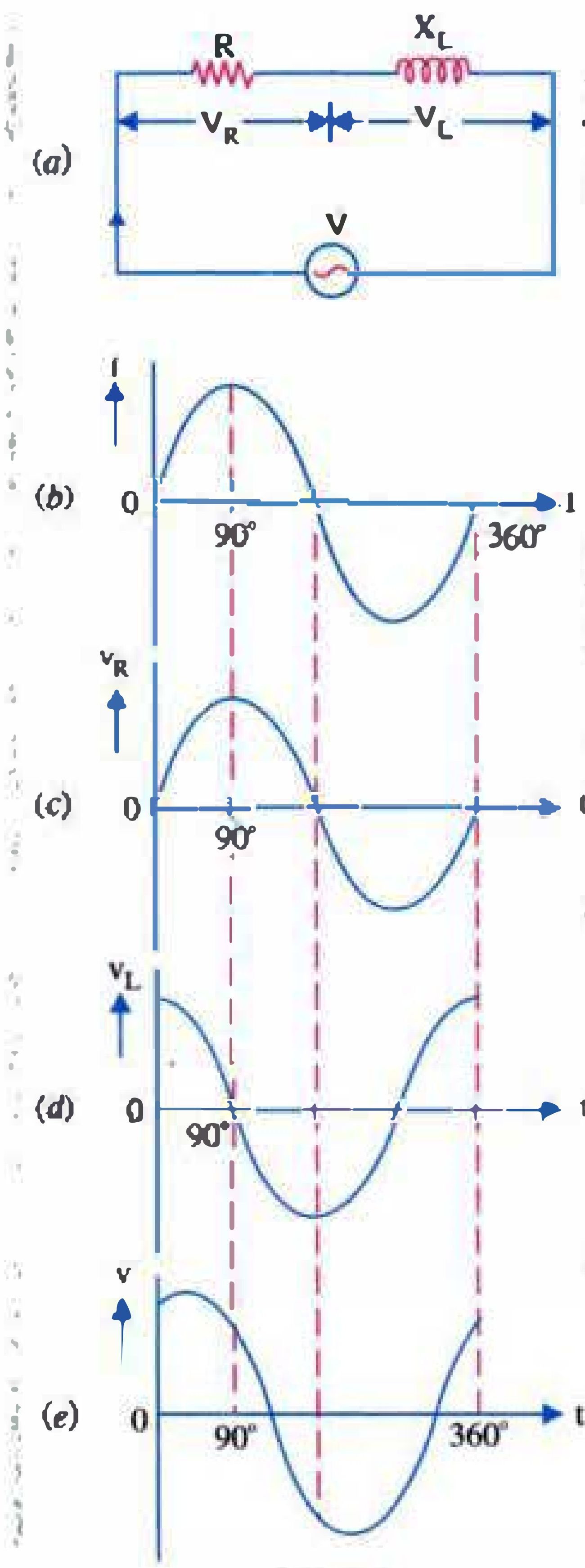


Fig. 9.1

Since in a series combination, same current flows through the two components, it has been taken as the reference quantity. That is why current vector has been taken along the horizontal or reference axis. As seen from Fig. 9.2 (*a*).

$$V = \sqrt{V_R^2 + V_L^2} = \sqrt{(IR)^2 + (IX_L)^2}$$

$$= I\sqrt{R^2 + X_L^2} = IZ \quad \text{or} \quad I = \frac{V}{Z}$$

The quantity $(R^2 + X_L^2)^{1/2}$ is called *impedance* (Z) of the circuit and is shown separately in Fig. 9.2 (*b*). Obviously, Z is the vector sum of R and X_L as shown in the impedance triangle of Fig. 9.2 (*b*).

It is also seen that current I lags behind the applied voltage V by angle ϕ such that

$$\tan\phi = X_L/R$$

Since pure inductive coil consumes no power, the power drawn by the circuit is the same as dissipated by R.

$$\therefore \quad P = I^2R$$

$$= I.I.R = I.\frac{V}{R}.R$$

$$= VI\frac{R}{Z} = VI\cos\phi \quad \text{— Fig. 10.2}$$

The terms 'cos ϕ' is called the power factor of the R-L circuit.

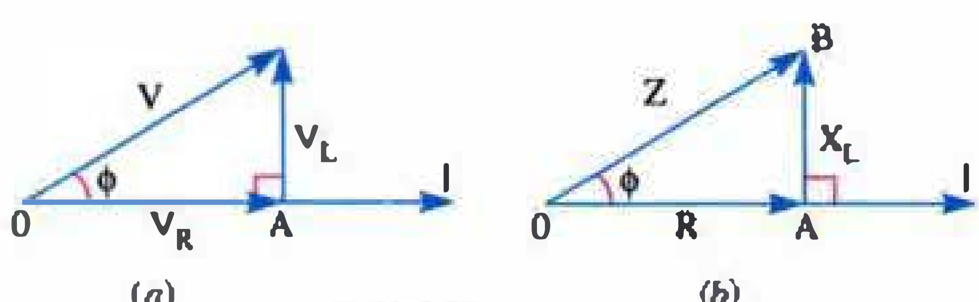


Fig. 9.2

Example 9.1. *A coil having L = 0.14 H and R = 9.43 Ω is connected across a 50 Hz, 135V supply. Compute*

(*i*) X_L (*ii*) Z (*iii*) I (*iv*) R_V (*v*) V (*vi*) ϕ (*vii*) power factor and (*viii*) power absorbed.

Solution. (*i*) $X_L = 2\pi f L = 2\pi \times 50 \times 0.14 = \mathbf{44\ \Omega}$

(*ii*) $Z = \sqrt{R^2 + X_L^2} = \sqrt{9.43^2 + 44^2} = 45\ \Omega$

(*iii*) $I = \frac{V}{Z} = \frac{135}{45} = 3\text{A}$

(*iv*) $V_R = IR = 3 \times 9.43 = \mathbf{28.3\ V}$

(*v*) $V_L = IX_L = 3 \times 44 = \mathbf{132\ V}$

(*vi*) $\cos\phi = R/Z = 9.43/45 = \mathbf{0.21}$

(*vii*) $\phi = \cos^{-1}(0.21) = \mathbf{77.6°}$ **(lag)**

It means that current lags behind the applied voltage by 77.6°.

(*viii*) Power absorbed $= VI\cos\phi = 135 \times 3 \times 0.21 = \mathbf{85\ watt}$

or $P = I^2R = 3^2 \times 9.43 = \mathbf{85\ W}$

9.2. Q Factor of a Coil

The quality factor Q of a coil is given by

$$Q = \frac{X_L}{R} = \frac{\omega L}{R} = \frac{2\pi f L}{R}$$

where L is the inductance of the coil and R its resistance.

The Q-value of a coil may vary from less than 10 to about 1000. The radio-frequency (RF) coils usually have a Q of about 30 to 500. At low frequencies, R is just equal to the d.c. resistance of the coil but at radio-frequencies, it represents the a.c. effective resistance R_e of the coil which is much greater than R. The factors which make R_e greater than R are (*i*) skin effect (*ii*) eddy currents and (*iii*) hysteresis loss. Hence, Q of the coil is decreased at high frequencies because it is given by

$$Q = \frac{X_L}{R_e}$$

The Q of a coil can be measured with the help of a Q-meter.

9.3. Skin Effect

For d.c. and low frequency a.c., current through a conductor flows uniformly over its entire cross-section as shown in Fig. 9.3 (*a*). As the frequency is increased, current tends to flow towards the outer parts of the conductor [Fig. 9.3 (*b*)]. At radio-frequencies, the current is practically confined to the outer surface of the conductor as shown in Fig. 9.3 (*c*). The gradual shift of current flows from centre to the surface of the conductor is known as *skin effect*. It results in the conductor offering greater resistance at higher frequencies.

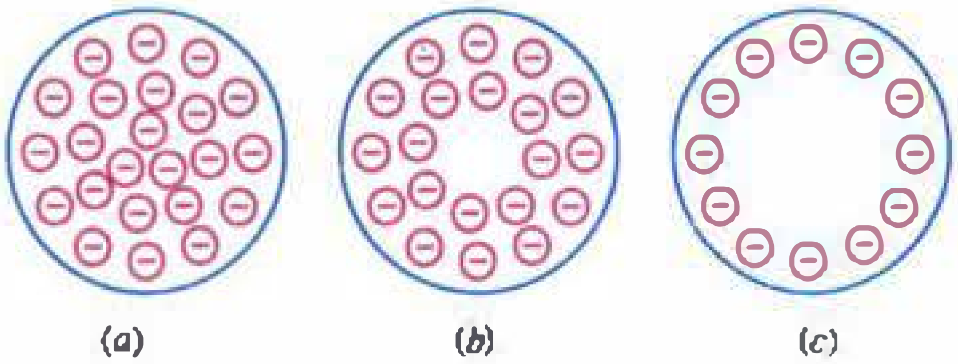


Fig. 9.3

The skin effect is due to the fact that current encounters more inductance at the centre of the conductor than near its surface. It is so because magnetic flux is more concentrated at the centre than near the edges of the conductor where part of the flux passes through air. That is why conductors for very high frequency (VHF) currents are made of hollow tubing.

Skin effect can be minimised by forming the conductor from a large number of interwoven wires connected in parallel at their ends but insulated from each other throughout the rest of their length. In this way, each conductor is linked with the same amount of magnetic flux and carries equal current thereby greatly increasing the useful cross-section of the conductor. Such a stranded conductor is called a Litz conductor.

Example 9.2. *A 100 μH coil has a Q-value of 500 at 5 MHz. What is its effective resistance?*

Solution. $R_e = \dfrac{2\pi f L}{Q} = \dfrac{2\pi \times 5 \times 10^6 \times 100 \times 10^{-6}}{500} = \mathbf{6.2\ \Omega}$

9.4. R.C. Circuit

Such a series combination connected across an a.c. voltage of rms value V is shown in Fig. 9.4. Here

$V_R = IR$ = drop across R (in phase with I)

$V_C = IX_C$ = drop across C (lagging I by 90°)

Since capacitive reactance X_C is taken negative, V_C is drawn along negative Y-axis as shown in Fig. 9.4 (*b*).

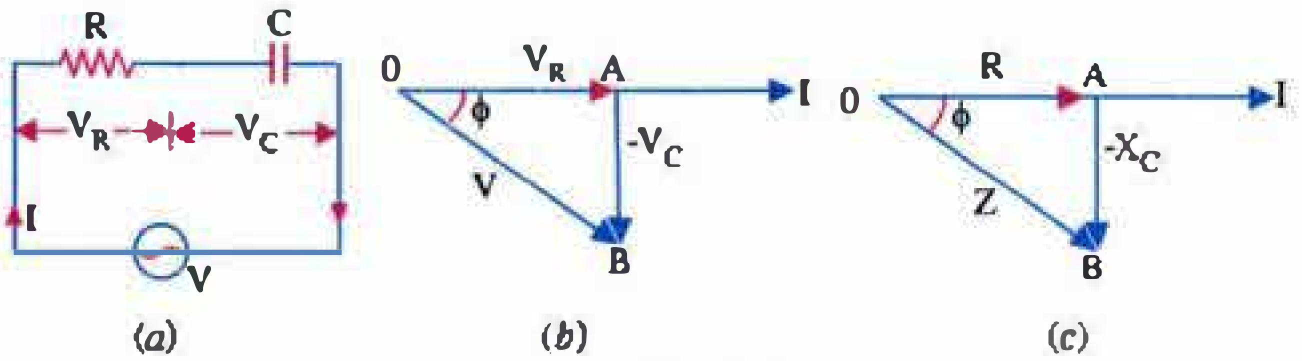


Fig. 9.4

$\therefore \quad V = \sqrt{V_R^2 + V_C^2} = \sqrt{(IR)^2 + (-IX_C)^2} = I\sqrt{R^2 + X_C^2} = IZ$

$\therefore \quad I = \dfrac{V}{Z}$

It is seen that current *leads* the applied voltage by an angle ϕ such that

$\tan\phi = \dfrac{-X_C}{R}$ — Fig. 10.4 (*b*)

Since a pure capacitor consumes no power, the entire circuit power consumption is due to resistor only.

$\therefore \quad P = I^2 R = VI\cos\phi$ — as in an *RL* circuit

Example 9.3. *A capacitor having a capacitance of 10 μF is connected in series with a pure resistance of 120 Ω across a 100 V, 50 Hz supply. Calculate*

(a) current *(b) phase angle, ϕ* *(c) power consumed.*

Solution. $X_C = \dfrac{1}{2\pi f C} = \dfrac{1}{2\pi \times 50 \times 10 \times 10^{-6}} = \dfrac{10^6}{100\pi} = 318\ \Omega$

$Z = \sqrt{120^2 + 318^2} = 340\ \Omega$

(*a*) $I = \dfrac{V}{Z} = \dfrac{100}{340} = \mathbf{0.294\ A}$

(*b*) $\tan\phi = 318/100 = 3.18 \quad \therefore \phi = \tan^{-1}(3.18) = \mathbf{69.3°}$

(*c*) $P = 0.294^2 \times 120 = \mathbf{10.4\ W}$

9.5. Coupling Capacitor

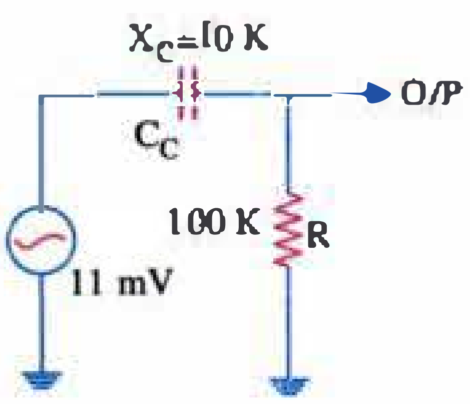


Fig. 9.5

An *R-C* circuit is often used in electronic circuits for passing on a *high-frequency signal* from one circuit to another. The capacitor used in the circuit is called coupling capacitor because it *couples* or joins the two circuits so far as a.c. signal is concerned but, by blocking d.c. keeps them isolated from each other. The low reactance C_C of the coupling capacitor (Fig. 9.5) allows practically all the a.c. signal to be dropped across *R* which passes it on to the next circuit. Very little signal is developed across C_C itself.

Usually, reactance of C_C is about one-tenth of *R*. Suppose, an a.c. signal of 11 mV is to be coupled from the signal source in Fig. 9.5 to a circuit on the right, say, the next stage of an audio amplifier.

Drop across $C_C = 11 \times \dfrac{10}{(10 + 100)} = 1\ \text{mV}$

Drop across $R = 11 \times \dfrac{100}{110} = 10\ \text{mV}$

It is seen that practically 91 per cent of the input signal appears across *R* and can be passed on to the next amplifier stage.

9.6. R-L-C Circuit

As shown in Fig. 9.6, the series combination is connected across a sinusoidal voltage of rms value V.

Let $V_R = IR$ — in phase with I

$V_L = IX_L$ — leading I by 90°

$V_C = IX_C$ — lagging I by 90°

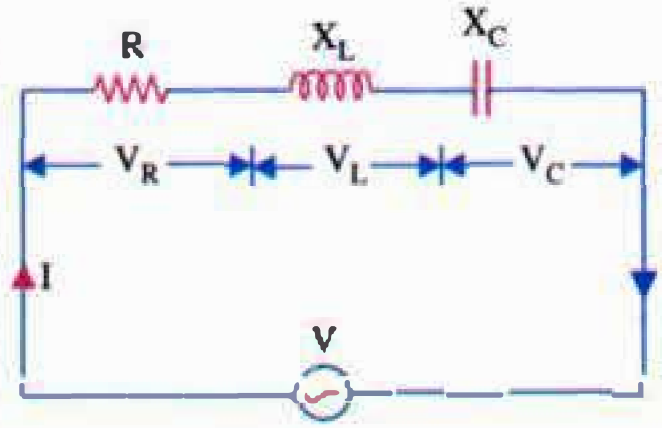


Fig. 9.6

Since V_L is ahead of I by 90° and V_C is behind it by 90°, the phase difference between the two is 180° *i.e.*, they are in direct opposition to each other as shown in Fig. 9.7 (*a*).

In the voltage triangle of Fig. 9.7 (*a*), V_L has been assumed greater than V_C which makes I lag behind V. If $V_C > V_L$, then I leads V. Subtracting AC from $AB = BD$, we get the net reactive drop

$AD = V_L - V_C = I(X_L - X_C) = IX$

From the voltage triangle OAD of Fig. 9.7 (*a*), we have

$$OD = \sqrt{OA^2 + AD^2}$$

or
$$V = \sqrt{(IR)^2 + (IX_L - IX_C)^2}$$

$$= I\sqrt{R^2 + (X_L - X_C)^2}$$

$$= I\sqrt{R^2 + X^2} = IZ$$

$$\therefore \quad I = \frac{V}{Z} = \frac{\text{applied voltage}}{\text{impedance}}$$

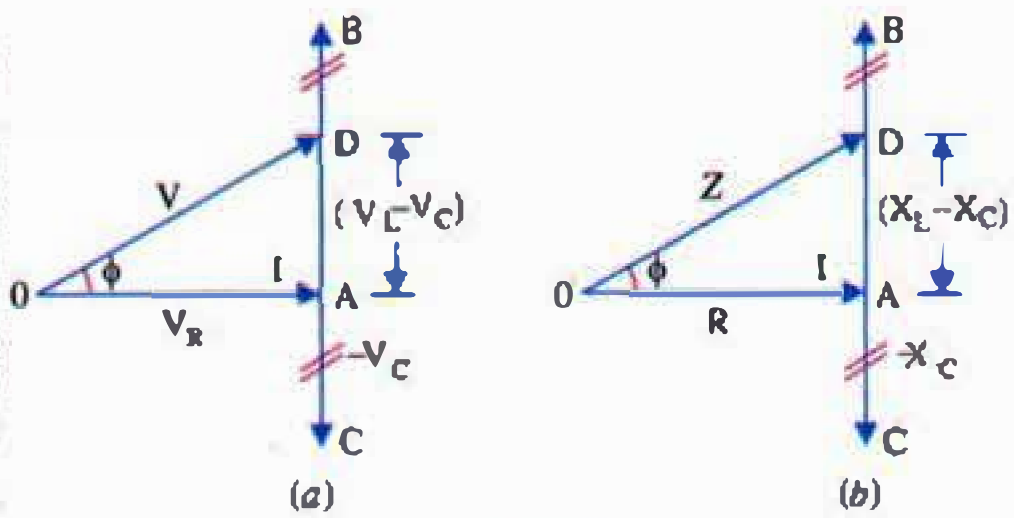


Fig. 9.7

The phase angle ϕ is given by $\tan\phi = X/R$

where X is the net reactance and is inductive in the present case. If V_C would have been greater than V_L, then X would have been capacitive. If $X_L = X_C$, then $X = 0$ and the circuit is said to be in electrical *resonance*.

9.7. Resonance in an R-L-C Circuit

If a sinusoidal voltage of variable frequency is applied across an *R-L-C* circuit, it encounters different impedance at different frequencies. As frequency is increased, X_L is increased but X_C is decreased. There is a certain frequency of the applied a.c. voltage for which $X_L = X_C$. It is called resonance. Obviously, the only impedance offered by the circuit is R and is the *lowest* it can offer. Hence, under resonant condition, circuit current is maximum and is given by

$$I_m = V/R$$

Moreover, this current is in phase with the applied voltage. Hence, the circuit behaves like a purely resistive circuit with a power factor of unity. The resonant frequency can be found from the condition

$$X_L = X_C \quad \text{or} \quad 2\pi f_0 L = \frac{1}{2\pi f_0 C}$$

$$\therefore \quad f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{0.159}{\sqrt{LC}} \cong \frac{0.16}{\sqrt{LC}}$$

If L is in henrys and C in farads, then f_0 is in hertz. Obviously, f_0 can be changed by changing either L or C. It should be noted that resistance R plays *no part in determining the resonant frequency* although it does limit the current at resonance and also affects the off-resonance behaviour of the circuit.

9.8. Resonance Curve

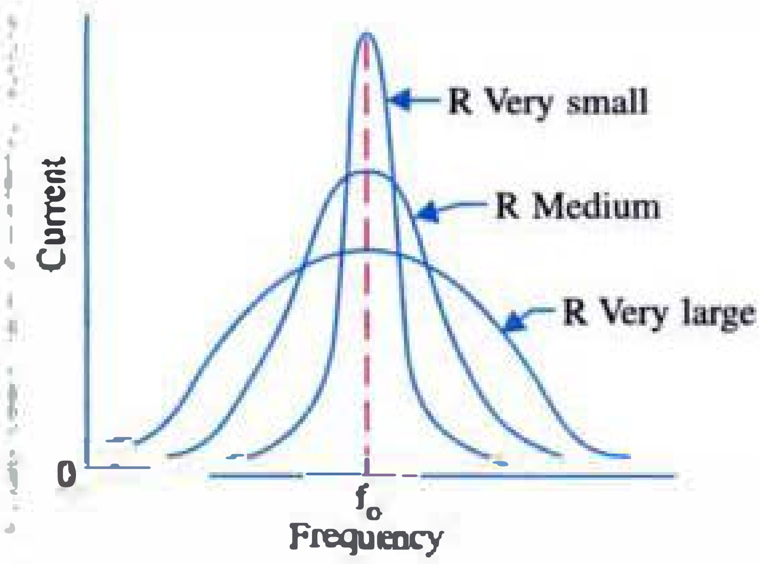


Fig. 9.8

It is the curve which shows variation in circuit current with change in the frequency of the applied voltage. The shape of such a curve for various values of R is shown in Fig. 9.8. For smaller values of R, the resonance curve is not only sharply peaked but also has very steep sides. For large values of R, the curve is flat and broad-sided.

It should be particularly noted that the value of R not only affects the value of circuit current I, it also affects the *shape* of the resonance curve itself. For low values of R, sides of the curve are very steep which means that current falls off very rapidly as the frequency changes from resonance to off-resonance value. For large values of R, curve is broad-sided which means limited change in current for resonance and off-resonance conditions.

As seen from above, smaller the R, steeper the sides of the resonance curve and consequently sharper the tuning of the circuit.

9.9. Main Characteristics of Series Resonance

Following main points about series resonance are worth noting :

1. The circuit current is maximum and is given by $I_m = V/R$.
2. The circuit offers minimum impedance $Z_{min} = R$.
3. The circuit behaves like a pure resistive circuit and has a power factor of unity.
4. Voltage drops V_L and V_C are maximum and equal in magnitude but cancel out since they are 180° out of phase with each other.
5. Resonant frequency is given by

$$f_0 = \frac{0.159}{\sqrt{LC}} \cong \frac{0.16}{\sqrt{LC}}$$

9.10. Bandwidth of a Tuned Circuit

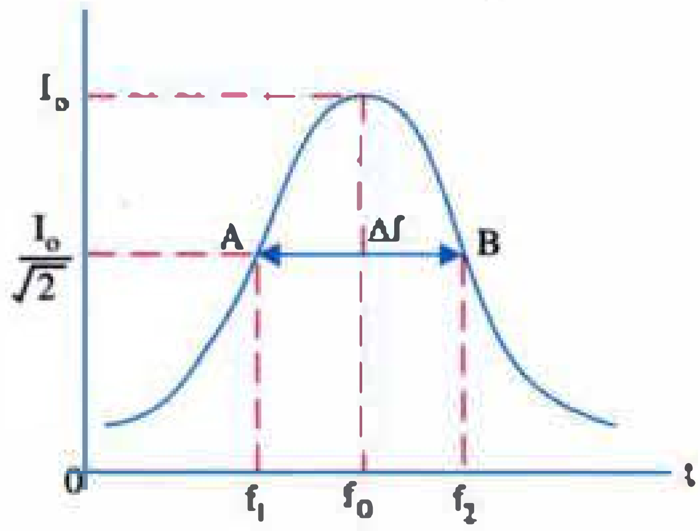


Fig. 9.9

Bandwidth of a tuned circuit is given by the band of frequencies which lie between two points on either side of its resonance curve where current is $1/\sqrt{2}$ or 0.707 of its maximum value at resonance. As shown in Fig. 9.9, bandwidth or passband is given by

$BW = \Delta f = f_2 - f_1$

It can be shown that

$$BW = f_2 - f_1 = \frac{R}{2\pi L} \quad \text{or} \quad BW = \frac{f_0}{Q} \quad \text{— how ?}$$

It can also be proved that *edge* frequencies are given by

$$f_1 = f_0 - \frac{\Delta f}{2} = f_0 - \frac{BW}{2} = f_0 - \frac{R}{4\pi L}$$

Similarly, $$f_2 = f_0 + \frac{\Delta f}{2} = f_0 + \frac{BW}{2} = f_0 + \frac{R}{4\pi L}$$

It may be noted that points A and B in Fig. 9.9 are also called *half-power* points because power developed at each of these points is half the power developed at resonance. Hence, edge frequencies f_1 and f_2 are known as lower half-power frequency and upper half-power frequency respectively. All the frequencies lying between f_1 and f_2 are called *useful* frequencies because they produce currents which when passed through headphones produce a sound that is not much weaker than that produced by maximum current I_m at resonance. Hence, bandwidth of a resonant circuit, in fact, represents the range of its useful frequencies.

9.11. Sharpness of Resonance

It is defined as the ratio of the bandwidth of the circuit to its resonance frequency.

$$\text{Sharpness of resonance} = \frac{f_2 - f_1}{f_0} = \frac{\Delta f}{f_0} = \frac{BW}{f_0} = \frac{1}{Q_0}$$

It shows that as value of Q_0 increases, bandwidth decreases. As bandwidth decreases, selectivity of the circuit increases.

Fig. 9.10 (*a*) shows the resonance curve of a circuit having comparatively large value of R. The passband of the circuit is from 980 kHz to 1020 kHz. Its bandwidth is 40 kHz so that its sharpness of resonance is 40/1000 = 0.04. Similar value for the circuit of Fig. 9.10 (*b*) is 20/1000 = 0.02. This circuit has a selectivity of 20 kHz as compared to 40 kHz of the first circuit. The circuit shown in Fig. 9.10 (*a*) has poorer selectivity because *it does not reject frequencies close to its resonance frequency.*

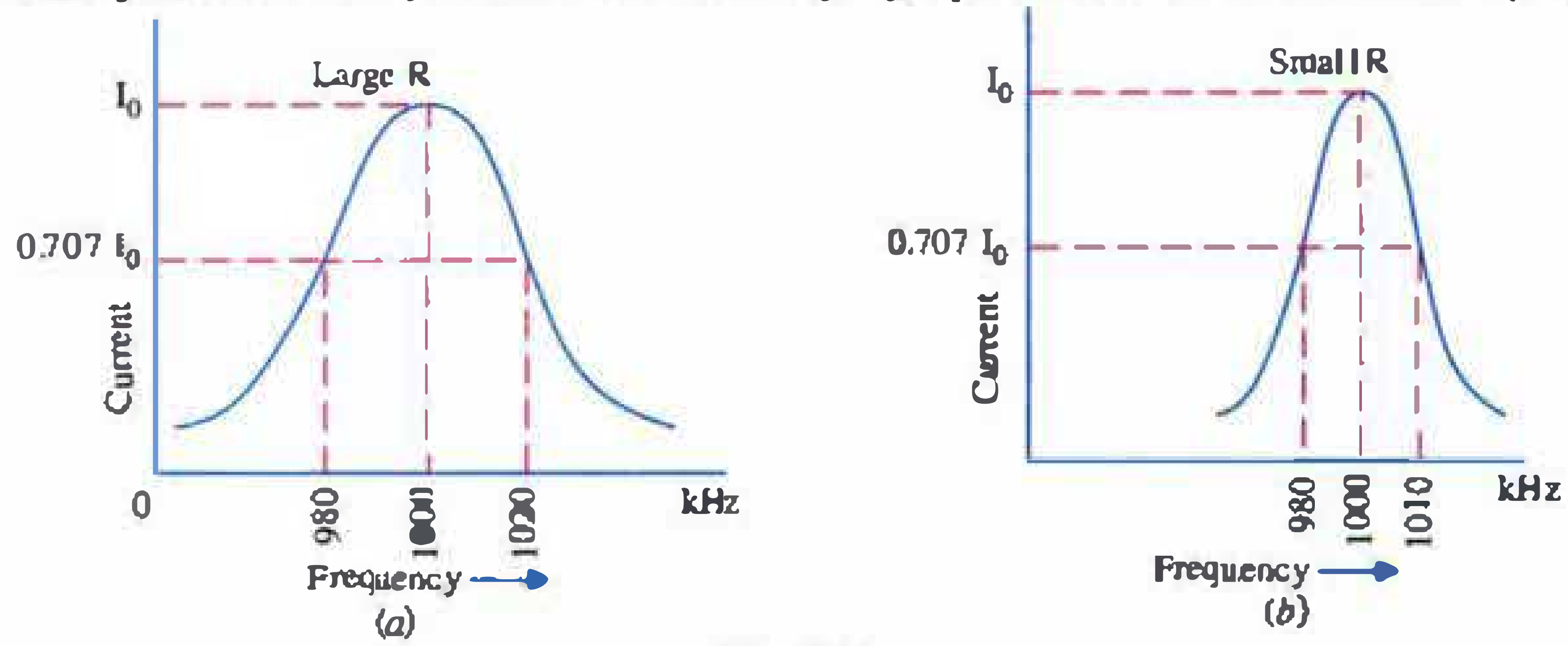


Fig. 9.10

9.12. Tuning

It means obtaining resonance at different frequencies by changing either L or (more often) C of an LC circuit. As shown in Fig. 9.11 (*a*), the variable capacitor C can be adjusted to tune the R-L-C

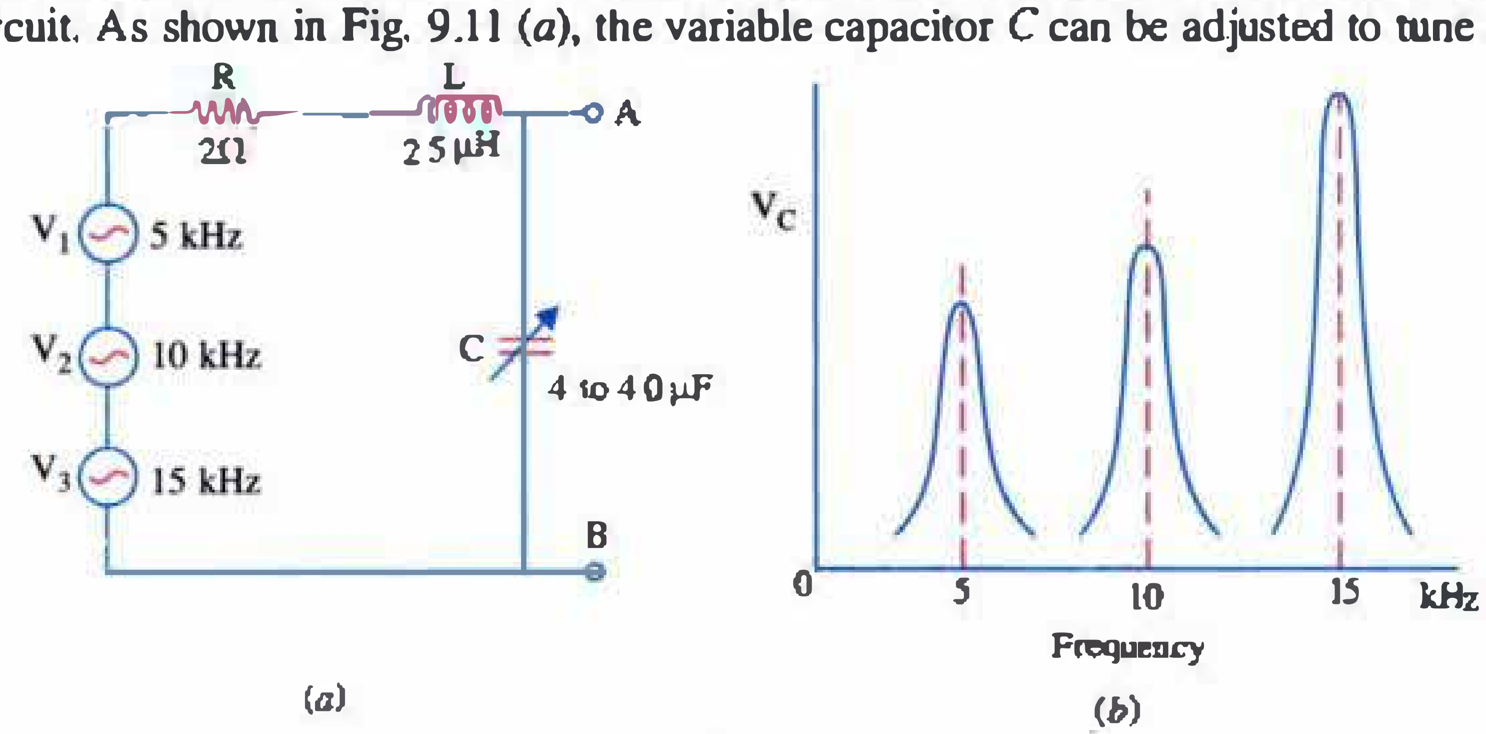


Fig. 9.11

circuit to resonance at any one of the three different frequencies produced by the three signal generators V_1, V_2 and V_3. Which of these frequencies will be selected for maximum output depends upon the resonance frequency of the LC circuit ? When C is adjusted to 40 μF, its resonance frequency becomes

$$f_0 = \frac{1}{2\pi\sqrt{25 \times 10^{-6} \times 40 \times 10^{-6}}} = 5000 \text{ Hz} = 5 \text{ kHz}$$

Hence, out of the three input voltage, only V_1 having a frequency of 5 kHz is selected to produce a resonant rise of current which results in maximum output voltage across C. Of course, some current from V_2 and V_3 will also be produced but it would insignificant.

Suppose, we now adjust $C = 10$ μF, then circuit resonant frequency becomes

$$f_0 = \frac{0.159}{\sqrt{25 \times 10^{-6} \times 10 \times 10^{-6}}} = \mathbf{10 \text{ kHz}}$$

Now, the circuit will offer minimum impedance to V_2 so that input signal of 10 kHz will produce maximum current and hence maximum output voltage V_C. Other signals being too off-resonance will be practically suppressed. In a similar way, by adjusting value of C to 4.44 μF, V_3 can be tuned in. Though we have considered three frequencies only, the LC circuit can be tuned to select any desired frequency.

An inductor plays the same role in an L-C circuit that a spring like this does when connected to a mass. It provides a restoring force that always tries to return the system to equilibrium.

Tuning in radio, radar and TV receivers are all examples of resonance phenomenon. Instruments like wavemeter etc., utilize the tuning properties of an LC circuit. In fact, resonant circuits are widely used in both radio transmitting and radio receiving circuits.

9.13. Tuning Ratio

For a given value of L, the resonant frequency is inversely proportional to the square root of C as seen from the relation

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \text{or} \qquad f_0 \propto \frac{1}{\sqrt{C}}$$

$$\therefore \qquad \frac{f_0}{f_0'} = \sqrt{\frac{C'}{C}} \qquad \text{or} \qquad \frac{f_0'}{f_0} = \sqrt{\frac{C}{C'}}$$

It means that if C is reduced to one-fourth of its previous value, frequency becomes double. In the example considered in Art. 9.12, when C changes from 40 μF to 10 μF, resonant frequency *increases* from 5 kHz to 10 kHz *i.e.*, it is doubled. Suppose, we want to tune through the whole frequency range of 5 to 15 kHz which represents a tuning ratio of 3 : 1 from the highest to the lowest frequency. Then capacitance must be varied from 40 μF to 4.44 μF—a 9 : 1 capacitance ratio.

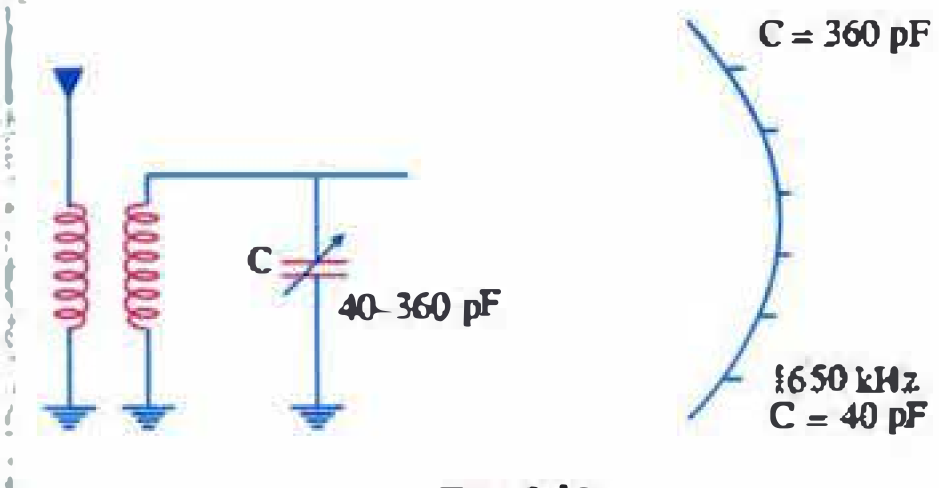


Fig. 9.12

9.14. Radio Tuning Dial

In Fig. 9.12 is shown how resonant circuits can be used in tuning a radio receiver to the carrier frequency of a broadcasting station in the medium band (550 to 1650 kHz). The tuning is done with the help of a variable capacitor C whose capacitance can be varied from 360 μF when plates are completely in mesh to 40 μF when they are out of mesh.

It will be seen that lowest frequency is tuned with highest capacitance and *vice-versa*. Since frequency tuning ratio is 3 : 1, the capacitance ratio is 9 : 1.

Example 9.4. *An RLC circuit consists of a capacitor of reactance 120 Ω and a coil having a resistance of 60 Ω and inductive reactance of 180 Ω. The combination is connected across a 200 V, 50 Hz source. Compute (i) current (ii) p.f. and (iii) power taken by the circuit.*

Solution. $X_L = 180\,\Omega, \quad X_C = -120\,\Omega$

net reactance $X = 180 - 120 = 60\,\Omega$ (inductive)

$$Z = \sqrt{R^2 + X^2} = \sqrt{60^2 + 60^2} = 84.8\,\Omega$$

(*i*) $I = V/Z = 200/84.8 = \mathbf{2.36\ A}$

(*ii*) $\cos\phi = R/Z = 60/84.8 = \mathbf{0.707\ (lag)}$ $\quad \because X_L > X_C$

(*iii*) $P = VI\cos\phi = 200 \times 2.36 \times 0.707 = \mathbf{333\ kW}$

or $P = I^2R = 2.36^2 \times 60 = \mathbf{333\ kW}$

Example 9.5. *A circuit consists of a capacitor of 100 pF connected in series with a coil of resistance 5 Ω and inductance 100 μH. Calculate (i) resonance frequency (ii) Q-factor (iii) band width.*

Solution. (*i*)
$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{0.159}{\sqrt{LC}} = \frac{0.159}{\sqrt{100 \times 10^{-6} \times 100 \times 10^{-12}}}$$
$$= \frac{0.159}{10^{-7}} = 1.59 \times 10^6 = \mathbf{1.59\ MHz}$$

(*ii*)
$$Q_0 = \frac{2\pi f_0 L}{R} = \frac{2\pi \times 1.59 \times 10^6 \times 100 \times 10^{-6}}{5} = \mathbf{200}$$

(*iii*) bandwidth,
$$\Delta f = \frac{f_0}{Q_0} = \frac{1.59 \times 10^6}{200} = \mathbf{7.95\ kHz}$$

Incidentally, $f_1 = 1590 - 7.95 = 1582.05$ kHz

$f_2 = 1590 + 7.95 = 1597.95$ kHz

Example 9.6. *An R L C resonant circuit has a resonant frequency of 2 MHz and a Q-factor of 100. Calculate (i) the bandwidth of the circuit (ii) lower and upper half-power frequencies (iii) selectivity and (iv) sharpness of resonance.*

Solution. (*i*)
$$BW = \Delta f = \frac{f_0}{Q_0} = \frac{2000\text{ kHz}}{100} = \mathbf{20\ kHz}$$

(*ii*)
$$f_1 = f_0 - \frac{\Delta f}{2} = 2000 - 10 = \mathbf{1990\ kHz}$$
$$f_2 = f_0 + \frac{\Delta f}{2} = 2000 + 10 = \mathbf{2010\ kHz}$$

(*iii*) Selectivity = BW = **20 kHz**

(*iv*) Sharpness of resonance $= \dfrac{\Delta f}{f_0} = \dfrac{20}{2000} = \mathbf{\dfrac{1}{100}}$

9.15. Parallel Resonance

In Fig. 9.13 (*a*) is shown a circuit consisting of a capacitor in parallel with a coil of negligible small resistance. When fed from an a.c. voltage source, the capacitor draws a leading current whereas coil draws a lagging current.* This circuit resonates to a frequency which makes $X_L = X_C$ so that the two branch currents are equal but opposite. Hence, they cancel out with the result that current drawn from the supply is zero. In practice, however, line current drawn is not zero but has minimum value due to small resistance R of the coil.

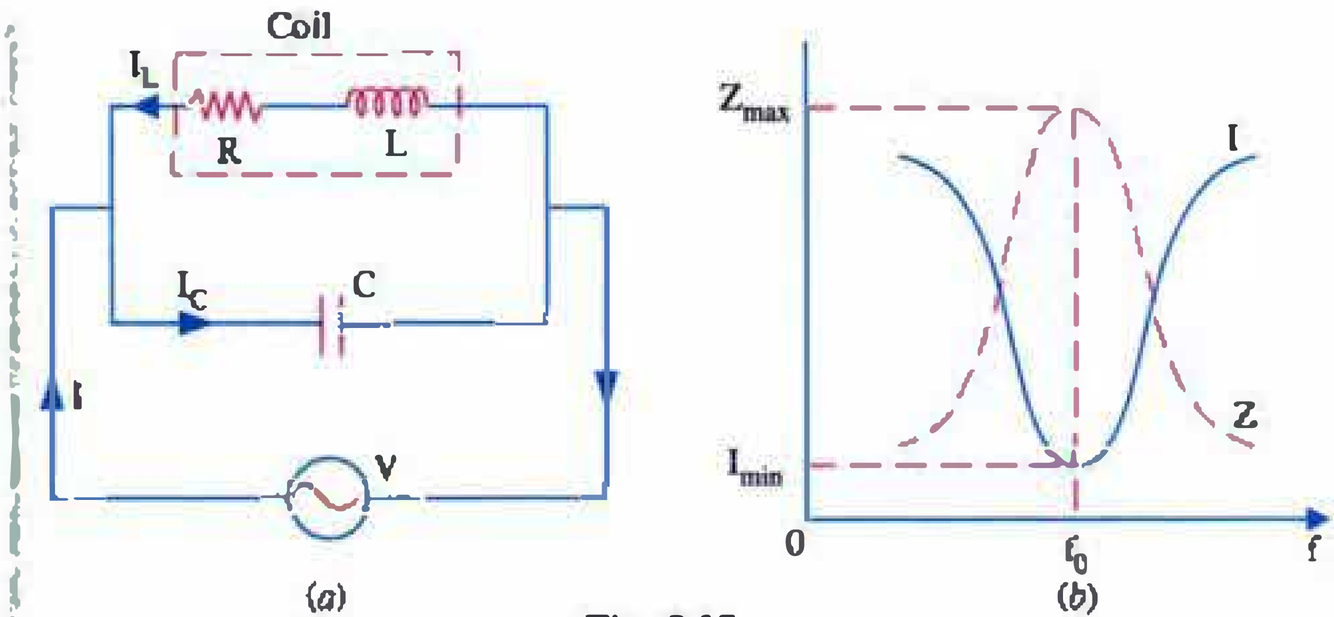


Fig. 9.13

Since current drawn by the circuit is minimum, it means it offers maximum impedance to the applied voltage under resonance condition.

If R is neglected, then

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \text{— as for series circuit}$$

$$I_{min} = \frac{V}{L/CR} \qquad \text{and} \qquad Z_{max} = L/CR$$

As seen from Fig. 9.13 (*b*), current is minimum at f_0 but increases for off-resonance frequencies due to decrease in the circuit impedance.

Main application of a parallel resonant circuit is to act as a load in the output circuit of an RF amplifier. Since impedance is maximum at f_0, amplifier gain is also maximum at f_0. The advantages of using such a circuit as load are that

(*i*) it offers maximum impedance only to the a.c. signal which is required to be amplified,

(*ii*) since coil resistance is almost negligible, there is practically no d.c. voltage drop across it.

The Q-factor of the parallel circuit is essentially the same as that of the coil and is given by

$$Q = \frac{2\pi f_0 L}{R}$$

when R is coil resistance.

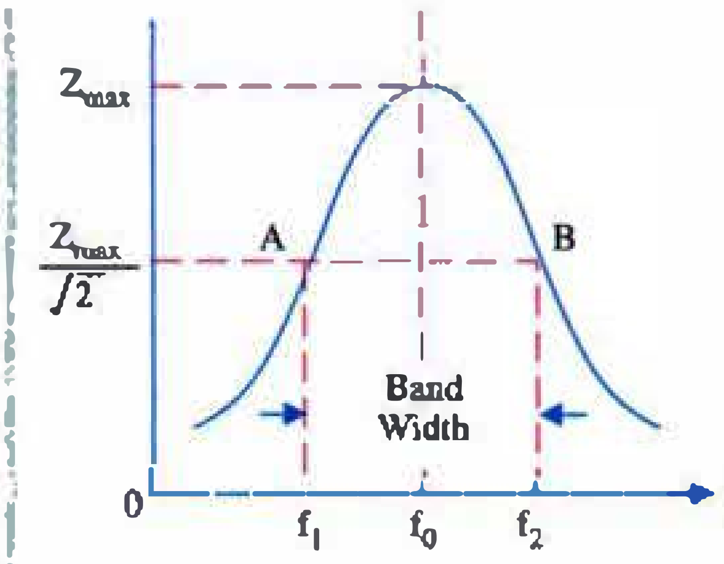


Fig. 9.14

In the case of a resonant parallel circuit, the bandwidth is defined by the two points on either side of the resonant frequency where value of impedance drops to 0.707 or $1/\sqrt{2}$ of its maximum value at resonance (Fig. 9.14).

$$BW = \Delta f = f_2 - f_1 = \frac{f_0}{Q_0}$$

Example 9.7. *A parallel circuit consisting of a 200 pF capacitor and a coil of inductance 200 μH and resistance 5 Ω is connected across a 0.2 V, 800 kHz signal source. Determine for the circuit (i) resonant frequency (ii) Q-value (iii) impedance offered (iv) current drawn and (v) bandwidth of the circuit.*

* The two branch currents are shown flowing in opposite directions in Fig. 9.13 (*a*). It is so because when coil draws in the current, the capacitor discharges out at the same time and *vice-versa*.

Solution. The circuit is diagrammed in Fig. 9.15.

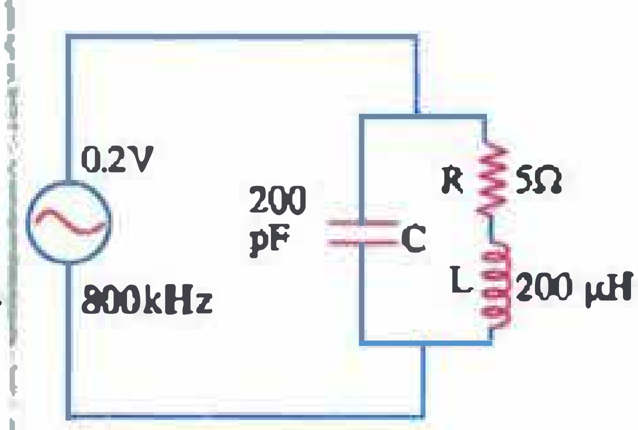


Fig. 9.15

(*i*) $$f_0 = \frac{0.159}{\sqrt{LC}} = \frac{0.159}{\sqrt{200 \times 10^{-6} \times 200 \times 10^{-12}}}$$
$$= 800 \text{ kHz}$$

Obviously, the circuit is in resonance with the input signal.

(*ii*) $$Q_0 = \frac{2\pi f_0 L}{R} = \frac{2\pi \times 800 \times 10^3 \times 200 \times 10^{-6}}{5}$$
$$= \frac{1000}{5} = 200$$

(*iii*) $$Z_{max} = \frac{L}{CR} = \frac{200 \times 10^{-6}}{200 \times 10^{-12} \times 5} = 200,000\ \Omega$$

(*iv*) $$I_{min} = \frac{V}{Z_{max}} = \frac{0.2}{200,000} = 1\ \mu\text{A}$$

(*v*) $$BW = \frac{f_0}{Q_0} = \frac{800}{200} = 4 \text{ kHz}$$

CONVENTIONAL PROBLEMS

1. A 30 Ω resistor and a pure 40 Ω inductor are connected in series across a 200 V supply. Determine (*i*) Z (*ii*) I (*iii*) V_R (*iv*) V_L (*v*) phase angle ϕ (*vi*) power absorbed.
[(*i*) 50 Ω (*ii*) 4 A (*iii*) 120 V (*iv*) 160 V (*v*) 53° (*vi*) 480 W]

2. An *RF* coil has an inductive reactance of 600 Ω at a certain frequency and an a.c. resistance of 10 Ω. Calculate its *Q*-factor. **[60]**

3. A smoothing choke used in a radio receiver circuit has L = 20 H and R = 300 Ω. What impedance will it offer at the ripple frequency of 100 Hz ? **[12,560 Ω]**

4. At what frequency does a 1 kΩ resistor in series with a 2 H choke coil offer an impedance of 1181 Ω? **[50 Hz]**

5. In tone control circuit of a receiver, a 1 kΩ resistor is joined in series with a 0.1 μF capacitor. Calculate the impedance of the combination at 2 kHz and 10 kHz. **[1261 Ω, 1012 Ω]**

6. A 100 Ω resistor and a 2 μF capacitor are connected in series across a 16 V, 1 kHz source. Determine (*i*) X_C (*ii*) Z (*iii*) I (*iv*) V_R (*v*) V_C (*vi*) p.f. and (*vii*) power absorbed.
[(*i*) 80 Ω (*ii*) 128 Ω (*iii*) 0.125 A (*iv*) 12.5 V (*v*) 10 V (*vi*) 0.78 (lead) (*vii*) 1.56 W]

7. A series *R-L-C* circuit has R = 5 Ω, L = 200 μH and C = 0.4 μF. If it is connected across an a.c. voltage source of 10 V at $\omega = 10^5$ radian/second, determine (*i*) current (*ii*) p.f. and (*iii*) power absorbed.
[(*i*) 1.414 A (*ii*) 0.707 (lead) (*iii*) 10 W]

8. What is the resonance frequency of a series *L-C* circuit if L = 200 μH and C = 200 pF ?
[800 kHz]

9. A series *R-L-C* circuit consists of a capacitor of capacitance 200 μF and a coil of resistance 10 Ω and inductance 200 μF. Calculate

(*i*) resonance frequency (*ii*) *Q*-factor
(*iii*) bandwidth (*iv*) lower and upper half-power frequencies.

[(*i*) 800 kHz (*ii*) 100 (*iii*) 8 kHz (*iv*) 792 kHz, 808 kHz]

SELF EXAMINATION QUESTIONS

A. Fill in the blanks by the most appropriate word(s) or numerical value (s).

1. In a series R-L circuit, voltage .... the current.
2. Impedance of an R-L circuit is given by the .... sum of resistance and reactance.
3. Skin effect increases the resistance of a conductor at .... frequencies.
4. Skin effect may be minimised by using .... conductor.
5. If in an R-L circuit, $V_R = 30$ V and $V_L = 40$ V, then applied voltage must be .... V.
6. A pure inductor or capacitor dissipates ....power.
7. Power factor is given by the ratio of circuit resistance and ....
8. The power factor of an R-L circuit lies between .... and ....
9. A series circuit becomes resonant when algebraic sum of X_L and X_C equals ....
10. Resonance curve shows variation of circuit current with ....
11. Higher the Q-factor of a circuit, ... its bandwidth.
12. Lower the resistance of a resonant circuit, ... its selectivity.
13. At half-power frequencies, the current in a series R-L-C resonant circuit is .... times the maximum value of current.

B. Answer True or False

1. The impedance of a series R-L circuit is given by the algebraic sum of R and X_L.
2. The power factor of an a.c. circuit can lie between -1 and $+1$.
3. Skin effect at high frequencies can be neutralized by using conductors made of hollow tubes.
4. Out of the input signals having different frequencies, a series resonant circuit allows that one to pass through whose frequency equals its own lies close to it.
5. A parallel resonant circuit rejects the signal having same frequency as its own resonance frequency.
6. For sharper tuning, series resistance should be decreased.
7. Bandwidth of a circuit can be increased by decreasing inductance but increasing resistance.
8. Greater the bandwidth, higher the selectivity.

C. Multiple Choice Items

1. The power in an a.c. circuit is given by
   (a) $VI\cos\phi$ (b) $VI\sin\phi$
   (c) I^2Z (d) I^2X_L
2. In a series R-L-C circuit, $R = 100\,\Omega$, $X_L = 300\,\Omega$, and $X_C = 200\,\Omega$. The phase angle ϕ of the circuit is .... degrees.
   (a) 0 (b) 90
   (c) 45 (d) 60
3. In a series circuit with $R = 10\,\Omega$, $X_L = 25\,\Omega$ and $X_C = 35\,\Omega$ and carrying effective current of 5 A, the power dissipated is .... watt.
   (a) $250\sqrt{2}$ (b) 50
   (c) 100 (d) 250
4. A resonance curve for a series circuit is a plot of frequency versus ....
   (a) voltage (b) impedance
   (c) current (d) reactance
5. The power factor of a resonant series circuit is
   (a) 1 (b) 0
   (c) -1 (d) 0.5
6. At half-power points of a resonance curve, the current is .... times the maximum current.
   (a) 2 (b) $\sqrt{2}$
   (c) $1/\sqrt{2}$ (d) $1/2$
7. Higher the Q of a series circuit,
   (a) greater its bandwidth
   (b) sharper its resonance curve
   (c) broader its resonance curve
   (d) narrower its passband
8. The selectivity of a series circuit can be increased by
   (a) reducing its resonance frequency
   (b) increasing its Q value
   (c) increasing its resistance
   (d) increasing its bandwidth
9. The resonance frequency of a series resonant circuit is given by
   (a) $f_0 = \sqrt{CR}$
   (b) $f_0 = 2\pi\sqrt{LC}$
   (c) $f_0 = 12\pi\sqrt{LC}$
   (d) $f_0 = 2\pi/\sqrt{LC}$

10. Out of the many input signals of different frequencies, a series resonant circuit will accept one which has
   (*a*) the highest frequency
   (*b*) lowest frequency
   (*c*) frequency farthest from its resonance frequency
   (*d*) frequency closest to its resonance frequency.

ANSWERS

A. Fill in the blanks

1. leads 2. vector 3. high 4. Litz 5. 50
6. no 7. impedance 8. 0; 1 9. zero 10. frequency
11. narrower 12. better 13. 0.707

B. True or False

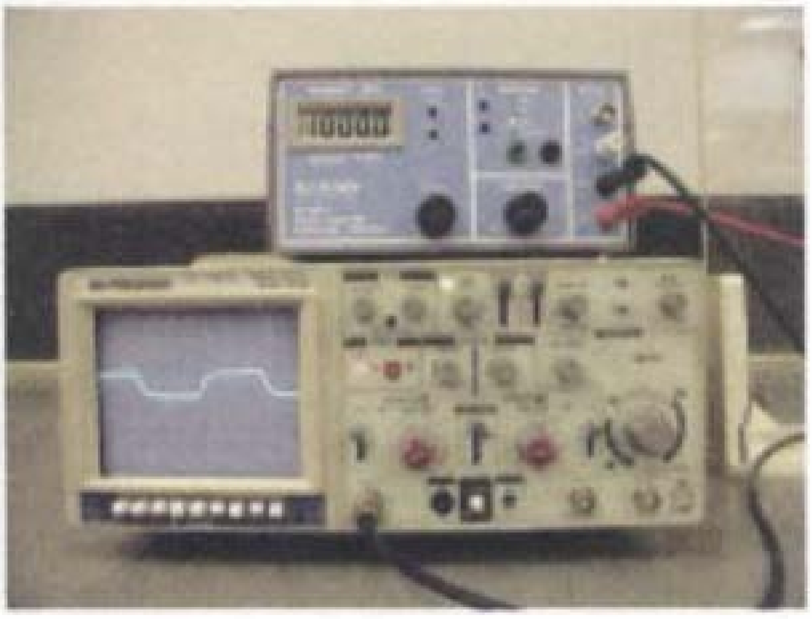
1. F 2. F 3. F 4. T 5. T 6. T 7. T 8. F

C. Multiple Choice Items

1. *a* 2. *c* 3. *d* 4. *c* 5. *a* 6. *c* 7. *d* 8. *b* 9. *c* 10. *d*

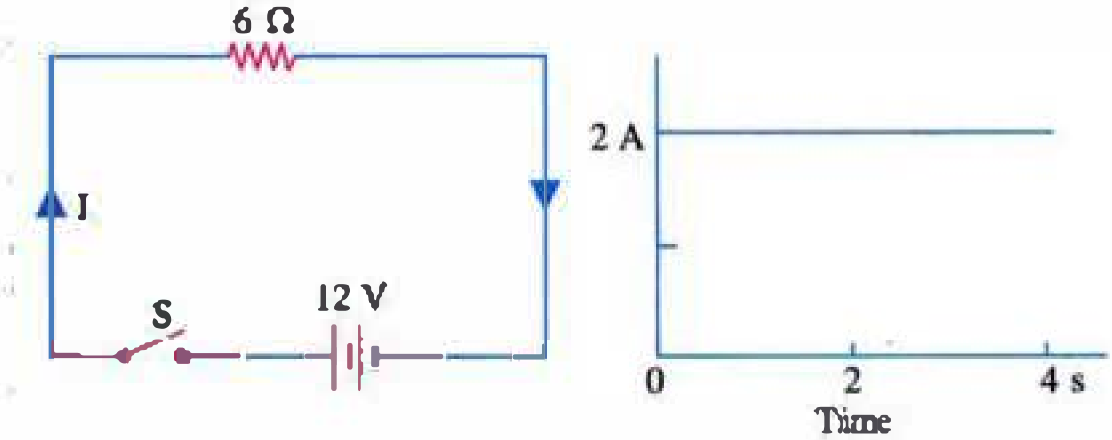
10 CHAPTER

Time Constant



10.1. Rise and Fall of Current in Pure Resistance

A pure resistor is defined as one which possesses ohmic resistance only and has neither inductance nor capacitance*. Such a resistor of $R = 6$ ohm is shown connected across a 12 V battery via a switch S in Fig. 10.1 (*a*). When S is closed, a current of 2 A (as given by Ohm's law) is set up in the circuit *instantly i.e.*, current changes from 0 to 2 A in no time as shown in Fig. 10.1 (*b*). Similarly, it is found that if S is opened, current drops to zero *instantly*. It is obvious from the above that a pure resistor offers only opposition to the flow of current but *no reaction to its change*. The reason for this is that (unlike an inductor) R has no concentrated



(*a*) (*b*)

Fig. 10.1

* Actually, it is impossible to get such an ideal resistor.

magnetic field to oppose any changes in current and also (unlike a capacitor), it does not store any *charge* which opposes any change in *voltage*.

10.2. Time Constant of an R-L Circuit

Consider the circuit of Fig. 10.2 where L is in series with R (which may be either the coil resistance, external resistance or both). When switch S is closed, current starts increasing exponentially from 0 to its final steady value of 1 A as given by Ohm's Law [Fig. 10.2 (*b*)]. However, this Ohm's Law value of the current is not achieved *instantly* but after lapse of some time (theoretically, infinite time) determined by the values of R and L. The reason is that during the exponential build-up of the current from 0 to 1 A, every change of current is opposed by the induced emf in the coil. This transient response of the circuit lasts till steady-state current of 1A is reached after some time.

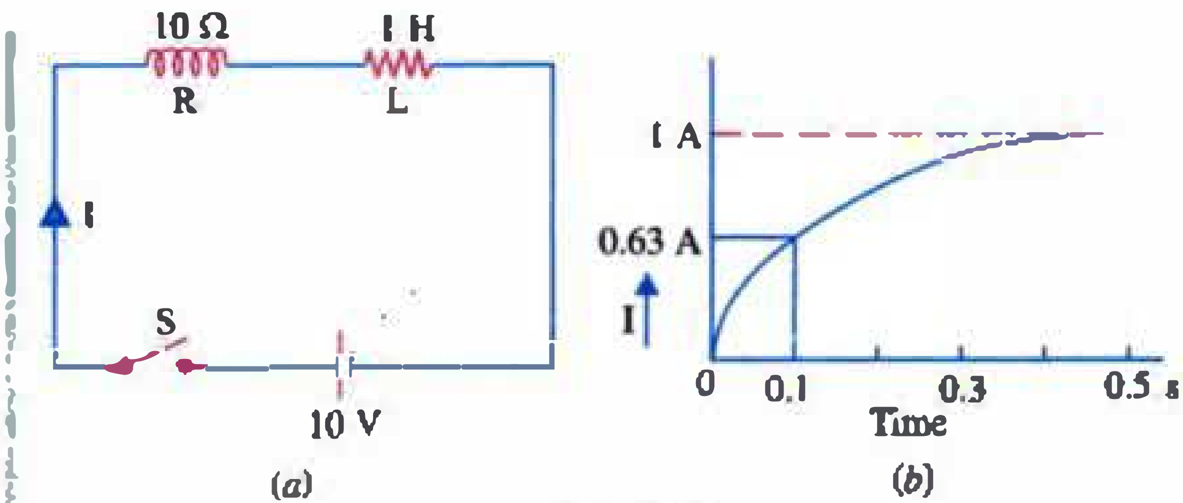


Fig. 10.2

Similarly, when S is opened, current does not drop to zero instantly but takes certain definite amount of time. This, again, is due to the fact that every change in current is opposed by the induced or counter-emf, thereby delaying its decay to ultimate value of zero.

This delay in both rise and decay of current in an inductive circuit is dependent on its time constant (λ) which is given by the ratio L/R.

Time constant, $$\lambda = \frac{L}{R} \text{ second}$$

Here, L is in henrys and R in ohms. With reference to Fig. 10.2 (*b*), it is seen that

$$\lambda = 1/10 = 0.1 \text{ second}$$

Time period (λ) may be defined as the time taken by the current to rise to 63.2% (or approximately, 63%) of its final (or maximum or steady) value.

The maximum (or Ohm's Law) value of the circuit current is 1 A. Hence, when S is closed, current will rise to a value of 0.63 A in 0.1 second.

Time constant of an R-L circuit may also be defined as the time during which current falls to 37% or 0.37% or 0.37 of its maximum value while decaying.

In the present case, it means that when S in Fig. 10.2 (*a*) is opened, current will fall from its initial value of 1 A to 0.37 A in 0.1 second. These facts have been shown in Fig. 10.3. However, it is generally accepted that the circuit current, while rising, achieves its final maximum value after a period equal to FIVE time constants *i.e.*, = 5λ seconds. Similarly, current practically decays to zero after a time interval equal to five time-constants of the circuit.

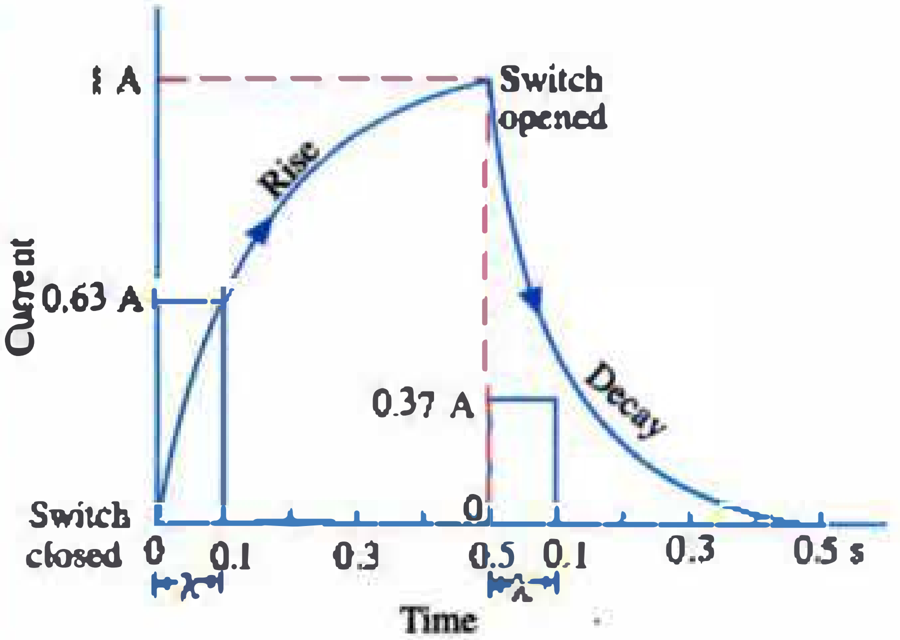


Fig. 10.3

It may be noted that λ becomes longer with larger values of L but shorter with larger values of R.

10.3. Circuit Conditions

In Fig. 10.4, the R-L combination becomes connected to battery of V volts when switch S is in position 1 and is short-circuited when S is in position 2.

When S is in position 1, following circuit conditions exist :

1. At the initial instant of switching on, circuit current is zero *i.e.*, $i = 0$. Hence, $v_R = 0$.

2. Initially, the rate of increase of current is maximum *i.e.*, di/dt is maximum ($= V/L$ amperes second) when $i = 0$. Hence, v_L has maximum value almost equal to V.

3. Thereafter, current rises in the circuit at progressively diminishing rate of increase. Hence, v_R increases but v_L correspondingly decreases because at all times

$$V = v_R + v_L$$

4. When after sometime ($\cong 5\ \lambda$), current reaches its maximum steady value, $v_L = 0$ and hence v_R becomes equal to V.

5. Under the steady or equilibrium conditions, the circuit appears as only a resistor. The effect of inductance has disappeared.

6. However, maximum magnetic flux exists in L and so maximum energy ($=1/2\ LI^2$) is stored in the inductor.

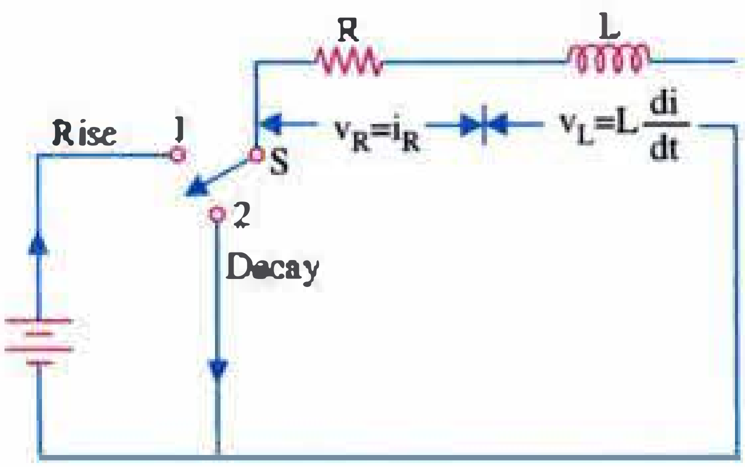


Fig. 10.4

Now, when S is shifted to position 2, the circuit is short-circuited and following conditions exist :

1. Initial rate of current decay is most rapid ($= V/L$ ampere/second). Hence, maximum voltage of opposite polarity is induced in L which would try to prolong the current decay.

2. As current decays at a progressively diminishing rate, v_R also decays to zero.

3. Voltage v_L will also decay towards zero though the rate of current decay would become progressively less.

The mathematical expression for current rise through such an inductive circuit is

$$i = I_m\,(1 - e^{-t/\lambda})$$

Similar expression for current decay is

$$i = I_m\, e^{-t/\lambda}$$

Example 10.1. *A coil having $R = 120\ \Omega$ and $L = 24$ H is connected across a 12 V battery. Find*

(*i*) *time constant of the circuit* (*ii*) *current after 0.2 second*

(*iii*) *current after 1 second* (*iv*) *current after 0.4 second*

Solution. (*i*) $\lambda = \dfrac{L}{R} = \dfrac{24}{120}$ = **0.2 second**

(*ii*) Now, the given time of 0.2 second represents the time constant of the circuit. Hence, circuit current would be 0.63 I_{max}.

Now, I_{max} = 12/120 = 0.1 A = 100 mA

$\therefore$ Current after 0.2 s = 0.63 × 100 = **63 mA**

(*iii*) Now, the given time of 1 s = 5 λ. Hence, during this time, current would rise to its maximum value of **100 mA.**

(*iv*) The given time of 0.4 s is twice the time constant of the circuit. In the first time constant *i.e.*, first 0.2 s, current would become 63 mA. The balance of current left would be = (100 – 63) =

37 mA. In the next 0.2 s, the current will increase by 63% of 37 mA *i.e.*, by 0.63 × 37 = 23.3 mA. Hence, current after 0.4 second or after 2 time constants would be

$$= 63 + 23.3 = 86.3 \text{ mA}$$

10.4. Inductive Kick

When a current-carrying R-L circuit is opened, the time constant L/R for current decay becomes very *short because of the extremely high resistance of the open circuit*. Consequently rate of fall of current is much faster than its rate of rise when switch is closed. As a result, very high voltage (much greater than the applied voltage) is induced in the coil on opening the circuit. However, duration of this high voltage peak is proportionately smaller because there is no gain in the energy stored in the magnetic field of the coil.

The above fact can be demonstrated with the help of a neon glow bulb N shown connected across the coil in Fig. 10.5. The bulb presents a very high resistance until a firing voltage of about 90 is applied to its terminals after which it starts glowing. Obviously, the 10 V source by itself is not capable of lighting it. When switch S is closed, current rises to its maximum steady value of 10/100 = 0.1 A in 5 time constants.

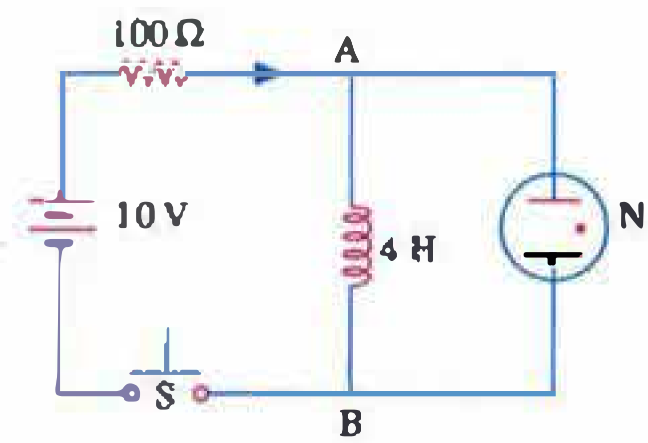


Fig. 10.5

Time constant = 4/100 = 0.04 s. Hence, current achieves Ohm's Law value in 5 × 0.04 = 0.2 second. At that time, v_R = 10 V, v_L = 0 and I_m = 0.1 A.

Now, when S is opened, battery is cut off but the self induced emf in the coil tends to maintain the circuit current of 0.1 A. However, due to high resistance of the neon bulb (about 50 K), time constant becomes very small and, consequently, rate of fall of current becomes exceedingly rapid.

Now, $$\lambda = \frac{L}{R} = \frac{4}{50 \times 10^3} = 8 \times 10^{-5} \text{ second}$$

During this time, current will fall by 63% of its initial maximum value of 0.1 A *i.e.*, it will decrease by 0.1 × 0.63 = 0.063 A. Hence, di = 0.063 A and dt = 8 × 10^{-5} second.

$$\therefore \quad e_L = L\frac{di}{dt} = 4 \times \frac{0.063}{8 \times 10^{-5}} = 3150 \text{ V}$$

This voltage, is high enough to flash the neon bulb.

In general, whenever an inductive circuit is interrupted or opened abruptly, the high induced voltage causes

1. arcing and burning of switch contacts,
2. large beat dissipation which is likely to break down coil insulation,
3. possible danger to the persons handling the equipment.

Hence, sufficient care must be taken while opening an inductive circuit because of the 'inductive kick' *i.e.*, high induced voltage. However, this inductive kick has been usefully employed in the ignition system of an automobile. In this system, a battery circuit in series with a highly-inductive spark coil is opened by the breaker points of the distributor to produce high voltage (15 to 20 kV) to fire the spark plugs. Another application of this 'inductive kick' is the production of high voltage of 10 to 25 kV for the anode of the picture tube in a TV receiver.

10.5. Time Constant of an RC Circuit

In this case, the time constant indicates the rate of charge or discharge of the capacitor. It is given by

$$\lambda = RC \text{ seconds}$$

where R is in ohms and C in farads. If R is in MΩ and C in μF, then, again, RC is in seconds.

It is seen from above that time constant depends both on R and C. More C means that the capacitor can store more charge and hence takes longer time to get this charge. Similarly, more resistance means reduced rate of charging thus taking longer to charge the capacitor.

It may also be noted that RC merely specifies the *rate* of charge. The actual voltage across the capacitor depends both on the applied voltage and the RC time.

In this circuit also, time constant may be defined in the following two ways :

1. It is the time during which the charging current falls to 37% of initial maximum value [Fig. 10.7 (*a*)].

or

2. It is the time during which capacitor voltage rises to 63% of its final steady value [Fig. 10.7 (*b*)].

10.6. Charging and Discharging of a Capacitor

In Fig. 10.6, the R-C combination becomes connected to the battery of V volts when switch S is in position 1 but is short-circuited when S is shifted to position 2.

When S is in position 1, following circuit conditions exist :

1. At the instant of switching on $V_C = 0$ but charging current is maximum given by $I_m = V/R$ as shown in Fig. 10.7 though its rate of decrease is also maximum.

2. Hence, at the start, v_R has maximum value equal to $I_m R = 1$ V. At any other time after switching on

$$V = v_R + v_C = i_R + v_C = i_C r + v_C$$

$\because\ i = i_C$

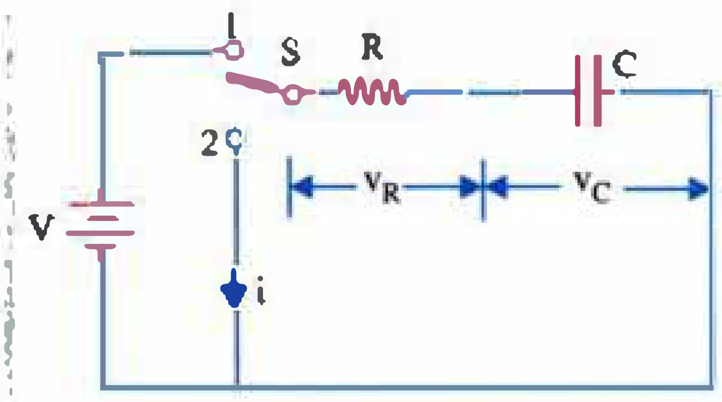


Fig. 10.6

3. As charge starts collecting on C, v_C start decreasing at a progressively diminishing rate as shown in Fig. 10.7.

4. After about five time constants *i.e.*, after 5 RC seconds, charging current becomes zero and hence $v_R = iR$ becomes zero. But v_C achieves maximum value equal to V.

5. Under these steady conditions, *the circuit appears as only a capacitor.*

6. Since capacitor is fully charged to a potential difference of V volts, it has maximum energy stored in it

$$= \tfrac{1}{2} CV^2$$

7. The exponential build-up of voltage across C is given by the equation

$$v_C = V(1 - e^{-t/\lambda})$$

Similarly, the gradual tapering of charging current is given by the relation

$$i = I_m e^{-t/\lambda}$$

Now, when S is shifted to position 2, battery is cut out of the circuit but capacitor is short-circuited through R and, hence, starts discharging.

1. Initially, the discharging current is maximum $= -v/R$ because full capacitor voltage $v_C = V$ is applied across R. Moreover, its rate of discharge is maximum initially but keeps decreasing thereafter. The negative sign of current indicates that it is flowing in a direction opposite to that of the charging current.

2. Hence, $v_R = -I_m R$ but gradually tends towards zero as does v_C.

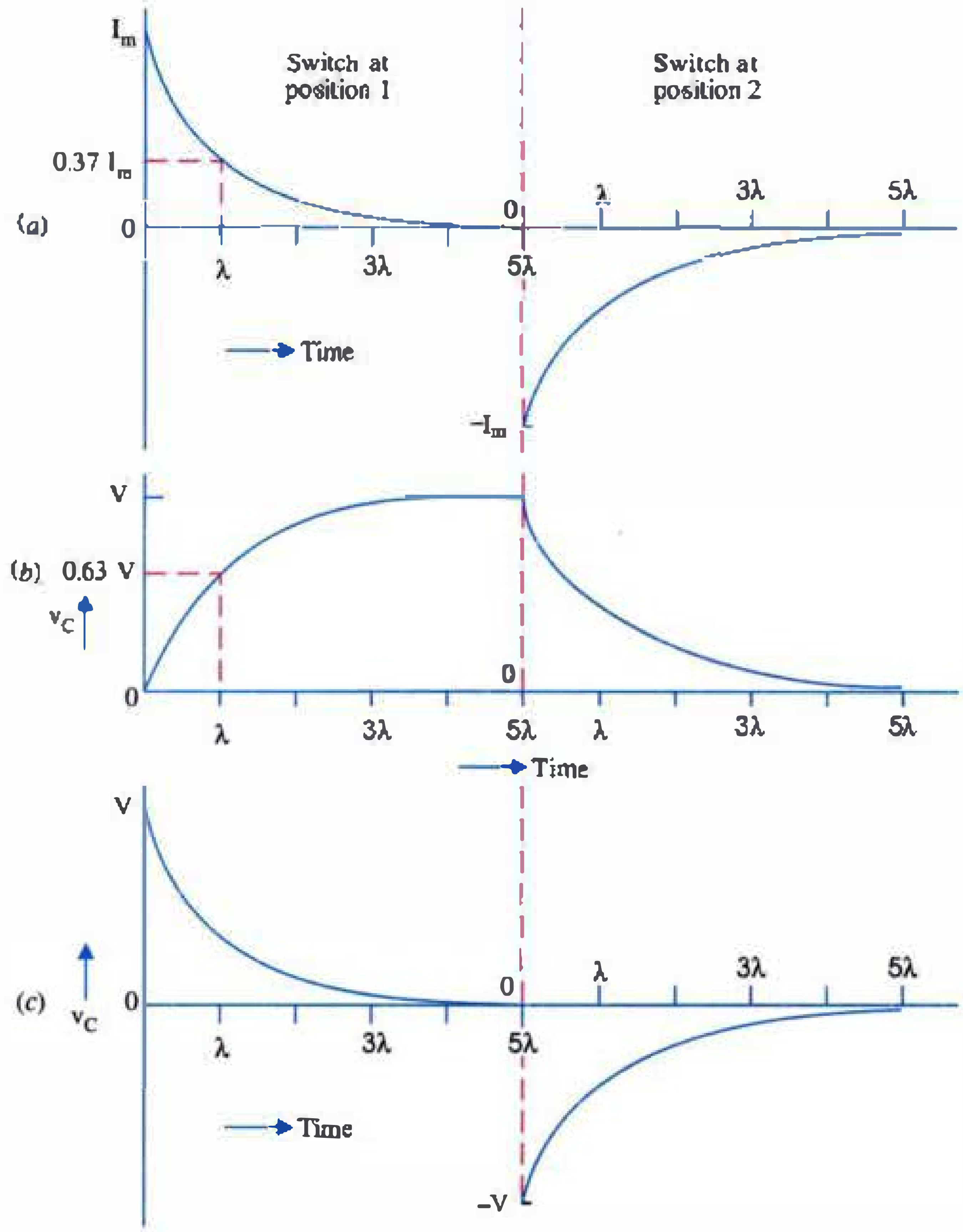


Fig. 10.7

3. After lapse of time equal to about five time-constants, v_C becomes zero and so does the discharge current. The entire circuit becomes passive by that time.

The progressive decrease of capacitor voltage is given by the equation

$$v_C = V - e^{-t/\lambda}$$

Similarly, the exponential decrease of discharge current is given by the relation

$$i = -I_m\, e^{-t/\lambda}$$

Example 10.2. *A series combination having $R = 2$ MΩ and $C = 0.02$ μF is connected across a dc voltage source of 100 V. Determine*

(*i*) *time constant of the circuit*

(*ii*) *capacitor voltage after 0.02 s, 0.04 s, 0.1 s and 2 hours.*

(*iii*) *charging current after 0.02 s, 0.04 s and 0.1 s.*

Solution. (*i*) $\lambda = RC = 2 \times 0.01 = $ **0.02 s**

(*ii*) (*a*) **t = 0.02 second**

Since this time happens to be equal to the time constant of the circuit,

$\therefore \quad v_C = 0.63\ V = 0.63 \times 100 =$ **63 V** (*b*) $t = 0.04$ **second**

This time equals two time constants. In the first time constant, $v_C = 63$ V. In the second time constant, v_C increases by $0.63 \times 37 = 23.3$ V. Hence, after 0.04 s

$$v_C = 63 + 23.3 = \mathbf{86.3\ V}$$

(*c*) $t = 0.1$ **second**

This time equals 5 time constants by which time v_C becomes practically equal to the applied voltage.

$$\therefore \quad v_C = \mathbf{100\ V}$$

(*d*) Provided circuit remains connected to the voltage source, v_C would remain constant at 100V for any length of time after 5λ.

(*iii*) (*a*) $t = 0.02$ s; $i_C = 0.37$ of I_m

Now, $I_m = 100/2\ M\Omega = 50\ \mu A$

$\therefore \quad i_C = 0.37 \times 50 = \mathbf{18.5\ \mu A}$

(*b*) $t = 0.04$ **s**

In the first time constant of 0.02 s, the charging current becomes (as found above) 18.5 μA. In the second time constant, current further decreases by 63% of the balance of the current *i.e.*, by $0.63 \times 18.5 = 11.6\ \mu A$

$\therefore \quad i_C = 18.5 - 11.6 = \mathbf{6.9\ \mu A}$

(*c*) $t = 0.1$ **s**

After this time, i_C is almost zero since 0.1s represents five time constants.

10.7. Decreasing Time Constant

The time constant of a given capacitor circuit can be increased by increasing R and can be decreased by decreasing R. Suppose we first charge a capacitor slowly with a small charging current through a high resistance and then discharge it through a low resistance. Since resistance during discharge would be small, we will get a momentary surge or pulse of discharge current.

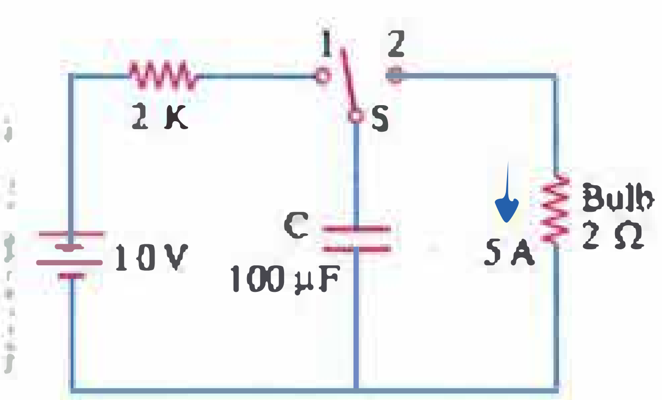


Fig. 10.8

The above method is employed in the operation of battery capacitor unit used for firing flash bulbs for photo cameras. Let us suppose that a flash bulb needs 5 A current to ignite. Such a heavy current would be too much of a load for a small 10 V battery (Fig. 10.8) whose normal current rating may be as low as 25 mA. By shifting switch S to position 1, the capacitor C is first charged from the battery through 2 K resistor. The charging time constant is $= RC = 2 \times 10^3 \times 100 \times 10^{-6} = 0.2$ second. The peak charging current = 10/2 K = 5 mA which can be easily supplied by the battery. Hence, after a time lapse of $5 \times 0.2 = 1$ s, the capacitor is charged to 10 V. Next, S is shifted to position 2 for discharging the capacitor through the flash bulb. The peak discharge current = 10/2 = 5 A which is enough to fire the flash bulb.

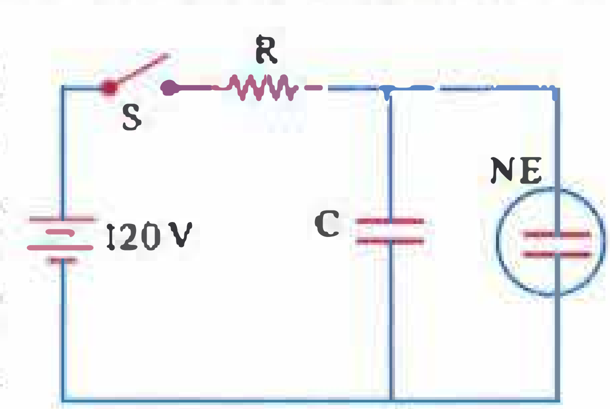


Fig. 10.9

10.8. Flasher

A practical demonstration of time constant of an *R-C* circuit can be given with the help of the circuit shown in Fig. 10.9. The neon glow lamp has a high resistance when not glowing. If a voltage of 90 V is applied, it will 'fire' *i.e.*, glow and also offer very low resistance while burning.

When switch S is closed, C starts to charge. When voltage across C reaches 90 V, neon lamp fires and starts to glow. Because of its very low resistance while glowing, C starts getting rapidly discharged through it. But soon after, the bulb goes out due to decrease in v_C and C starts to charge again. When v_C again reaches 90 V, bulb starts glowing once again but is soon extinguished when C discharges through it. In this way, neon bulb will glow each time the voltage across it reached 90 V and go out soon after due to decrease in voltage across it.

Obviously, it acts as a flasher or blinker although technically, it is called a 'relaxation oscillator'. By changing the circuit time constant, flashing rate may be controlled.

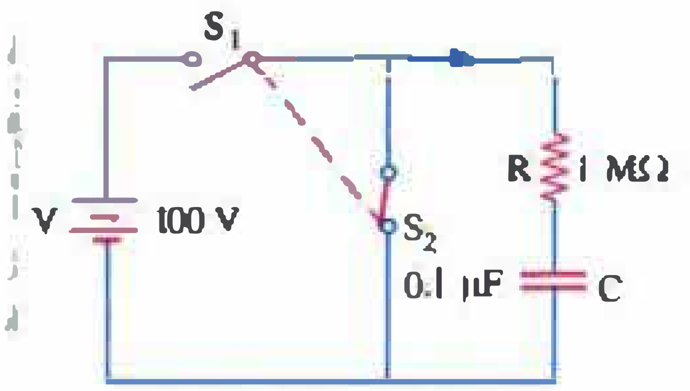


Fig. 10.10

10.9. Pulse Response of an RC Circuit

It is very instuctive to investigate the response of an RC circuit when a square voltage pulse (of time period = 2 × circuit time constant) is applied across it. Fig. 10.10 shows a circuit in which S_1 is closed and opened at regular intervals of 0.1 second which equals the time constant of the RC circuit. When S_1 is closed for 0.1 s, 100 V is applied across the circuit. When S_1 is opened, then no voltage is applied. This process of closing and opening S_1 is equivalent to applying a square voltage pulse of amplitude 100 V, time period = 0.2 s and frequency of 1/0.2 = 5 Hz as shown in Fig. 10.11 (a). Let us now examine the voltage and current waveshapes in the RC circuit of Fig. 10.11. Moreover, it should be noted that when S_1 closes, S_2 gets opened up and *vice-versa*. With S_2 closed, C gets discharged through R.

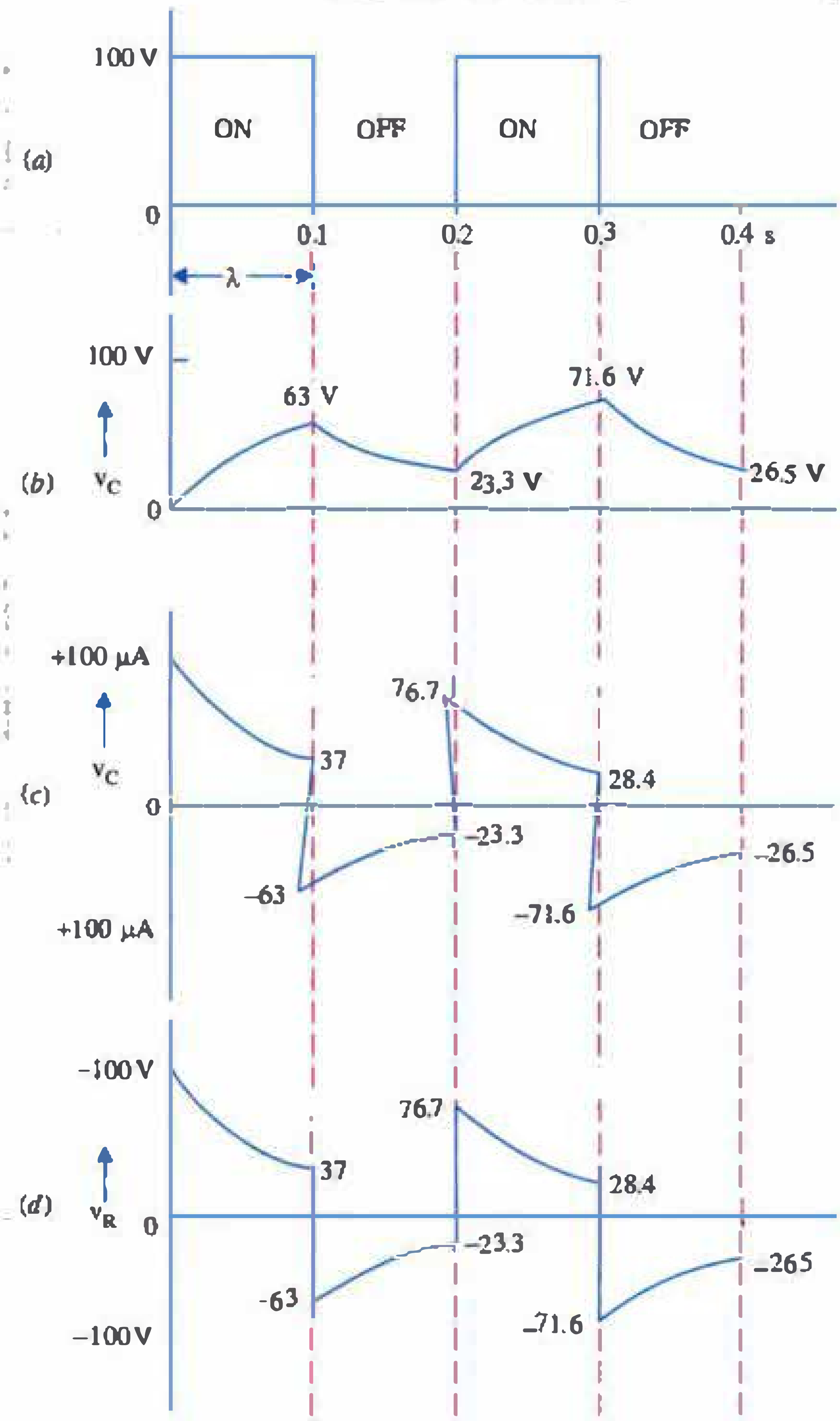


Fig. 10.11

(a) Capacitor Voltage (v_C)

As seen from Fig. 10.11 (b) during one time constant of 0.1s, the capacitor charges to just about 63 V. In the next time constant, applied voltage is zero, hence C discharges to 37% of 63 V = 0.37 × 63 = 23.3 V.

The next charge cycle begins when C is already charge to 23.3V. Consequently, the net charging voltage = 100 − 23.3 = 76.7 V. Obviously, during the next pulse, the capacitor, voltage increases by 63% of 76.7 V $= 0.63 \times 76.7 = 48.3$ V. Hence, during second pulse, v_C becomes $= 23.3 + 48.3 = 71.6$ V. During the next 0.1 s, v_C drops to 37% of 71.6 V = 26.5 V and so on.

(b) Charge and Discharge Current (i_C)

As shown in Fig. 10.11 (c), capacitor charging current has its peak value at the start of charging when the full pulse voltage of 100 V is applied. Since just at the start $v_C = 0$ but $v_R = V$, maximum value of $i_C = V/R$. Similarly, at the start of discharge, i_C is again maximum because capacitor is fully charged to V volts. But this time, i_C flows in the opposite direction and its initial peak value is given by $-V/R$ because $v_C = V$. As seen, i_C has an ac waveform around the zero axis.

(c) Voltage Across R (v_R)

Since at every instant, $v_R = iR = i_C R$, its waveshape is similar to that of the circuit current *i.e.*, i_C. The drop v_R has an ac waveshape as shown in Fig. 10.11 (d). Since waveshapes of i_C and v_R are similar, it is a general practice to connect an oscilloscope across R for studying i_C waveshape.

10.10. Effect of Long and Short Time Constants

It is easier to obtain different time constants in an RC circuit (by adjusting either R or C) than in an R-L circuit where it is difficult to change coil resistance and also impossible to eliminate capacitive effects between its different turns. Hence, RC circuits are commonly used for obtaining useful voltage and current waveshapes with required time constants.

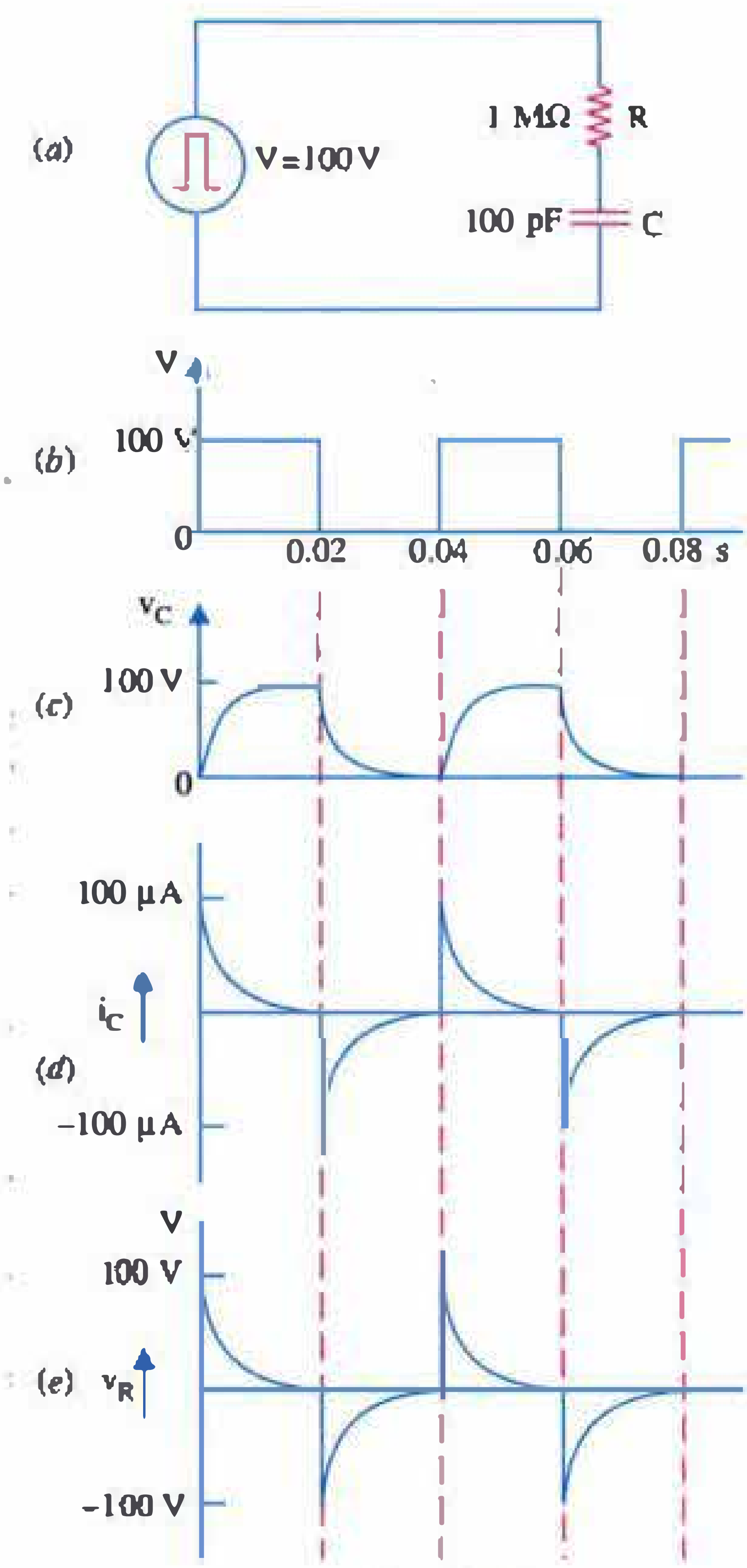


Fig. 10.12

(a) Long Time Constant

Whether an RC time constant is long or short depends on its relationship with the pulse width of the applied voltage. Any time constant which is at least five times longer than the pulse width is considered a long time constant. Suppose the pulse width of a given square voltage wave is 0.5 μs and the time constant of the RC circuit is 0.1 ms. Obviously, this time constant would be considered long because it is = 0.1 ms/0.5 μs = 200 times the pulse width. This time constant is too long for capacitor voltage v_C to rise appreciably before the applied voltage pulse drops to zero, thereby forcing C to discharge. Consequently, C takes on very little charge. Similarly, on discharges also, C discharges very little before the next pulse of the applied voltage comes on to make C charge again. Long time constants are usually employed for integrating circuits.

(b) Short Time Constant

A short RC time constant may be defined as any time constant which is no more than one-fifth the pulse width of the applied voltage. For example, a $\lambda = 0.1$ ms is considered a short time constant as compared to a pulse width of 0.02 s. As seen, λ is $0.1 \times 10^{-3}/0.02 = 1/200$ of the pulse duration. It means that voltage would remain applied across V for 200 time constants thereby allowing it to become fully charged. Similarly, when applied voltage drops to zero, C discharges completely and remains in this condition till the next voltage pulse comes on after a comparatively long time. On the next cycle of the applied voltage pulse, C charges and discharges completely once again and so on.

Such short time constants are generally used for differentiating circuits for providing sharp pulse of v_R.

10.11. Square Voltage Wave Applied to Short λ RC Circuit

As shown in Fig. 10.12 (*b*), a square voltage wave of amplitude 100 V, time-period 0.04 s and frequency 25 Hz is applied across an RC circuit of $\lambda = 0.1$ ms. Obviously, time constant λ is 1/200 of the pulse width (of 0.02 s = 20 ms). Here, time axis is calibrated in seconds and not in time constants. Let us, now, examine the waveshapes of v_C, i_C and v_R one by one.

(*a*) Waveshape of v_C

Since λ is very short as compared to pulse width, C gets charged fully and, for the same reason, gets discharged also completely during each half-cycle of the applied voltage. Hence, waveshape of v_C is essentially the same as that of the applied voltage as shown in Fig. 10.12 (*c*). In fact, it very closely resembles V except for slightly rounded corners of its curve.

(*b*) Waveshape of i_C

This waveshape shows peaks both for the charge and discharge which coincide with the leading and trailing edges of the applied voltage pulse as depicted in Fig. 10.12 (*d*). Each peak value = $100/R = 100/1\ \text{M}\Omega = 100\ \mu\text{A}$. In fact, the current pulses are much sharper than shown in the figure because they are not to scale horizontally.

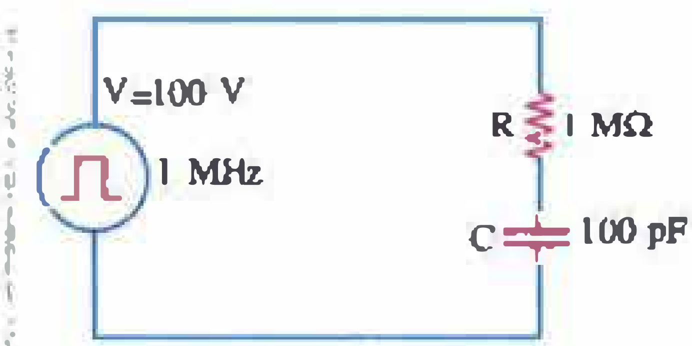


Fig. 10.13

(*c*) Waveshape of v_R

It follows the waveshape of i_C because $v_R = iR = i_C R$. Each 100 μA current pulse produces a voltage pulse of 100 V. In fact, before C begins to charge, peak value of v_R equals the applied voltage of 100 V. Afterwards, as v_C increases, v_R decreases at all times

$$V = v_R + v_C$$

At the instant of discharge, full capacitor voltage of 100 V is applied across R so that v_R peak on discharge equals −100 V. Then in five time constants, v_R drops to zero as shown in Fig. 10.12 (*e*). Such v_R pulses that match the edges of the applied square-wave voltage are used as timing pulses. We may use either the positive or negative pulses.

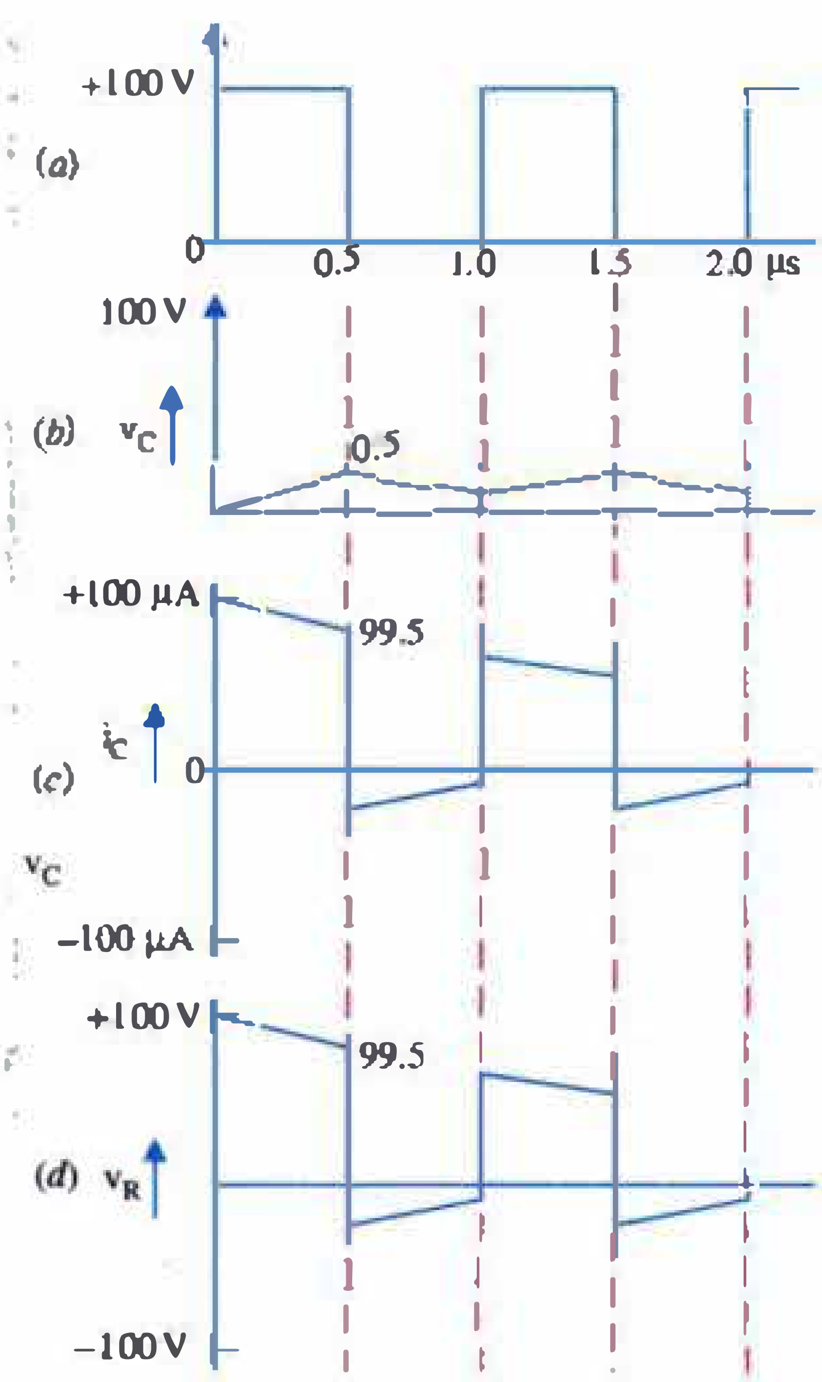


Fig. 10.14

10.12. Square Voltage Wave Applied to Long λ RC Circuit

As shown in Fig. 10.13, the RC time constant is the same as before *i.e.*, 0.1 ms but now it becomes 200 times longer than the pulse width of 0.5 μs of the applied square voltage wave which has a frequency of 1 MHz. The time axis has been calibrated in microseconds (μs) and not in time constants. Let us, now, examine the waveshapes of v_C, i_C and v_R one by one.

(*a*) Waveshape of v_C

As explained earlier in Art. 10.10, in view of the extremely short duration of the applied voltage pulses, C has hardly any time to get charged. Since pulse width is 1/200 of λ, v_C would hardly achieve a value of 100/200 = 0.5 V before it is compelled to discharge as shown in Fig. 10.14 (*b*). Similarly, C is hardly given any time to discharge with the result that v_C drops by a very little amount.

(*b*) Waveshape of i_C

The initial charging current is maximum = V/R = 100/1 M = 100 μA. Hence, waveshape for i_C stays close to 100 μA throughout the duration of the pulse. It is so because C does not have much charge (*i.e.*, v_C is negligible), thereby allowing applied voltage V to keep the charging current near about 100 μA. The decrease is 100/200 = 0.5 μA. Hence, during the pulse period, the charging current falls from 100 μA to 99.5 μA as shown in Fig. 10.14 (*c*).

(*c*) Waveshape of v_R

As shown in Fig. 10.14 (*d*), it follows the waveshape for i_C. In fact, waveshapes of both i_C and v_R are essentially the same as that of the applied square-wave pulse voltage. Eventually, v_C will climb to an average value of 50 V, i_C will vary ± 50 μA above and below zero whereas v_R will vary (like V) ± 50 V above and below zero.

CONVENTIONAL PROBLEMS

1. An inductive coil has a resistance of 100 Ω and an inductance of 2 H. It is connected across a dc voltage of 10 V. Determine
   (*i*) time constant of the coil (*ii*) current after one time constant
   (*iii*) current after two time constants. **[(*i*) 0.2 s (*ii*) 63 mA (*iii*) 86.3 mA]**
2. A dc voltage source of 100 V is in series with a series combination of 2 MΩ and 2 μF capacitor. Determine
   (*a*) time required by v_C to become 63 V (*b*) value of v_C after 20 seconds
   [(*a*) 4 s (*b*) 100 V]
3. A 100 V d.c. source is applied to a 1 MΩ resistor connected in series with a 4 μF capacitor which is already charged to 63 V. What will be the value of v_C after 4 s ? **[86.3 V]**
4. A 0.05 μF capacitor charges through a 2 MΩ resistor but is discharged through a 20 kΩ resistor. Determine
   (*a*) charging time constant (*b*) discharging time constant
   (*c*) rate of voltage rise (*d*) rate of voltage fall.
   [(*a*) 0.1 s (*b*) 0.001 s (*c*) 1000 V/s (*d*) 100 kV/s]

SELF EXAMINATION QUESTIONS

A. Fill in the blanks by the most appropriate word(s) or numerical value (s).

1. A pure resistor does not ....any change in the current flowing through it.
2. In an *R-L* circuit, time constant is given by the ratio of .... and ....
3. In one time constant, current through a series *R-L* circuit rises to nearly .... per cent of its final steady value.
4. In one time constant, current through an *R-L* circuit decreases by about ....per cent.
5. In a series *R-L* circuit
   (*a*) initial rate of rise of current is ....
   (*b*) the initial current is ....
   (*c*) rate of rise of current keeps ....
   (*d*) sum of resistive and inductive voltage drops equals the .... voltage.
   (*e*) current reaches its maximum value in about .... time constants.
   (*f*) current decays at a progressively .... rate.
6. In a long time constant *R-C* circuit, capacitor hardly gets enough time either to .... or .... itself.

B. Answer True or False

1. A pure resistor offers only resistance to the flow

of current through it but no reaction to its change.

2. The delay in the establishment of full current in an R-L circuit is primarily due to its inductance.
3. Resistance of a coil plays no part in determining the rate of rise or decay of current through it.
4. The time constant of a series R-L circuit can be doubled by doubling the value of R.
5. In every time constant, current through a coil increases by 63% of the remaining current.
6. The rate of rise of current through a coil keeps decreasing though amount of current flowing through it keeps increasing.
7. In about five time constants, current through a coil is considered to have reached its final steady value.
8. In one time constant, the current through a series R-L circuit decays by about 37% of its initial ....value.
9. Under conditions of equilibrium, an R-C circuit appears as only a capacitor.
10. In a series R-C circuit, charging current decreases but voltage across the capacitor increases.
11. R-C circuits are often used to get useful voltage and current waveshapes of any desired time constant.
12. When a square wave voltage is applied to an R-C circuit having long time constant, it produces highly-peaked output wave shapes.

C. Multiple Choice Items

1. During one time constant, current through an R-L circuit
   (*a*) rises by 63% of its initial value
   (*b*) rises by 37% of its final steady value
   (*c*) decays to 63% of its initial value
   (*d*) rises to 63% of its final steady value
2. In an R-L circuit with $R = 100\ \Omega$ and $L = 0.2$ H and $V = 5$ volts, current will reach a steady value after about .... milliseconds.
   (*a*) 2 (*b*) 10
   (*c*) 20 (*d*) 5
3. The arcing across a switch which opens an R-L circuit is due to
   (*a*) very low resistance of the switch
   (*b*) high resistance of the circuit
   (*c*) high self-induced emf in the coil
   (*d*) long time constant of the circuit
4. The time constant of an R-C circuit is defined as the time during which capacitor charging current becomes .... per cent of its .... value.
   (*a*) 37, final (*b*) 63, final
   (*c*) 63, initial (*d*) 37, initial
5. During five time constants of an R-C circuit, the capacitor is usually considered to be .... per cent charged.
   (*a*) 37 (*b*) 100
   (*c*) 63 (*d*) 50
6. A square voltage wave is applied to an R-C circuit having a short time constant. The waveshape of the charging current
   (*a*) resembles the waveshape of the applied voltage
   (*b*) has rounded corners
   (*c*) has sharp peaks coinciding with leading edge of the applied voltage pulse
   (*d*) is triangular.

ANSWERS

A. Fill in the blanks

1. oppose 2. inductance, resistance 3. 63 4. 63 5. (*a*) maximum (*b*) zero (c) decreasing (*d*) applied (*e*) five (*f*) diminishing (or decreasing) 6. charge, discharge.

B. True or False

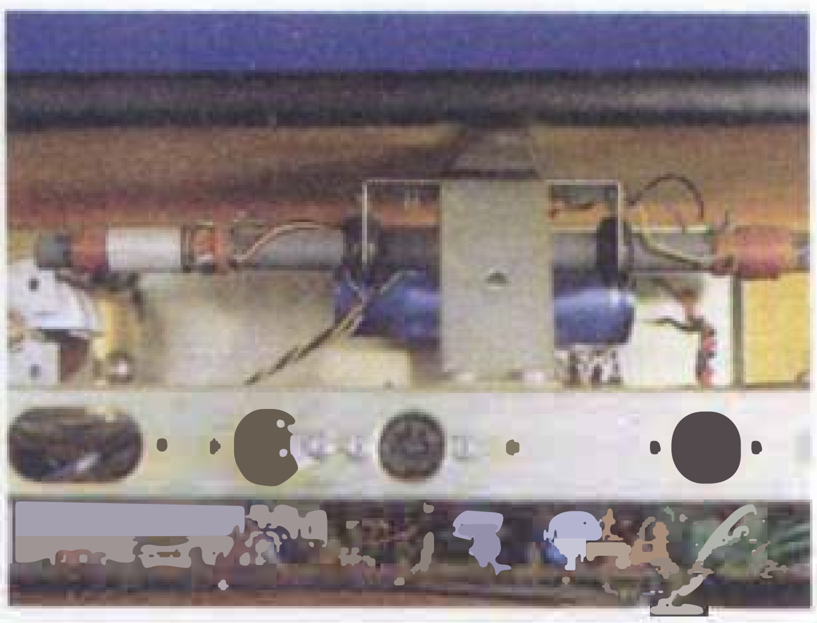
1. T 2. T 3. F 4. F 5. T 6. T 7. T 8. F 9. T 10. T 11. T 12. F

C. Multiple Choice Items

1. *d* 2. *b* 3. *c* 4. *d* 5. *b* 6. *c*

CHAPTER 11

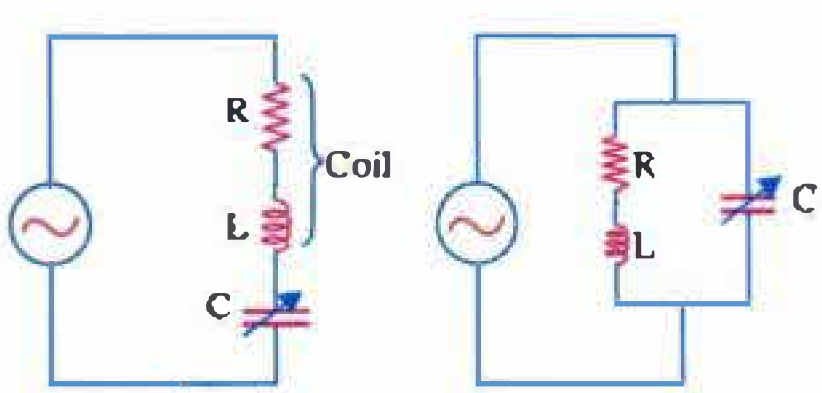
Tuning Circuits And Filters



11.1. What is a Tuning Circuit ?

It is a circuit whose parameters can be varied in order to tune it to any desired frequency *i.e.*, to make it resonant at any particular frequency.

The process of selecting the desired frequency is called *tuning*.



(*a*) (*b*)

Fig. 11.1

It could be either a series or a parallel *RLC* circuit as shown in Fig. 11.1. Such circuits are the basis of all transmitter, receiver and antenna operation. No radio communication is possible without them. For example, the desired programme in a radio or TV is obtained by tuning the receiver to a particular broadcasting station. In fact, we select the desired station by adjusting the tuning circuit of the receiver so as to bring it in resonance with the carrier frequency transmitted by that station.

11.2. Tuned Circuit

It is a circuit whose parameters have values that will make it resonant to a particular frequency.

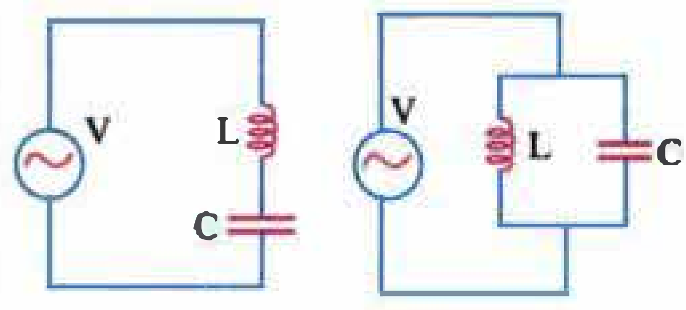
11.3. Operating Characteristics of a Tuning Circuit

A tuning circuit is required to perform the following three functions :

1. to select the desired signal out of the many available.
2. to reject all undesired signal.
3. to increase the voltage of the desired signal before passing it on to the next circuit.

The ability to perform the first function is called *sensitivity*, the second *selectivity* and the third *fidelity*.

11.4. Resonance



(*a*) (*b*)

Fig. 11.2

A circuit is said to be in electrical resonance when its inductive reactance equals its capacitive reactance. Consequently, net reactance offered by the circuit is zero. Consider the series and parallel LC circuits shown in Fig. 11.2. We will first consider the case of an ideal coil and an ideal capacitor. The coil is supposed to have only inductance but no resistance and hence no I^2R loss. Similarly, the capacitor has no leakage current *i.e.*, its dielectric is a perfect insulator.

The series circuit of Fig. 11.2 (*a*) is in resonance or it resonates at that frequency for which

$$X_L = X_C$$

or $$2\pi f L = \frac{1}{2\pi f C} \qquad \text{or} \qquad f_0 = \frac{1}{2\pi\sqrt{LC}}$$

The subscript 0 has been added to indicate that this frequency refers to the resonant condition. It is seen that f_0 depends on the values of both L and C.

When in resonance, the circuit offers zero impedance to the applied voltage. Hence, current under resonant condition is

$$I_0 = \frac{V}{X} = \frac{V}{(X_L - X_C)} = \frac{V}{0} = \infty\,!$$

Now, every *actual* coil (as opposed to an *ideal* one) does have some resistance. Hence, actually the current is never zero though theoretically it may be so.

The resonant frequency of the parallel circuit shown in Fig. 11.2 (*b*) is also the same. However, it is interesting to note that except for the initial current drawn by the circuit when it is first connected to the supply, the circuit draws no current thereafter. The current drawn initially keeps circulating between the two branches because current requirements of L and C are 180° out of phase with each other. Hence, under parallel resonant conditions, $I_0 = 0$.

$$\therefore \qquad Z = \frac{V}{I_0} = \frac{V}{0} = \infty\,!$$

It means that impedance offered by such a circuit when in resonance is infinity ! In other words, it acts like an open switch to an input signal of a particular frequency.

However, as all actual coils do have some resistance, current is not exactly zero so that impedance is not infinite but extremely high.

11.5. Actual Series Resonance

An actual coil always possesses some resistance as shown in Fig. 11.1 (*a*). At any frequency of the applied voltage, impedance offered by the circuit is

$$Z = R + j\,(X_L - X_C) = R + jX$$

or $$Z = \sqrt{R^2 + X^2}$$

At resonance,

$$X = 0 \text{ or } X_L - X_C = 0 \text{ or } X_L = X_C$$

$$\therefore \quad f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{0.159}{\sqrt{LC}} \text{ Hz}$$

It is seen that resonant frequency *does not depend on the coil resistance.*

Though main points regarding series resonance have already been discussed in Chapter 9, we will briefly touch upon the following item :

1. Q-Value

It is also called quality factor or figure of merit. It is defined as under :

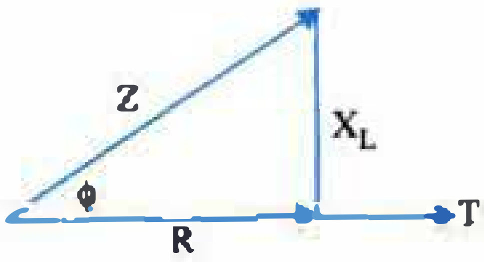


Fig. 11.3

(*a*) $$Q = \frac{X_L}{R} = \frac{\omega_0 L}{R}$$

The Q-factor of a coil can be increased by making its R as low as possible and L as high as practicable. An ideal coil whose $R = 0$ has a Q of infinity !

Moreover, Q of a given coil will become less at high frequencies because of increase in R due to skin effect.

(*b*) Also $$Q_0 = \frac{1}{\omega_0 CR} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega_0}{\Delta\omega}$$

$$= \frac{f_0}{f_2 - f_1} = \frac{f_0}{\Delta f}$$

When applied to a tuning circuit, it measures the selectivity or sharpness of the tuning circuit. Fig. 11.4 shows how sharpness of tuning varies with the Q-value. Values of Q_0 of the order of 200 are common in radio circuits.

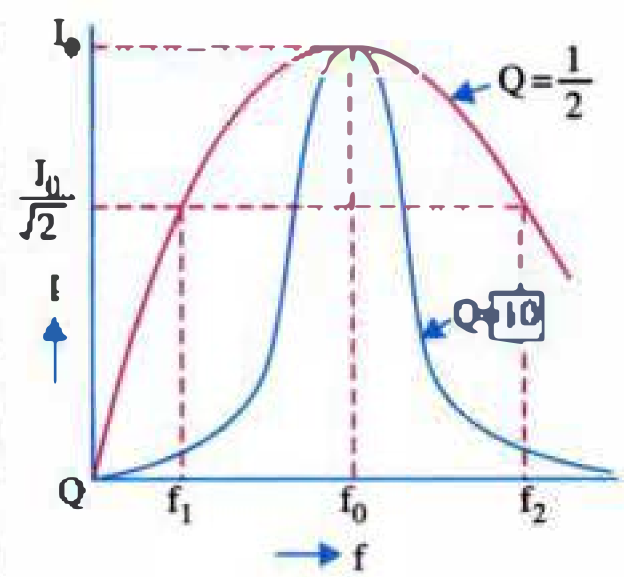


Fig. 11.4

2. Bandwidth

It has already been discussed in Art. 9.10. The bandwidth (BW) of a series resonant circuit is given by

$$BW = f_2 - f_1 = \Delta f = \frac{f_0}{Q_0} = \frac{R}{2\pi L}$$

Obviously, higher the value of Q_0, narrower the bandwidth and higher the *selectivity* of the circuit. As seen, for getting high selectivity, coil resistance should be low but inductance high. Also, bandwidth depends on the R/L ratio and not on the *individual values of R and L as such.*

It should also be noted that bandwidth *does not depend on C at all.* Value of C only affects f_0.

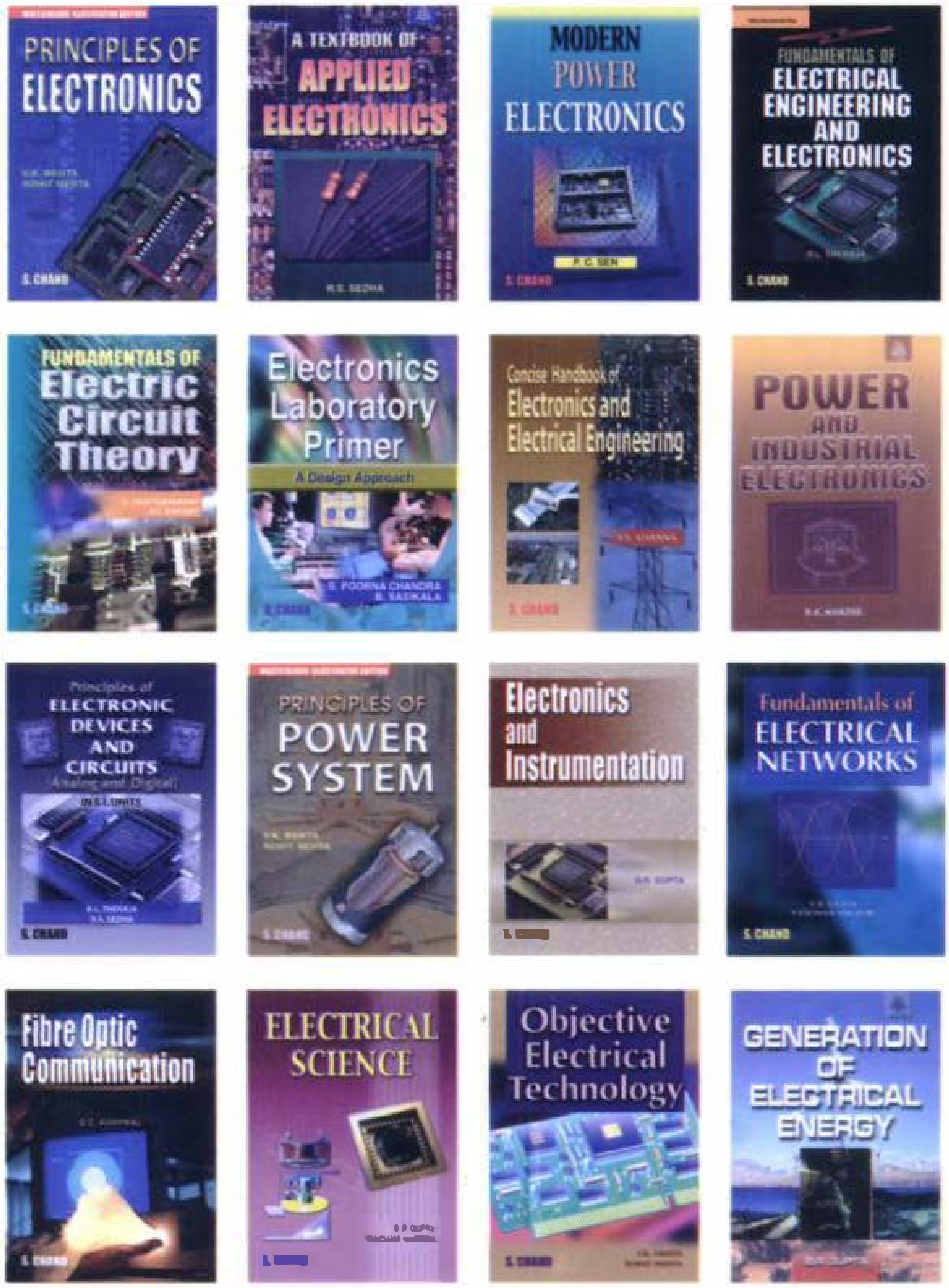
3. LC Product

It determines the value of f_0. Values of L and C may be changed but so long as their product remains constant, f_0 remains constant. If the LC product for a desired frequency is known, the capacitance or inductance required can be found.

11.6. Is it Series or Parallel Resonance ?

A tuned circuit commonly used in radio receivers is shown in Fig. 11.5. It, in fact, represents a transformer with tuned secondary which at first glance looks like a parallel resonant circuit. But,

OTHER IMPORTANT BOOKS



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