UNIT 1 INTRODUCTION TO ELECTRICITY

Structure

1.1 INTRODUCTION

Electricity is the most conventional form of energy and has multiple applications like lighting, communication, heating, transportation, air conditioning, etc. The flow of electricity can be compared with the flow of water in a pipe. Flowing water is a good analogy of electricity. When water flows through a pipe, or down stream, there is a water current. Similarly, electric current or simply current is the flow of electrons in an electric circuit. The flow of current depends upon amount of charge or the number of electrons flowing. If we have to measure how fast the water is flowing in a pipe, we may say it is so many gallons per minute. When we measure how much current is flowing through a wire, it is based on the number of electrons flowing past that cross-section of wire in one second. There is a unit of measure called the **Coulomb**, which enables us to measure the amount of charge in an object (e.g. an electron). Since there are billions of electrons flowing through the wire, we instead measure the charge with unit Coulomb, which is 6,240,000,000,000,000,000 (6.24 billion-billion) electrons, flowing through the wire to measure electric current.

Ampere is the basic unit of electric current. When one Coulomb of electrons passes through a wire in one second, we say that there is one Ampere of current. It is sometimes referred to as Amps. Hence, I = Charge/Time, $I = dq/dt$.

Water flows through a pipe because of water pressure. Water pressure forces the water to flow. Likewise, **Electromotive Force** (EMF) is the pressure that forces electrons to flow through a circuit. Electromotive force is also known as voltage. The basic unit of electromotive force is Volt. In the same fashion as water flows down in the stream, through a pipe, current can flow in a circuit. Water is limited by the amount of friction it encounters as it flows. Electricity is limited by the amount of resistance it meets as it passes through a circuit. Resistance limits the current that flows through a circuit for a particular applied voltage. Hence, resistance acts as a friction in flow of current. However, if we increase the water pressure in a pipe, more water would flow. Similarly, if we turn up the voltage, then more current would flow.

The material or the medium plays an important role. There are some materials in which electricity flows easily. These materials, thus, have very low or negligible resistance and are called **conductors**. Most metals are conductors. Three good electrical conductors are gold, silver and aluminum. **Insulators** are materials that do not let electricity flow through them and, thus, have very high or almost infinite resistance. Four good insulators are glass, air, plastic and porcelain.

In this unit, basics of electricity like charge, potential difference, resistance and Ohm's laws are discussed with the application and working of batteries.

Objectives

After studying this unit, you should be able to

- explain the laws of electricity,
- evaluate the combination of series and parallel resistors and capacitors including Kirchhoff's laws,
- describe different types of cells and batteries, and
- explain the distribution of electricity.

1.2 ELECTRICITY

Every engineer is directly or indirectly concerned with the applications of electricity. Thus, a civil engineer requires some basic knowledge of electric motors, which are being widely used in the modern construction machinery.

Applications of Electricity

In the modern world, dependence on electricity is unavoidable. The ever increasing importance of electricity is due to its numerous applications for domestic and industrial purposes. A few important applications of electricity are discussed below :

Heating

One of the important applications of electricity is its use for heating purposes in the domestic and industrial field. In all electric heating appliances, electrical energy is converted into heat by passing an electric current through a wire of high resistance.

Domestic Applications : Electric press, heater, coffee percolator, toaster, electric kettle etc.

Industrial Applications : Electric ovens, electric furnaces etc.

Lighting

The other important application of electricity is its use for lighting purposes. In all such devices, electrical energy is converted into light energy by utilizing the effects of electricity.

Domestic Applications : Electric bulbs, fluorescent tubes, discharge lamps (sodium lamp, mercury lamp) etc.

Industrial Applications : All domestic lighting devices and lamps for cinema projectors, etc.

Electric Motors

The main application of electricity is its use for running electric motors. In all electric motors, electrical energy is converted into mechanical energy.

Domestic Applications : Hair drier, mixer, refrigerators, ceiling and table fans, air cooler, washing machine, etc.

Industrial Applications : Lifts, cranes, tube-wells, concrete mixer, lathes, etc.

Electroplating

Electricity is used for the process of electroplating, i.e. coating a layer of superior metal over inferior metal.

Domestic Applications : Tin plating of utensils, etc.

Industrial Application : Nickel plating of vehicles, watch cases, etc.

Electronics

All electronic devices require electricity for running the devices.

Advantages of Electricity

We have explored electricity about numerous domestic and industrial applications. Electrical energy has virtually established its superiority over other forms of energy. There are a number of reasons for preferring electrical energy over other forms of energy.

Convenient Form

It is a very convenient form of energy. It can be easily converted into other forms of energy. For example, if we want to convert electrical energy into heat energy, then electric current is passed through a wire of high resistance.

Easy in Handling

Electricity can be very easily handled. Wherever it is required, it can be taken with the help of conductors (copper or aluminum wires) and, thus, can be used for various purposes.

Low Cost

Low cost is another factor which goes in favour of electricity for its wide use. Electrical energy can be easily and cheaply produced.

No Fumes or Poisonous Gases

The use of electrical energy is not associated with smoke, fumes or other poisonous gases. Therefore, it can be safely used for domestic and industrial purposes.

Cleanliness

It is a very clean form of energy as compared to other forms of energy. As already explained, electricity is free from smoke, fumes or poisonous gases, therefore, its use for domestic and industrial purposes is on the increase.

More Efficient

Electric appliances are very efficient and, therefore, they are fast replacing manual labour.

Easy Transportation

Electricity is perhaps the only form of energy which can be transported very easily and with very high efficiency over distances as long as few thousand kilometers.

SAQ 1

(a) Mention some important applications of electricity.

(b) Mention various advantages of electrical energy over other types of energy.

1.3 CURRENT

1.3.1 Free Electron Theory

As we are aware, the atom is most fundamental unit of matter. Generally, according to atomic structure, the atom consists of a nucleus and electrons. All electrons move around the nucleus in different orbits or shells. These orbits are energy levels. The electrons present in the outermost orbit are called valence electrons in modern physics, and the valence electrons that are able to move from one atom to another atom, in a random manner, are known as 'free electrons'. Free electrons, thus, work as charge carriers, and can carry charge from one point to another point, when an external field is applied.

According to energy band theory, the forbidden energy gap is absent between valance and conduction band in good conductors. Thus metals, which work as good conductors, contain large number of free electrons at normal temperature without supplying any additional energy.

Materials which are bad conductors possessing a higher energy gap between the valence and conduction bands are called insulators.

1.3.2 EMF and Current

In the study of an atomic structure, a neutral atom contains equal number of protons in the nucleus and electrons in the shells. Protons are positively charged particles and electrons contain negative charge. Normally, an atom loses an electron when it becomes positively charged or positive ion. Similarly, after gaining an additional electron the atom becomes negatively charged and is known as negative ion.

The ability of two oppositely charged bodies to produce a flow of electricity between them is the potential for the production of electric current. Thus, a positively charged body is said to be at positive potential and a “+” sign is used to identify this potential. Similarly, a negatively charged body is described at negative potential and a “–” sign is used to identify this potential. The arithmetic difference between the two is called “potential difference” between them. It is measured in volts (V) and a term “voltage” is applied for “potential difference”. The magnitude of potential difference between two points is equal to the work done in moving a unit positive charge from one point to another. In electrical circuits, potential difference is provided by some external means like a cell or a battery. A cell or battery provides a electrical potential that tends to cause current to flow. It is also known as Electromotive Force (EMF) and is measured in “volts”.

When a suitable conductivity path or good conductor is used, then a current will flow as a result of electric pressure. The current flows from positive potential to negative potential. But actually the direction of flow of electrons is towards positive potential from negative potential, and may be considered as flow of equivalent positive charge in the opposite direction as shown in Figure 1.1. Conventionally, the current, produced by flow of electrons, is supposed to be the flow of + ve charge and, thus, flows from positive potential to negative potential. SI unit of current is Ampere (A) and its symbol is *I*.

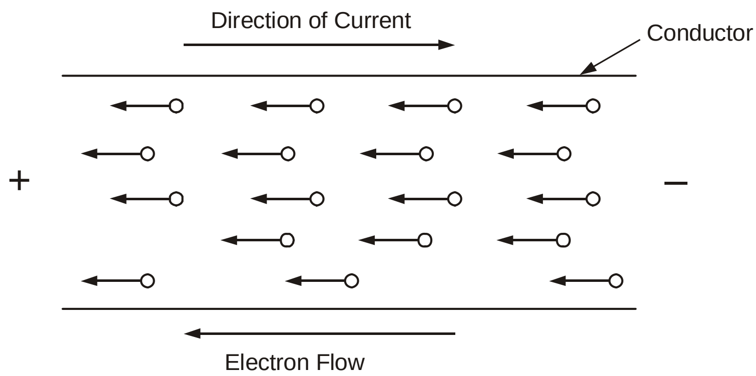

Figure 1.1 : Electron Flow

Current that flows continuously in one direction is known as direct current (DC). Direct current is supplied by voltage cell because the polarities of voltage cell do not reverse with passage of time. Thus, a voltage cell is termed as direct voltage source (DC voltage source) as shown in Figure 1.2.

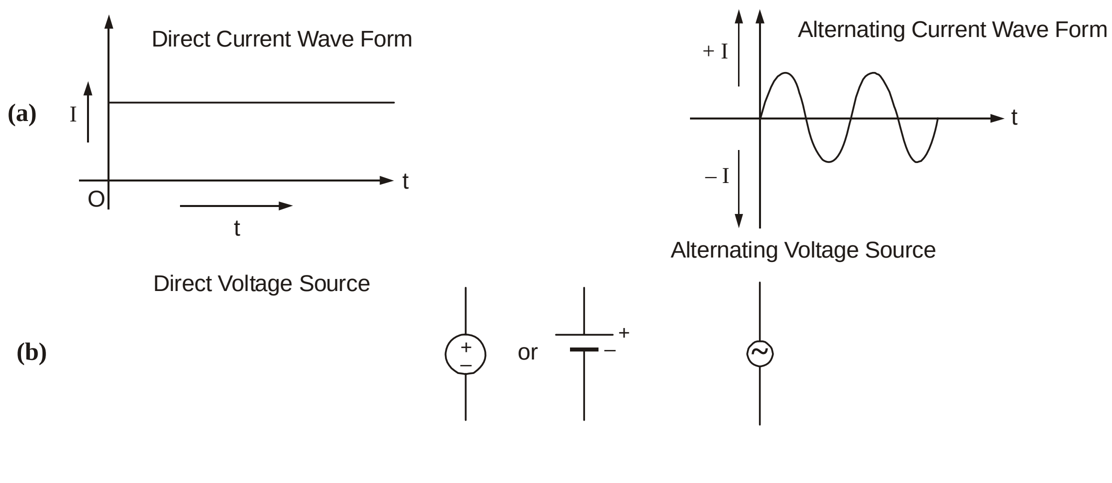

Figure 1.2 : Direct and Alternating Voltage Source

Alternating current (AC) is the current that flows first in one direction for a small time, and then reverses the flow in the opposite direction for a similar time. Voltage source capable of producing alternating current is called Alternating voltage source or AC voltage source.

1.3.3 Ohm's Law

The opposition to current flow that exists in every material is called 'Resistance'. It is the property of material by which we know how it resists flow of current. The property which supports flow of current is known as conductance. The reciprocal of resistance (R, symbol for a resistor) is conductance (G). The resistance is measured in ohms (Ω).

The conductance is given as,

$$\text{Conductance,} \quad G = \frac{1}{\text{Resistance}} = \frac{1}{R}$$

Siemens (S) is the unit of conductance.

According to Ohm's law, the current (*I*) flows through a resistor due to electric pressure and is directly proportional to the magnitude of electrical pressure (*V*).

$$\therefore \qquad \text{Current} = \frac{\text{Voltage}}{\text{Resistance}}$$

$$\text{or,} \qquad I = \frac{V}{R}$$

The resistance of a resistor depends on area, length and resistivity of material of resistor and is given by,

$$R = \frac{\rho l}{A} \quad \text{(Figure 1.3)}$$

Here, ρ = Resistivity,

l = Length of resistor, and

A = Area of cross section.

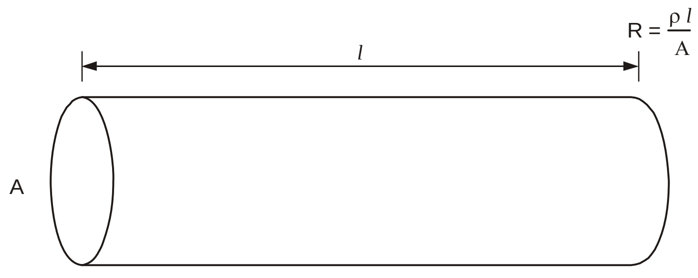

Figure 1.3 : Resistor

Resistivity is the property of material and depends upon the internal structure of a metal or a conductor. It is measured in ohm-m or ohm-cm.

1.3.4 Effects of Electric Current

When an electric current flows in a conductor, heat is dissipated as a result of work done in moving electrons. For example, work is performed in a lamp filament when the electric current is converted into light. The power (*P*) is the rate of doing work.

If work done is w, then

$$\text{Power} = w / t$$

The SI unit of power is Joules/second (J/s) termed as Watt (W).

In a resistance, heat is produced by flow of current due to work done in moving charge q across potential V, which is given by

$$W = V \times q$$

Thus, $$\text{Power} = \frac{w}{t} = V \times \frac{q}{t} = V \times I = \text{Voltage} \times \text{Current}$$

Therefore, $$P = V \cdot I = I\,R\,.\,I \qquad \text{(using Ohm's law)}$$

$$P = I^2 R$$

The unit of electrical power is Watt (W) or kilo Watt (kW).

This power is wasted in electronic circuits but in order to protect the equipment, fuses are used. Fuses are designed in such a way that the current flow exceeds the design limit, the power is dissipated in fuse to cause it to melt and blow off to protect a device by interrupting the current flow in the circuit.

The electrical appliances are rated in W or kW consumed energy. Thus, the energy is the consumption of power in a specified time

$$w = P \cdot t$$

Its SI unit is kWh and is measured by energy meters.

Example 1.1

Calculate current flow through the 5 Ω resistor when a 100 V battery is connected across it. Also calculate conductance of the resistor and the power dissipated by this resistor.

Solution

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

So, $$I = \frac{100}{5} = 20 \text{ A}$$

Power dissipated, $$P = I^2 R = 20^2 \times 5 = 2000 \text{ W}$$

$$= 2 \text{ kW}$$

Now we know $$\text{Conductance} = \frac{1}{\text{Resistance}} = \frac{1}{5} = 0.2 \text{ Siemens}$$

Example 1.2

If the diameter of a conductor is increased to double, keeping length constant, what is the change in resistance?

Solution

We know that resistance of any conductor is inversely proportional to the area of conductor. Thus, diameter increased to double keeping length constant implies increase in area to four times and hence the resistance is reduced to one-fourth.

SAQ 2

Explain the terms voltage, current, resistance and relations between them.

1.4 RESISTANCE OF A CONDUCTOR

1.4.1 Resistance of Resistors in Series

Resistors are said to be in series when they are connected in such a way that there is only one path through which current can flow (Figure 1.4). This means current in a series circuit is the same in all parts of the circuit. The voltage drop across each component in a series circuit depends on the current level and the component resistance.

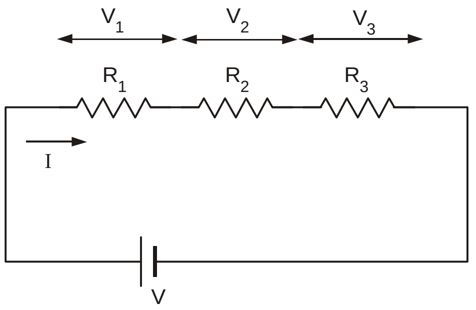

Figure 1.4 : Resistance of Resistors in Series

The total resistance across the voltage source in Figure 1.4 will be

$$R_{eq} = R_1 + R_2 + R_3$$

R_{eq} is called equivalent resistance of circuit for a series circuit with n resistors and is given as,

$$R_{eq} = R_1 + R_2 + R_3 + \ldots + R_n$$

If the resistance of all resistors are same, then

$$R_{eq} = n \cdot R$$

The current flow in the circuit will be

$$I = \frac{E}{R_{eq}} = \frac{E}{R_1 + R_2 + \ldots + R_n}$$

The current in series circuit produces voltage drop across resistors as shown in Figure 1.4 :

$$V_1 = IR_1, \ V_2 = IR_2 \text{ and } V_3 = IR_3.$$

Therefore, $V = V_1 + V_2 + V_3$

$$V = I\,(R_1 + R_2 + R_3)$$

$$V = I \cdot R_{eq}$$

or $I = \dfrac{V}{R_{eq}}$

Example 1.3

A series combination of two resistors having resistances R_1 and R_2 is connected across a voltage cell of V volts as shown in Figure 1.5. Find current flowing through the circuit and voltage drop across resistors.

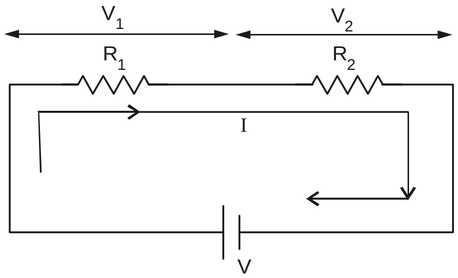

Figure 1.5

Solution

Here $R_{eq} = R_1 + R_2$

We know, current $I = \dfrac{V}{R_{eq}} = \dfrac{V}{R_1 + R_2}$

$\because$ Voltage drop across R_1 is $V_1 = I \cdot R_1$.

So, $\Rightarrow V_1 = \dfrac{V}{R_1 + R_2} \cdot R_1 = \dfrac{V R_1}{R_1 + R_2}$

Similarly, voltage drop across R_2 is V_2

$$\Rightarrow V_2 = \frac{V R_2}{R_1 + R_2}$$

After illustration of Example 1.3, we know that in a series circuit the portion of applied emf developed across each resistor is the ratio of the resistor to the total series resistance. Thus, two or more series connected resistors, as shown in Figure 1.4, can be used as a voltage divider. A potentiometer is a variable voltage divider. The series connected resistors are used for the purpose of voltage dropping or current limiting.

1.4.2 Resistance of Resistors in Parallel

Resistors are said to be connected in parallel when the same voltage appears across each component with different current flows through each resistor. The total current flow into and out of parallel combination is the sum of all the individual resistor currents as shown in Figure 1.6.

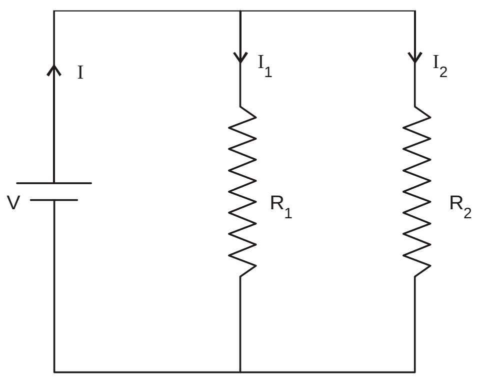

Figure 1.6 : Parallel Resistance

Two resistors connected in parallel may be used as a current divider.

The voltage V appears across each resistor

Then $\quad I_1 = \dfrac{V}{R_1}$ and $I_2 = \dfrac{V}{R_2}$

But total current $\quad I = I_1 + I_2$

For n resistors in parallel

$$I = I_1 + I_2 + I_3 + \ldots + I_n$$

Here, $\quad I = I_1 + I_2.$

$$= \frac{V}{R_1} + \frac{V}{R_2}$$

If, $\quad I = \dfrac{V}{R_{\text{eq}}}$

Then, $\quad \dfrac{V}{R_{\text{eq}}} = \dfrac{V}{R_1} + \dfrac{V}{R_2}$

or $\quad \dfrac{1}{R_{\text{eq}}} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$

For n resistors,

$$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

or $\quad R_{\text{eq}} = \dfrac{1}{\left(\dfrac{1}{R_1} + \dfrac{1}{R_2} + \ldots + \dfrac{1}{R_n}\right)}$

Now $\quad I_1 = \dfrac{V}{R_1}$

Using $V = I\ R_{\text{eq}}$, we get

$$I_1 = \frac{I\ R_{\text{eq}}}{R_1}$$

But here, $\quad R_{\text{eq}} = \dfrac{1}{\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)} = \dfrac{R_1\ R_2}{R_1 + R_2}$

$$\Rightarrow\ I_1 = \frac{\dfrac{I \cdot R_1\ R_2}{(R_1 + R_2)}}{R_1}$$

$$I_1 = I\left(\frac{R_2}{R_1 + R_2}\right)$$

Similarly $\quad I_2 = I\left(\dfrac{R_1}{R_1 + R_2}\right)$

Thus, we see that two parallel connected resistors functioned as a current divider.

Example 1.4

Determine current I_1, I_2 and total current in circuit shown in Figure 1.7.

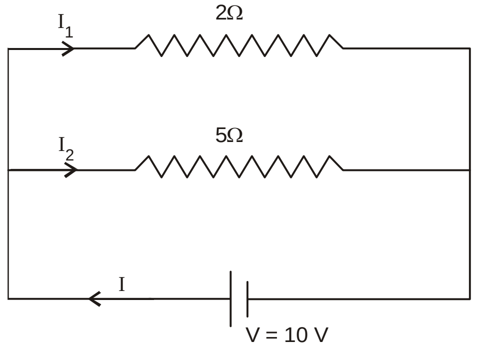

Figure 1.7

Solution

We know $$R_{eq} = \frac{R_1 \; R_2}{R_1 + R_2} = \frac{10}{7}$$

$$I = \frac{V}{R_{eq}} = \frac{10}{\frac{10}{7}} = 7 \text{ A}$$

Now, $$I_1 = I \cdot \frac{R_2}{R_1 + R_2} = \frac{7 \times 5}{2 + 5}$$

$$I_1 = 5 \text{ A}$$

and, $$I_2 = I - I_1$$

$$= 7 - 5$$

$$= 2 \text{ A}$$

Also, $$I_2 = I \cdot \frac{R_1}{R_1 + R_2} = \frac{7 \times 2}{2 + 5} = \frac{7 \times 2}{7} = 2 \text{ A}$$

1.4.3 Series and Parallel Combination of Resistors

Generally, most of the circuits have series and parallel combinations. The simplest approach to analyse a series-parallel circuit is to resolve each purely series or purely parallel group into its single equivalent resistance till we arrive at a single equivalent resistance across voltage source.

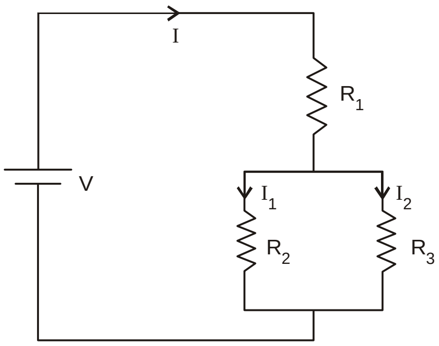

Figure 1.8(a) : Combination of Series and Parallel

Example 1.5

If $R_1 = 5\ \Omega$, $R_2 = 2\ \Omega$ and $R_3 = 3\ \Omega$ and voltage cell of 10 V connected across these for an arrangement shown in Figure 1.8(a), then calculate the current in all three resistors.

Solution

This circuit can be simplified by replacing parallel connected resistors with its equivalent resistance

$$R_{eq_1} = \frac{R_2\ R_3}{R_2 + R_3}$$

The circuit can then be reduced by replacing series resistances R_1 and R_{eq_2} with R_{eq_2}.

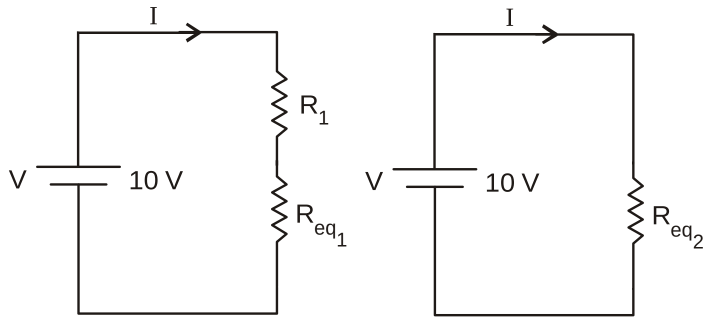

Figure 1.8(b) : Equivalent Circuit

Thus, $$R_{eq_1} = \frac{R_2\ R_3}{R_2 + R_3} = \frac{2 \times 3}{2 + 3} = \frac{6}{5}\ \Omega$$

and $$R_{eq_2} = R_1 + R_{eq_1} = 5 + \frac{6}{5} = \frac{31}{5}\ \Omega$$

Now, $$I = \frac{V}{R_{eq_2}} = \frac{10}{\frac{31}{5}} = \frac{50}{31}\ \text{A}$$

Current I flows through R_1 and R_{eq_1}

Now, find currents flowing through R_2 and R_3 by using current divider.

Current in R_2 is $$I_1 = \frac{I \cdot R_3}{R_2 + R_3} = \frac{\frac{50}{31} \times 2}{5} = \frac{20}{31}\ \text{A}$$

Current in R_3 is $$I_2 = \frac{I \cdot R_2}{R_2 + R_3} = \frac{\frac{50}{31} \times 3}{5} = \frac{30}{31}\ \text{A}$$

Example 1.6

Using values given in Example 1.5, find currents in R_1, R_2 and R_3.

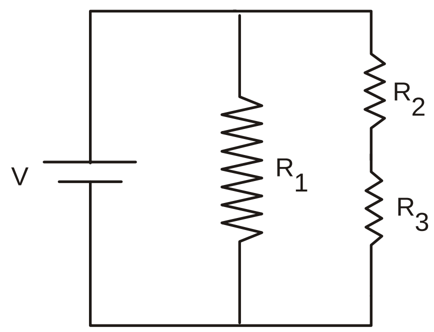

Figure 1.9(a)

Solution

To reduce above circuit, first replace series combination by its equivalent as shown in Figure 1.9(b).

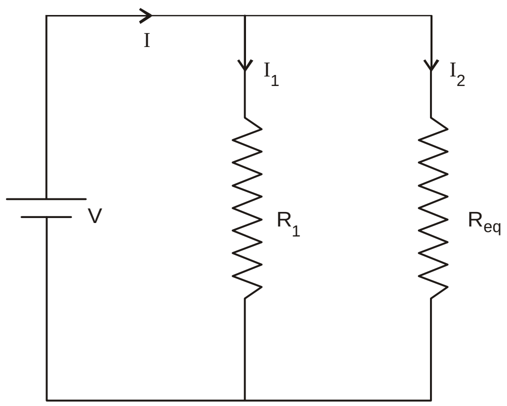

Figure 1.9(b) : Equivalent Circuit (For Example 1.6)

$$R_{eq} = R_2 + R_3$$

$$= 2 + 3 = 5\ \Omega$$

Now, the same voltage V appears across R_1 and R_{eq}

So, current in R_1, $I_1 = \frac{V}{R_1} = \frac{10}{5} = 2\ \text{A}$

and current in R_2 and R_3, $I_2 \Rightarrow \frac{V}{R_{eq}} = \frac{10}{5} = 2\ \text{A}$

SAQ 3

(a) A resistance A of 3 ohms in parallel with B produces a current of 3 Amperes when connected across a 6 V battery find :

  (i) Currents in A and B

  (ii) The resistance of B

  (iii) What resistance X must be put in series with AB combination to reduce the current to 2 Amps.

(b) A current of 20 amps flows through two resistors A and B joined in series. Across A, p. d. is 0.2 V and across B it is 0.3 V. Find how the same current will divide between *A* and *B* when they are joined in parallel.

(c) The resistance of two conductors is 25 ohms when connected in series and 6 ohms when joined in parallel :

  (i) Calculate the resistance of each wire.

  (ii) What ratio of current will be shared when in parallel?

1.5 KIRCHHOFF'S LAWS

These laws are more comprehensive than Ohm's law and are used in solving the electrical circuits which may not be solved by the latter.

1.5.1 Kirchhoff's Current Law (KCL)

In any circuit, the algebraic sum of all the currents meeting at a point is zero. The total current leaving a junction or point is equal to total current entering that junction. It proves conservation of charge as charge is not stored at a point and the charge entering a point has to be equal to charge leaving that point, i.e. $\Sigma I = 0$ (at a point or junction) as shown in Figure 1.10.

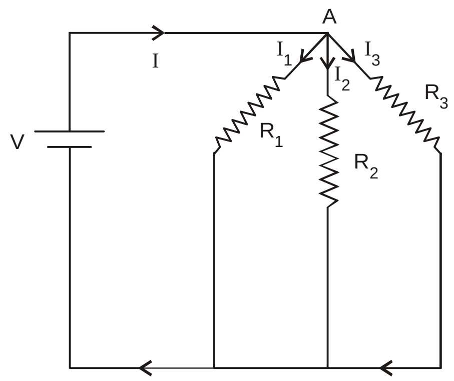

Figure 1.10 : Kirchhoff's Current Law

Here 'I' enters at junction and I_1, I_2 and I_3 are leaving the junction.

Assuming incoming currents + ve and outgoing currents as – ve, we have, algebraic sum of currents meeting at junction A as,

$$I - I_1 - I_2 - I_3 = 0$$

or $$I - (I_1 + I_2 + I_3) = 0$$

i.e. $$I = I_1 + I_2 + I_3.$$

Thus, KCL also implies that sum of incoming currents equals sum of outgoing current.

1.5.2 Kirchhoff's Voltage Law (KVL)

In any closed circuit the algebraic sum of the voltages reckoned in a particular direction is zero. Conventionally, voltage drop in the direction of traversal is taken as negative, while a rise in voltage is taken as positive. It may be remembered that across a resistor voltage drops in the direction of current while it rises in the opposite direction, as shown in Figure 1.11.

Thus, $\Sigma V = 0$ (Round a mesh or path).

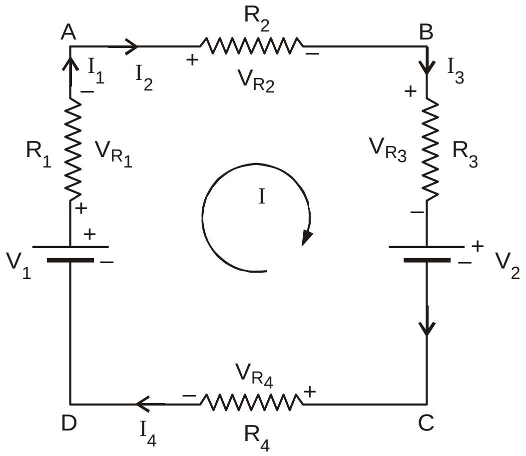

Figure 1.11 : Kirchhoff's Voltage Law

In a closed circuit *ABCDA*, in the clockwise direction the voltage drops are $I_1 R_1$, $I_2 R_2$, $I_3 R_3$, $I_4 R_4$ and V_2, while the voltage rise is V_2.

In a path *ABCDA*, considering a rise in voltage is positive and fall in voltage is negative. The polarity of voltage drop appears across any resistor, as shown in Figure 1.12.

The rise and fall in voltage should be as shown in Figure 1.12.

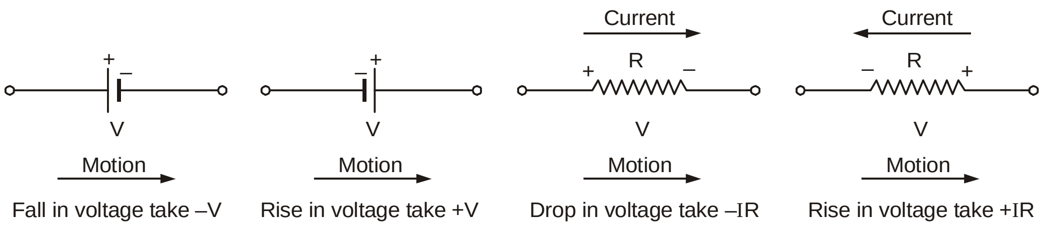

Figure 1.12

Using these conventions, we have algebraic sum of voltages in clockwise direction as

$$- V_{R1} - V_{R2} - V_{R3} - V_2 - V_{R4} + V_1 = 0$$

or, $$- I_1 R_1 - I_2 R_2 - I_3 R_3 - I_4 R_4 - V_2 + V_1 = 0$$

or, $$I_1 R_1 + I_2 R_2 + I_3 R_3 + I_4 R_4 = V_1 - V_2.$$

or, $$\Sigma\, IR = \Sigma \text{ EMFs}.$$

Thus, KVL also means that in a closed circuit total voltage drop across resistors is equal to algebraic sum of voltage sources reckoned in the direction of voltage drops across resistors.

In a closed circuit (as shown in Figure 1.13), if there is no source of EMF, then sum of voltage drops is equal to zero.

Thus, we get,

$$I_1 R_1 + I_2 R_2 + I_3 R_3 = 0$$

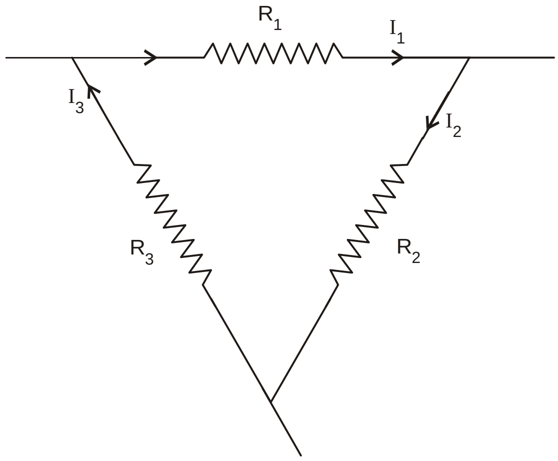

Figure 1.13

Example 1.7

In Figure 1.14, r_1, r_2 are internal resistances of batteries E_1 and E_2. Calculate the currents I_1, I_2, I_3, I_4 and I_5.

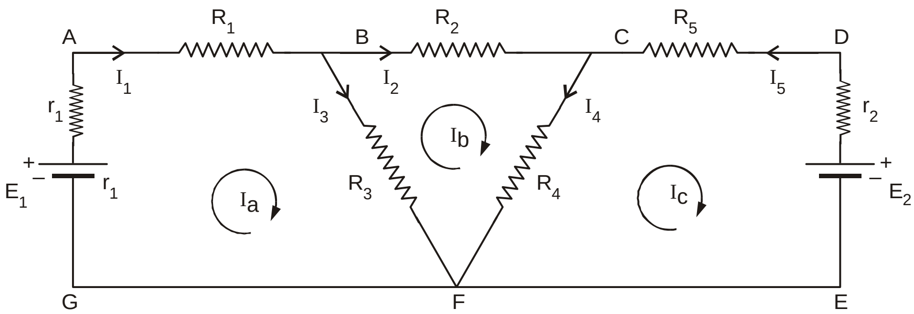

Figure 1.14

Solution

To solve for 5 currents I_1, I_2, I_3, I_4 and I_5, we require at least 5 equations of current.

At point B $\quad I_1 = I_2 + I_3$ . . . (i)

At point C $\quad I_4 = I_2 + I_5$ . . . (ii)

In loop a, i.e. closed mesh ABFGA

$$I_1 R_1 + I_1 r_1 + I_3 R_3 = E_1 \quad \text{. . . (iii)}$$

In loop b, i.e. closed mesh BCFB

$$I_2 R_2 + I_4 R_4 - I_3 R_3 = 0 \quad \text{. . . (iv)}$$

In loop c, i.e. closed mesh CDEFC

$$- I_4 R_4 - I_5 r_2 - I_5 R_5 = - E_2 \quad \text{. . . (v)}$$

or $\quad I_4 R_4 + I_5 r_2 + I_5 R_5 = E_2$

Thus, the whole circuit can be solved with the help of above equations.

For solving problems using mesh or loop analysis (i.e. by using KVL), usually the circuit is considered to be composed of small meshes with some mesh/loop current circulating in each mesh. The meshes are so chosen that each element of circuit is covered at least once in any of the meshes and removal of any mesh violates this condition.

The given circuit can, thus, be considered to be composed of 3 meshes *a*, *b* and *c* with mesh currents as I_a, I_b and I_c respectively. Note that $I_1 = I_a$, $I_2 = I_b$, $I_3 = I_a - I_b$, $I_4 = I_b - I_c$ and $I_5 = I_c$. Applying KVL in each mesh, we get 3 equations as,

$$E_1 - I_a r_1 - I_a R_1 - (I_a - I_b) R_3 = 0 \qquad \text{. . . (i)}$$

$$-(I_b - I_a) R_3 - I_b R_2 - (I_b - I_c) R_4 = 0 \qquad \text{. . . (ii)}$$

$$-(I_c - I_b) R_4 - I_c R_3 - I_c r_2 - E_2 = 0 \qquad \text{. . . (iii)}$$

The above 3 equations can be solved for I_a, I_b and I_c, which can then be used to derive I_1, I_2, I_3, I_4 and I_5 using relations given above.

SAQ 4

In the circuit shown in Figure 1.15, determine the current flowing through the 12 ohm resistance.

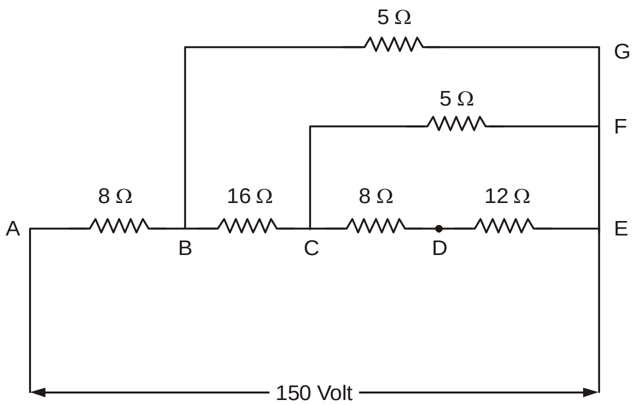

Figure 1.15

1.6 BATTERIES

A battery is a collection of two or more than two cells.

A cell is the smallest unit of a battery, which converts chemical energy to electrical energy. A cell always gives DC voltage (emf) and DC current. Cells are of two kinds – Primary cell and Secondary cell.

Primary Cell

A cell based on irreversible reactions, whose components must be renewed (or the cell itself be replaced) when it is rundown, is known as a primary cell, e.g. simple voltaic cell, Daniel cell, Lechlanche cell and Dry cell.

Secondary Cell

A cell based on reversible reactions, whose components (i.e. electrodes and electrolytes) can be brought back to normal state by passing a current through it in the opposite direction is known as a secondary cell, e.g. Lead-acid cell, Nickel Alkaline cell.

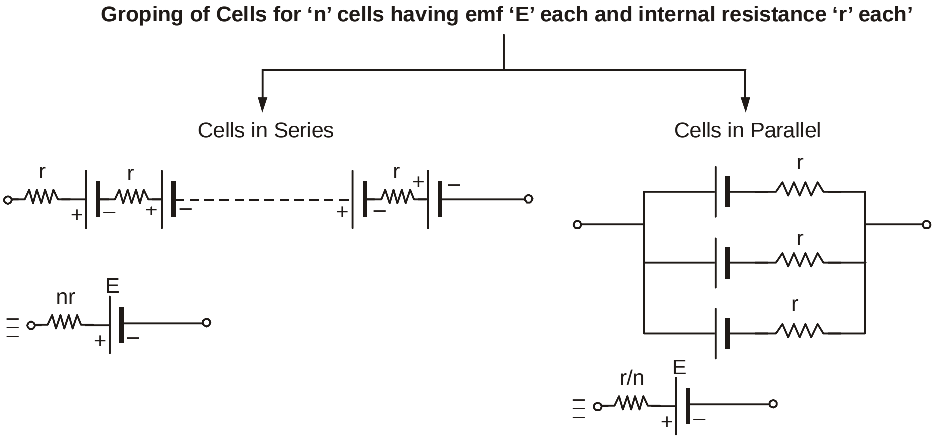

Figure 1.16 : Different Types of Cell

1.6.1 Construction of Lead Acid Battery

Positive and Negative Plates

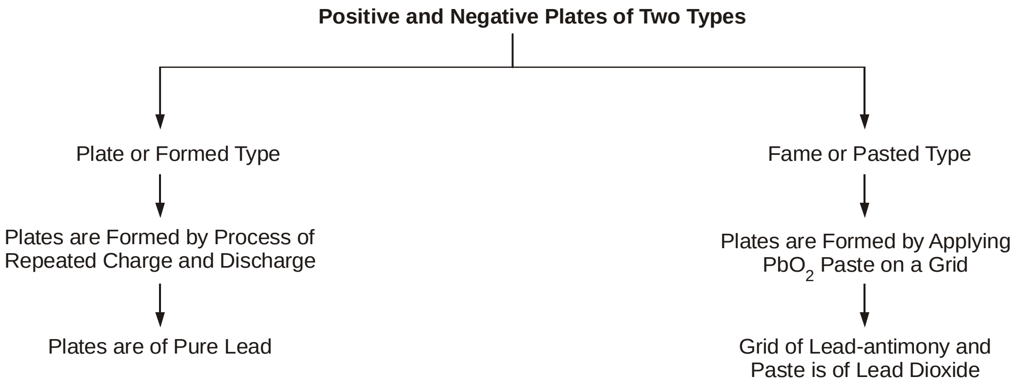

Figure 1.17 : Types of Lead Acid Accumulator

Separators

They are used for insulating the negative and positive plates. They are made of thin sheets of perforated hard rubber or plastic material of fibre glass or wood.

Electrolyte

Diluted sulphuric acid fills the cell compartment to immerse the plates completely.

Container

Battery parts are placed within the container and protected. Partition walls are provided in the container for cells.

Bottom Blocks

The bottom-groved support blocks are placed at the bottom of the container, which converts the active materials, which fall from plates. In this way, it prevents the short-circuiting of the plates.

Plate Connector

It is a lead plate, which is assembled to a group of positive plates or to a group of negative plates. An upward connection of the plate connector forms a terminal of a cell.

Cell Connector

Various cells constitute a battery. The negative terminal of one cell is arranged close to the positive terminal of the next cell and connected together so that the cells can be connected in series. These connectors are either of pure lead or of a special lead alloy.

Terminal Posts

They are the upward extension of the two extreme plate-connectors. The connections for outside circuit are taken from these terminal posts. They are marked (+)ve or (–)ve.

Vent Plug or Filler Caps

These are made of rubber or polystyrene and screwed to the cover of the cell. Their function is to prevent escape of electrolyte but allow free exit of gases.

External Connecting Straps

These are the antimony-lead alloy flat bars which connect the positive terminal post of one cell to the negative of the next across the top of the cover. These are of very solid construction, especially in starting batteries because they have to carry very heavy currents.

Active Materials of a Lead Cell

The active materials of a Lead-Acid Accumulator are

PbO_2 (*Lead Peroxide*)

It is a chocolate-brown coloured, hard and brittle rod, which forms the positive plate of the battery.

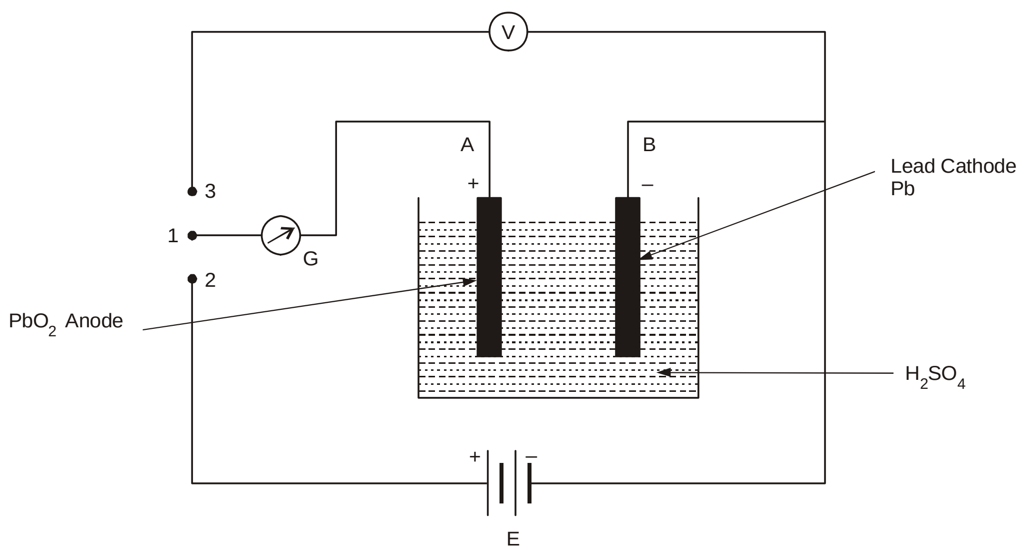

Figure 1.18

Pb (*Sponge Lead*)

It is pure lead in soft sponge or porous condition. It forms the negative plate of the battery.

Dilute H_2SO_4 (*Dilute Sulphuric Acid*)

Concentrated H_2SO_4 of specific gravity 1.84 is taken. One part of it is mixed with three parts of distilled water to prepare a diluted sulphuric acid of specific gravity 1.24.

Thus, the lead acid accumulator depends for its action in the presence of two plates of Pb / PbO_2 in a solution of diluted sulphuric acid of specific gravity 1.21 to 1.24 or near-about.

1.6.2 Chemical Reactions

Charging and Discharging of Lead Acid Batteries

In the process of manufacturing of cells, the plates are in the charged condition. In the charged condition, positive plate or anode consists of lead peroxide PbO_2 (dark chocolate brown) and the negative plates or cathode is in lead (Pb) (slate grey).

(a) *During Charging, the following reactions occur* :

$PbSO_4 + H_2 \rightarrow Pb + H_2SO_4$ . . . . (at cathode)

$PbSO_4 + SO_4 + 2H_2O \rightarrow PbO_2 + 2H_2SO_4$ . . . . . . (at anode)

At the end of charging (i.e. fully charged) :

(i) Anode becomes PbO_2 (Colour : Chocolate brown)

(ii) Cathode becomes Pb (Colour : Slate grey)

(iii) Density of electrolyte (i.e. its specific gravity becomes 1.23 to 1.28)

(iv) Approximate value of emf is 2.3 volts

(v) Cell stores energy

(b) *During Discharging, the following reactions occur* :

$PbO_2 + H_2 + H_2SO_4 \rightarrow PbSO_4 + 2\,H_2O$ (at anode)

$Pb + SO_4 \rightarrow PbSO_4$ (at cathode)

During Discharging

(i) Both anode and cathode become $PbSO_4$, which is whitish in colour.

(ii) Due to formation of water, in the anode reaction, the specific gravity of the electrolyte decreases and may even reach as low as 1.15 or 1.05.

(iii) Voltage (emf) of the cell decreases.

(iv) Cell gives out energy.

Single Reaction :

$PbO_2 + 2H_2SO_4 + Pb \rightarrow PbSO_4 + 2H_2O + PbSO_4$

PbO_2	$2H_2SO_4$	Pb	$PbSO_4$	$2H_2O$	$PbSO_4$
(+) ve Plate	Electrolyte	(–) ve Plate	(+) ve Plate	Water	(–) ve Plate

Initial Charging

Charging a new battery for the first time is called initial charging.

Steps

(a) Battery is cleaned.

(b) Electrolyte of specific gravity $P = 1.23$ is provided.

(c) Battery is allowed to cool for 14-16 days.

(d) Level of electrolyte, which decreases, is again brought back to the level by pouring more of it and again cooling for 3-6 days.

(e) Initial charging is done at a rate lower than the normal.

(f) At the end of charging (i.e. after 2-3 days), the '*P*' is adjusted by adding distilled water.

Thereafter, the battery is discharged at a rate lower than normal for the first one or two times. The battery is put to the normal service after charging and discharging.

1.6.3 Testing of Lead Acid Battery

To know the latest charged position, testing of battery is done by measuring the specific gravity of electrolyte and the voltage with a cell tester.

For a fully charged battery, the voltage of each cell should be about 2 V to 2.07 V while the specific gravity should be about 1.26.

1.6.4 Care and Maintenance of Lead Acid Battery

There are some important points, as listed below, which help in care and maintenance of battery like :

(g) Lead acid batteries should be brought up to full charge at the earliest. Avoid continuously operating batteries in a partially charged condition. This will shorten their life and reduce their capacity.

(h) Inactivity can be extremely harmful.

(i) When not in use, remove electrical connections from the battery including series/parallel connectors.

(j) Store battery in a cool place.

(k) Extreme temperatures can substantially affect battery performance and charging.

(l) Batteries should be kept clean, free of dirt and corrosion at all times.

(m) New batteries should be charged properly.

1.6.5 Trickling Charge

Under idle condition, the battery discharges very slowly due to self leakage. To keep the battery fully charged under critical operating conditions, it is continuously charged at the same rate as that of discharge. This slow charging of battery is called **trickle charging**.

Thus, when the battery is charged at a very low rate, i.e. about 2-3 % of the normal rate for a long time, then it is said to be under 'trickling charge'. In electrical power-sub-stations (where these batteries are the "heart" of the system), trickling charge is used.

1.6.6 Advantages of Storage Battery

(a) Storing of energy in the battery can be done at any convenient rate but may be delivered at any other rate.

(b) It is the most efficient device for supplying of electrical energy in a portable form.

(c) Energy stored in the battery is available immediately without any lag of time.

1.6.7 Applications of Lead Acid Battery

In electrical power stations and sub-stations, relays are operated by supplying electrical energy by the lead-acid batteries (120 such batteries of 2 V each are connected in series to give 240 V).

Other applications of lead acid batteries are as follows :

(a) Emergency light and fans, inverters etc.

(b) Cars, trucks, jeeps etc.

(c) Industries and mining.

(d) Ships and submarines.

(e) Standby power supply for telephone exchange, radio stations, etc.

SAQ 5

In the circuit, in Figure 1.19, find

(a) the value and direction of current in 10 Ω resistance, and

(b) the current supplied by each battery.

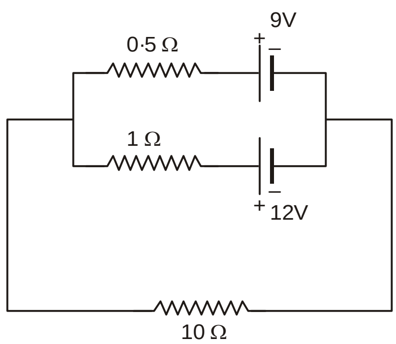

Figure 1.19 : Battery with Internal Resistance in Parallel

1.7 SUMMARY

After going through this unit, you should have understood the effects of electricity and also the properties of resistors and capacitors. You would also have a general understanding of Kirchhoff's laws, Ohm's law and principles of batteries operation.

1.8 ANSWERS TO SAQs

SAQ 3

(a)

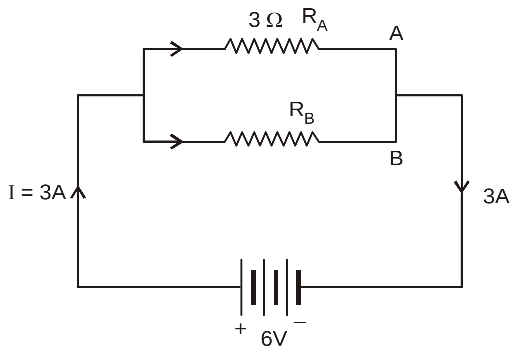

Figure for SAQ 3

(i) $I_A = \frac{6}{3} = 2$ Amp.

$I_B = 3 - 2 = 1$ Amp

(ii) $R_B = \frac{6}{I_B} = \frac{6}{1} = 6$ Ohms

(iii) Let a resistor, with resistance 'X', is connected in series as shown below.

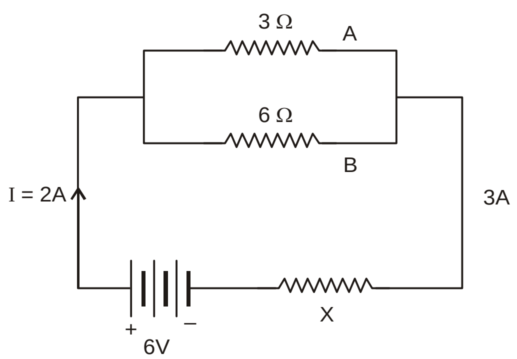

Figure for SAQ 3

Total resistance in the circuit = $\frac{6 \times 3}{6 + 3} + X$

$$= (2 + X)$$

Now $\quad I = \frac{6}{2 + X} = 2$

or, $\quad X = 1$ ohm

(b)

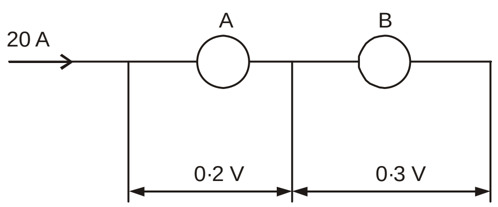

Figure for SAQ 3

Resistance of A, $R_A = \frac{0.2}{20} = 0.01\ \Omega$

Resistance of B, $R_B = \frac{0.3}{20} = 0.015\ \Omega$

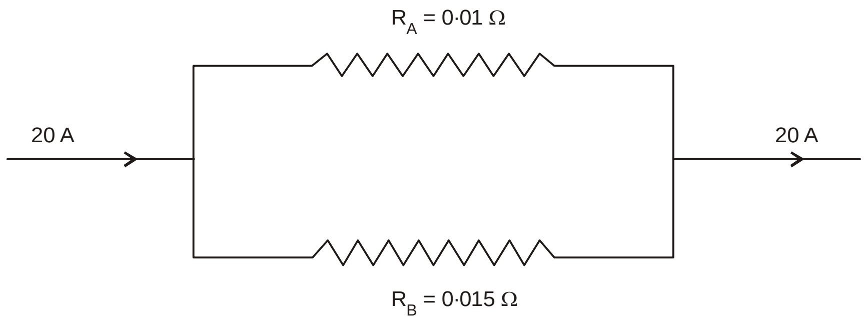

Figure for SAQ 3

When connected in parallel,

$$I_A = I \times \frac{R_B}{R_A + R_B} = 20 \times \frac{0.015}{0.01 + 0.015} = 12 \text{ Amps}$$

$$I_B = I - I_A = 20 - 12 = 8 \text{ Amps}$$

Also, $I_B = I \times \frac{R_A}{R_A + R_B} = 20 \times \frac{0.01}{0.01 + 0.015} = 8$ Amps

(c) (i) Let R_1 and R_2 be two resistances

Then in series, $R_1 + R_2 = 25$ Ohms . . . (1)

In Parallel, $\frac{R_1 R_2}{R_1 + R_2} = 6$ Ohms . . . (2)

From Eq. (1) and Eq. (2)

$$\frac{R_1 R_2}{25} = 6 \quad \text{or} \quad R_1 R_2 = 150 \qquad \text{. . . (3)}$$

From Eq. (1),

$$R_2 = (25 - R_1) \qquad \text{. . . (4)}$$

By putting Eq. (4) in Eq. (3), we get

$$R_1 (25 - R_1) = 150$$

or $R_1^2 - 25R_1 + 150 = 0$

or $R_1 = \frac{25 \pm \sqrt{(25)^2 - 4 \times 150}}{2} = \frac{25 \pm \sqrt{25}}{2}$

$$= \frac{25 \pm 5}{2} = 15 \text{ ohms or } 10 \text{ ohms}$$

Here $R_1 = 15$ ohms, $R_2 = 10$ ohms

or $R_1 = 10\ \Omega$, $R_2 = 15\ \Omega$

(ii) Let $R_1 = 15\ \Omega$, $R_2 = 10\ \Omega$

Total current = I amp

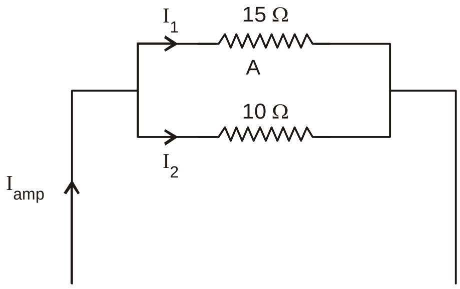

Figure for SAQ 3

Then $I_1 = I \times \dfrac{R_2}{R_1 + R_2}$

$$= I \times \frac{10}{25} = \frac{2}{5} I \text{ A.}$$

and $I_2 = I \times \dfrac{R_1}{R_1 + R_2} = I \times \dfrac{15}{25} = \dfrac{3}{5} I$

The ratio of currents in R_1 and R_2 = $\dfrac{2}{5} : \dfrac{3}{5}$

$$= 2 : 3$$

SAQ 4

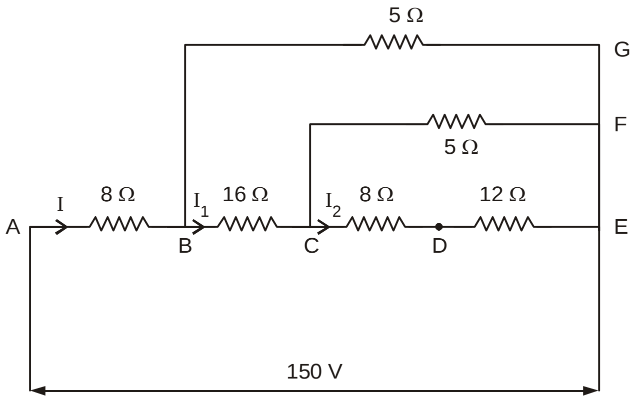

Figure for SAQ 4

Resistance of CEF = $\dfrac{5 \times (8 + 12)}{5 + (8 + 12)} = \dfrac{5 \times 20}{5 + 20} = 4\ \Omega$

Resistance of BEG = $\dfrac{5 \times (16 + 4)}{5 + (16 + 4)} = \dfrac{5 \times 20}{5 + 20} = 4\ \Omega$

Resistance of AE (Total resistance) = $8 + R_{BEG} = 8 + 4 = 12$ ohms

Current $I = \dfrac{V}{R} = \dfrac{150}{12} = 12.5$ Amps

Current $I_1 = I \times \dfrac{5}{5 + (16 + R_{CEF})} = I \times \dfrac{5}{5 + (16 + 4)}$

$$= 12.5 \times \frac{5}{25} = 2.5 \text{ Amps}$$

$$\text{Current } I_2 = I_1 \times \frac{5}{5 + (8 + 12)} = I_1 \times \frac{5}{25}$$

$$= 2.5 \times \frac{5}{25} = 0.5 \text{ Amps}$$

SAQ 5

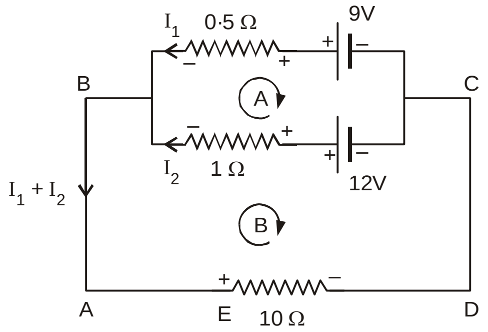

Figure for SAQ 5

Applying KVL in meshes *A* and *B*, we get

$$0.5 I_1 - 9 + 12 - I_2 = 0 \qquad \text{. . . (i)}$$

and

$$I_2 - 12 + 10\,(I_1 + I_2) = 0 \qquad \text{. . . (ii)}$$

Rearranging Eqs. (i) and (ii), we get

$$0.5 I_1 - I_2 = -3 \qquad \text{. . . (iii)}$$

$$10 I_1 + 11 I_2 = 12 \qquad \text{. . . (iv)}$$

Solving Eqs. (iii) and (iv), we get

$$I_1 = -1.35\ A\ ,\ I_2 = 2.32\ A$$

∴ (a) The value of current through 10 Ω resistor

$$I = I_1 + I_2 = -1.35 + 2.32 = 0.97\,A$$

Since *I* is + ve, the direction is same as assumed in above figure.

(b) Current supplied by Battery 1 is 1.35 A and is in a direction opposite to that of I_1.

Current supplied by Battery 2 is 2.32 A and is in a direction same as that of I_2.