Chapter 13

CURRENT ELECTRICITY

LEARNING OBJECTIVES

At the end of this chapter the students will be able to:

- Understand the concept of steady current.
- Describe some sources of current.
- Recognize effects of current.
- Understand and describe Ohm's law.
- Understand resistivity and explain its dependence upon temperature.
- Know the value of resistance by reading colour code on it.
- Know the working and use of rheostat in the potential divider circuit.
- Describe the characteristics of thermistor.
- Use the energy considerations to distinguish between emf and p.d.
- Describe the conditions for maximum power transfer.
- Know and use the application of Kirchhoff's first law as conservation of charge.
- Know and use the application of Kirchhoff's second law as conservation of energy.
- Describe the function of Wheatstone Bridge to measure the unknown resistance.
- Describe the function of potentiometer to measure and compare potentials without drawing and current from the circuit.

Q.1 Define current electricity.

Ans. **CURRENT ELECTRICITY**

The branch of physics which deals with charges in motion is called current electricity or electrodynamics. e.g.,

(i) A light bulb glows to the flow of electric current.

(ii) The current that flows through the coil of motor that causes its shaft to rotate.

(iii) Most of the devices in the industry and in our homes operate with current.

Q.2 Define electric current and conventional current.

Ans. ELECTRIC CURRENT

The charge per unit time passing through any cross section of a conductor is called electric current.

(OR)

The rate of flow of charge is also called the electric current.

It is represented by "I" and it is a scalar quantity. If a net charge ΔQ passes through any cross-section of a conductor in time Δt then, electric current I is

$$I = \frac{\Delta Q}{\Delta t}$$

Unit of Electric Current

The SI unit of electric current is "ampere". The current is said to be one ampere when one coulomb of charge is passing through any cross-section of wire in one second. It is represented by A

$$1A = \frac{1C}{1 \text{ sec.}}$$

- In metallic conductors the charge carriers are electrons.
- The charge carrier in electrolyte are positive and negative ions.
- In gases, the charge carriers are ions and electrons.

Interesting Information

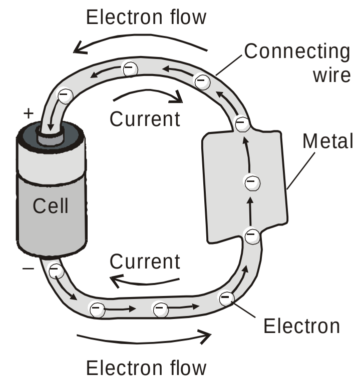
When eel senses danger, it turns itself into a living battery. Any one who attacks this fish is likely to get a shock. The potential difference between the head and tail of an electric eel can be up to 600 V.

Current Direction

Early scientists regarded an electric current as a flow of positive charge from positive to negative terminal of the battery through an external circuit. Later on, it was found that a current in metallic conductors is actually due to the flow of negative charge carriers called electrons moving in the opposite direction i.e., from negative to positive terminal of the battery, but it is a convention to take the direction of current as the direction in which positive charge flow. This current is referred as conventional current. The reason is that it has been found experimentally that positive charge moving in one direction is equivalent in all external effects to a negative charge moving in the opposite direction. As the current is measured by its external effects so a current due to motion of negative charges, after reversing its direction of flow can be substituted by an equivalent current due to flow of positive charges. Thus **"the conventional current in a circuit is defined as that equivalent current which passes from a point at higher potential (+ve) to a point at a lower potential (–ve) as if it represented a movement of positive charges".**

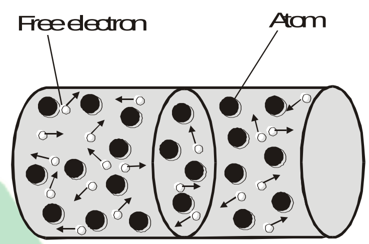
Q.3 Describe the current through a metallic conductor.

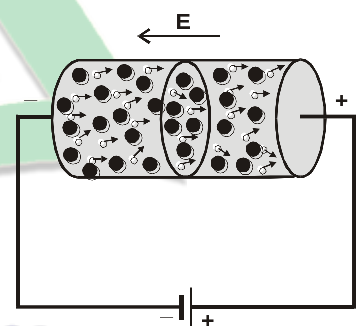
Ans. CURRENT THROUGH A METALLIC CONDUCTOR



In a metal, the valence electrons are not attached to individual atoms but are free to move about within the body. These electrons are known as **free electrons**. The free electrons are in random motion just like the molecules of a gas in a container and they act as charge carriers in metals. The speed of randomly moving electrons depends upon temperature.

If we consider any section of metallic wire, the rate at which the free electrons pass through it from right to left is the same as the rate at which they pass from left to right as shown. As a result the current through the wire is zero. If the ends of the wire are connected to a battery, an electric field $\vec{E}$ will be setup at every point within the wire. The free electrons will now experience a force in the direction opposite to $\vec{E}$. As a result of this force the free electrons acquire a motion in the direction of $-\vec{E}$. It may be noted that the **force experienced by the free electrons does not produce a net acceleration because the electrons keep on colliding with the atoms of the conductor. The overall effect of these collisions is to transfer the energy of accelerating electrons to the lattice with the result that the electrons acquire an average velocity, called the drift velocity in the direction of $-\vec{E}$. It may be defined as the velocity of the free electrons in the direction drift or effectively in the direction opposite to that of electric field in metal. The drift velocity is of the order of 10^{-3} ms^{-1} at room temperature. Due to their thermal motion is several hundred kilometers per second.**





Thus, when an electric field is established in a conductor, the free electrons modify their random motion in such a way that they drift slowly in a direction opposite to the field. In other words the electrons, in addition to their violent thermal motion, acquire a constant drift velocity due to which a net directed motion of charges takes place along the wire and a current begins to flow through it. A steady current is established in a wire when a constant potential difference is maintained across it which generates the requisite electric field $\vec{E}$ along the wire.

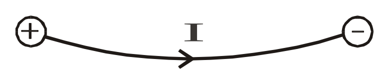


Fig Conventional current flows from higher to lower potential through a wire

Q.4 Describe the source of current.

Ans. **SOURCE OF CURRENT**

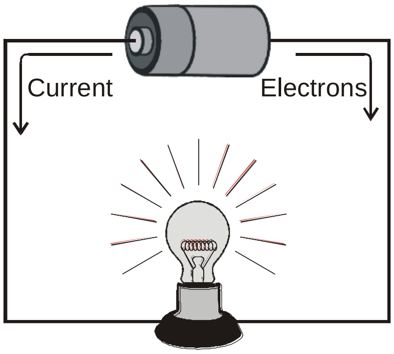


Fig. A source of current such as battery maintains a nearly constant potential difference between ends of a conductor.

To have a constant current the potential difference across the conductor should be maintained constant. This is achieved by connecting the ends of wire to the terminals of a device called a source of current. The source of current which converts some non-electrical energy such as, chemical, mechanical, heat or solar energy into electrical energy is called source of current. There are many types of sources of currents. For example;

* Cells which convert chemical energy into electrical energy.

Types of Cells

(i) **Primary cells:** Cells which cannot be recharged.

(ii) **Secondary cells:** Cell which can recharge

* Electric generators which convert mechanical energy into electrical energy.
* Thermocouples which convert heat energy into electrical energy.
* Solar energy which convert sunlight directly into electrical energy.

Q.5 What are the effects of current?

Ans. **EFFECTS OF CURRENT**

The presence of electric current can be detected by various effects it produces. There are three types

(i) Heating effect (ii) Magnetic effect (iii) Chemical effect

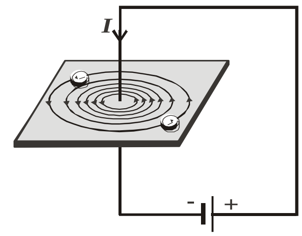
(i) Heating Effect

Current flow through a metallic wire due to motion of free electrons. During the course of their motion, they collide frequently with atoms of metal. At each collision, they lose some of their K.E and give it to atoms with which they collide. Thus as current flows through wire, it increases K.E of vibrations of the metal atoms i.e., it generates heat in the wire. Heat produced by a current I in the wire of resistance R during a time interval t is given by

$$H = I^2RT$$

For Your Information

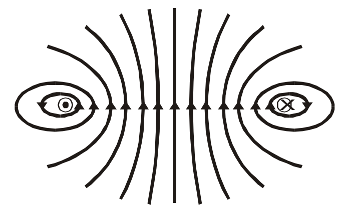
Heating effect of current is used in electric kettle.



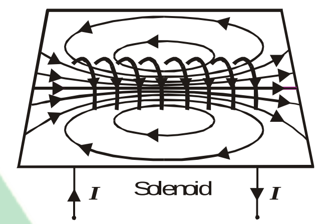
Uses: Heating effect of current is utilized in electric heaters, kettles, toaster and electric iron.

(ii) Magnetic Effect

The passage of current is always accompanied by a magnetic field in the surrounding space. The strength of field depends upon the value of current and the distance from the current element. The pattern of the field produced by a current carrying straight wire, a coil or solenoid is as shown.



Uses: All the machines involving electric motors also use magnetic effect of current.



(iii) Chemical Effect

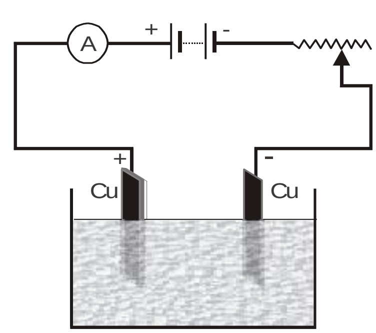
Certain liquids such as dilute sulphuric acid (H_2SO_4) or copper sulphate ($CuSO_4$) solution conduct electricity due to some chemical reactions that take place within them. The study of this process is known as **electrolysis**. The chemical changes produced during the electrolysis of a liquid are due to **chemical effects of the current**. It depends upon the nature of the liquid and the quantity of electricity passed through the liquid.

The liquid which conducts current is known as **electrolyte**. The material in the form of wire or rod or plate which leads the current into or out of the electrolyte is known as electrode. The electrode connected with the positive terminal of the current source is called anode and that connected with negative terminal is known as cathode. The vessel containing the two electrodes and the liquid is known as **voltameter**.

Example

We will consider the electrolysis of copper sulphate solution. The voltameter contains dilute solution of copper sulphate. The anode and cathode are both copper plates. When copper sulphate is dissolved in water, it dissociates into Cu^{++} and SO_4^{-} ions. On passing current through the voltameter, Cu^{++} moves towards the cathode and the following reaction takes place.

$$Cu^{++} + 2e^{-} \longrightarrow Cu$$



The copper atoms thus formed are deposited at cathode plate. While copper is being deposited at the cathode, the SO_4^{-} ions move towards the anode. Copper atoms from the anode go into the solution as copper ions which combine with sulphate ions to form copper sulphate.

$$Cu^{++} + SO_4^{-} \longrightarrow CuSO_4$$

As the electrolysis proceeds, copper is continuously deposited on the cathode while an equal amount of copper from the anode is dissolved into the solution and the density of copper sulphate solution remains unaltered.

Note: This example also illustrates the basic principle of electroplating - a process of coating a thin layer of some expensive metal (gold, silver etc.) on an article of some cheap metal.

Q.6 State and explain Ohm's law. Also define ohmic and non-ohmic substances.

Ans. **OHM'S LAW**

Introduction

When a battery is connected across a conductor, an electric current begins to flow through the conductor. A German physicist George Simon Ohm showed by experiments that the current through the metallic conductor is directly proportional to the potential difference across its ends. This fact is known as Ohm's law.

Statement

This law states that "The current flowing through a conductor is directly proportional to the potential difference across its ends provided the physical states such as temperature of the conductor remains unchanged".

Mathematically

If V is the voltage applied across the ends of the conductor and the current I is flowing through it therefore by ohm's law

$$I \propto V \quad \text{or} \quad V \propto I$$

$$V = IR$$

where R is constant of proportionally called the resistance of the conductor. The value of the resistance depends upon the **nature, dimensions** and the **physical state** of the conductor. It may be defined as **the opposition offered by the conductor to the flow of charges** i.e., free electrons due to their continuous collisions against the atoms of the lattice.

Unit

The SI unit of resistance is **"ohm"**. It is represented by Ω.

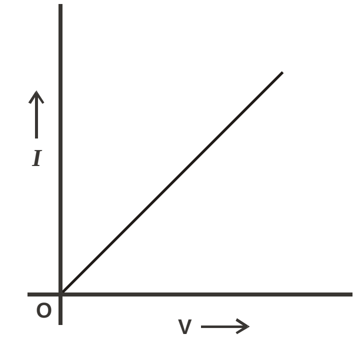
Ohm

"If a current of one ampere flows through any cross-section of a conductor due to a potential difference of one volt applied across its ends then resistance of conductor is said to be one ohm."

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

$$\therefore \quad 1\Omega = \frac{1V}{1A}$$

A conductor is said to obey ohm's law if its resistance remains constant i.e., graph between V and I is a straight line, as shown in figure.



Ohmic

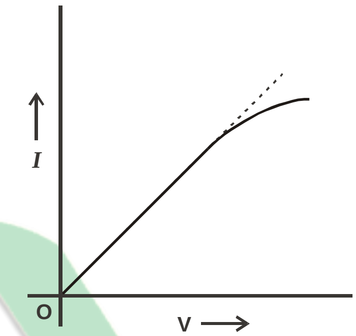
A conductor which strictly obeys ohm's law is called ohmic.

Example

Metals.

Non-ohmic

There are devices which do not obey ohm's law, are called non-ohmic devices.

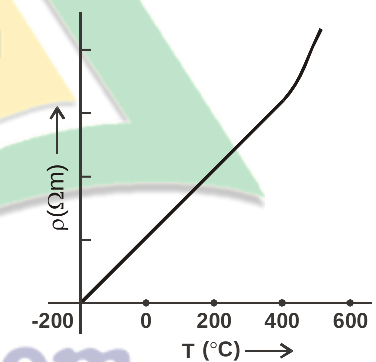


Example

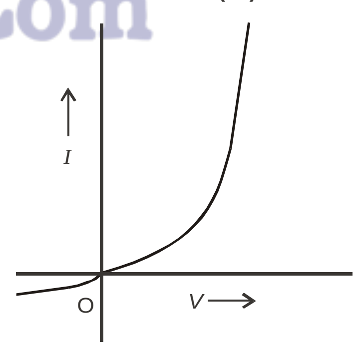
Filament of bulbs and semiconductor diodes are non-ohmic devices.

Explanation

Let us apply a certain potential difference across the terminals of filament lamp and measure the resulting current passing through it. If we repeat the measurement for different values of potential difference and draw a graph of voltage V versus current I, it will be seen that graph is not straight line. It means that filament is non-ohmic device. The deviation of V – I graph from straight line is due to the increase in the resistance of the filament with temperature.



As the current passing through a filament is increased from zero, the graph is straight line in the initial stage because change in the resistance of filament with temperature due to small current is not appreciable. As the current is further increased, the resistance due to rise in temperature is increased.

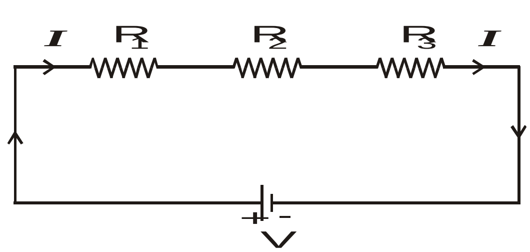


Another example of non semiconductor diode. The current-voltage graph of such a diode is shown in figure. As the graph is not straight line, so semi-conductor is also a non-ohmic device.

Review of Series and Parallel Combinations of Resistor

Series Combination of Resistance

If the resistors are connected end to end such that the same current passes through all of them, they are said to be connected in series as shown in figure.



$$V = V_1 + V_2 + V_3$$

According to ohm's law

$$IR_{eq} = I_1R_1 + I_2R_2 + I_3R_3$$

$$\therefore \quad I_1 = I_2 = I_3 = I$$

$$IR_{eq} = IR_1 + IR_2 + IR_3$$

$$IR_{eq} = I(R_1 + R_2 + R_3)$$

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

Characteristics of Series Combination

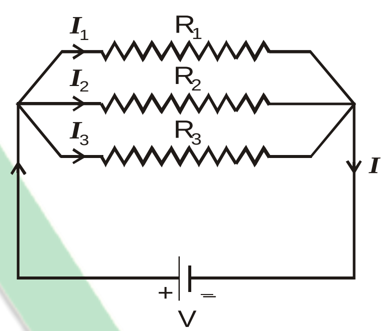
(i) Voltage across each resistance is different such that sum of voltages equal to applied voltage.

(ii) Current through all resistors are always same.

(iii) Equivalent resistance is always greater than the largest individual resistance.

Parallel Combination of Resistance

In parallel arrangement, a number of resistors are connected side by side with their ends joined together at two common points. From figure



$$I = I_1 + I_2 + I_3$$

From ohm's law

$$V = IR$$

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

$$I_1 = \frac{V}{R_1}, \quad I = \frac{V}{R_1}, \quad I_2 = \frac{V}{R_2}, \quad I_3 = \frac{V}{R_3}$$

So

$$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Characteristic of Parallel Combination

(i) Voltage across each resistance in parallel combination is same.

(ii) Current through each resistance is different such that sum of branch currents equals to current supplied by battery.

(iii) Equivalent resistance is smaller than the smallest individual resistance.

Q.7 Define resistivity and explain the dependence of resistance upon temperature.

Ans. RESISTIVITY AND ITS DEPENDENCE UPON TEMPERATURE

Resistivity

It has been experimentally seen that the resistance R of a wire is directly proportional to its length L and inversely proportional to its cross-sectional area A.

Mathematically

$$R \propto L \qquad \ldots\ldots \text{(i)}$$

$$R \propto \frac{1}{A} \qquad \ldots\ldots \text{(ii)}$$

Combining (i) and (ii)

$$R \propto \frac{L}{A}$$

$$R = \frac{\rho L}{A} \qquad \text{...... (iii)}$$

where ρ is a constant of proportionality known as resistivity of the material of wire. It is defined as the resistance of a meter cube of a conductor. It may be noted that resistance is the characteristic of a particular wire whereas the resitivity is the property of the material of the wire from which it is made.

Unit of Resistivity

$$\rho = \frac{RA}{L}$$

$$= \frac{\Omega m^2}{m}$$

$$\rho = \Omega m$$

So, SI unit of resistivity is "Ωm".

Conductance

Conductance is the reciprocal of resistance. i.e.,

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

SI unit of conductance ohm^{-1} (Mho) or Siemen.

Conductivity

Conductivity is the reciprocal of resistivity. i.e.,

$$\text{Conductivity} = \frac{1}{\text{Resistivity}}$$

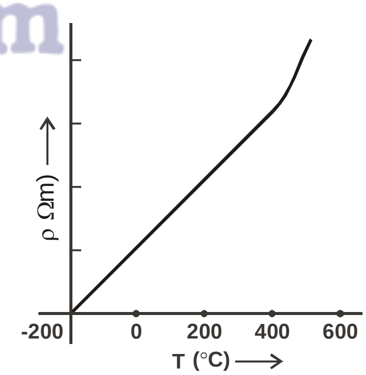
SI unit of conductivity is $ohm^{-1} . m^{-1}$ (mho m^{-1}).

TABLE		
Substance	**ρ (Ωm)**	**α (K^{-1})**
Silver	1.52×10^{-8}	0.00380
Copper	1.54×10^{-8}	0.00390
Gold	2.27×10^{-8}	0.00340
Aluminium	2.63×10^{-8}	0.00390
Tungsten	5.00×10^{-8}	0.00460
Iron	11.00×10^{-8}	0.00520
Platinum	11.00×10^{-8}	0.00520
Constenton	49.00×10^{-8}	0.00001
Mercury	94.00×10^{-8}	0.00091
Nichrome	100.0×10^{-8}	0.00020
Carbon	3.5×10^{-5}	–0.0005
Germanium	0.5	–0.05
Silicon	20-2300	–0.07

DEPENDENCE UPON TEMPERATURE

Resistance offered by a conductor is due to the collision of free electrons with the lattice atoms of metal. When temperature of the conductor increases then lattice atoms start vibrating with greater amplitude and this form a bigger target area for the flowing of free electrons. So the probability of the collisions of free electrons with the lattice atoms increases. This makes the collision between free electrons and the atoms more frequent and hence resistance of the conductor increases.

Conversely when temperature decreases then lattice atoms vibrate with smaller amplitude presenting smaller target area and this decreases the probability of collisions between the lattice atoms and free electrons. This makes collisions less frequent and hence resistance of the conductor increases.



Variation of resistivity of Cu with temperature.

Interesting Information

Inspectors can easily check the reliability of a concrete bridge made with carbon fibers. The fibers conduct electricity. If sensors show that electrical resistance is increasing over time the fibers are separating because of cracks.

Temperature Coefficient of Resistance

Definition

The fractional change in the resistance per kelvin temperature is known as temperature coefficient of resistance. It is represented by α.

Determination

Let R_o and R_t be the resistances at 0°C and t°C respectively. It is experimentally found that change in the resistance of a conductor is directly proportional to its original resistance. i.e.,

$$R_t - R_o \propto R_o \qquad \text{...... (i)}$$

Also the change in the resistance of a conductor is directly proportional to change in its temperature i.e.,

$$R_t - R_o \propto \Delta t \qquad \text{...... (ii)}$$

Combining (i) and (ii)

$$R_t - R_o \propto R_o\Delta t$$

$$R_t - R_o = \alpha R_o\Delta t$$

$$\alpha = \frac{R_t - R_o}{R_o\Delta t} \qquad \text{...... (iii)}$$

Where α is constant of proportionality named as temperature coefficient of resistance.

Also the resistivity is directly proportional to the resistance therefore eq. (iii) can be written as

$$\alpha = \frac{\rho_t - \rho_o}{\rho_o\Delta t}$$

where α is called the coefficient of resistivity. It may be defined the fractional change in the resistivity per kelvin temperature is called the temperature coefficient of resistivity.

Note: There are some substance like germanium, silicon etc., whose resistance decreases with increase in temperature. i.e., these substances have negative temperature coefficients.

Q.8 What are the colour code for carbon resistances?

Ans. **COLOUR CODE FOR CARBON RESISTANCES**

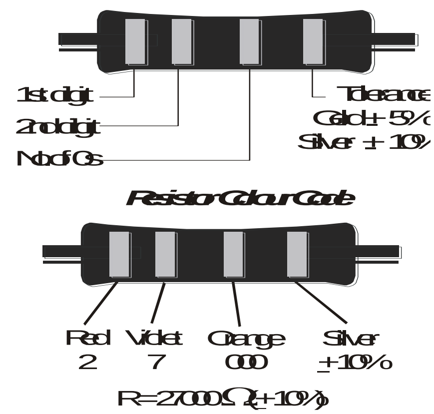
Carbon resistors are most common in electronic equipment. They consist of a high-grade ceramic rod or cone (called the substrate) on which is deposited a thin resistive film of carbon. The numerical value of their resistance is indicated by a colour code which consists of bands of different colours printed on the body of the resistor. The colour used in this code and the digits represented by them are given in table.

Table the Colour Code

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

Usually the code consists of four bands. Starting from left to right, the colour bands are interpreted as follows

(1) The first band 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 first two digits.

(4) The fourth band gives resistance tolerance. Its colour is either silver or gold. Silver band indicates a tolerance of ±10%, a gold band shows a tolerance of ±5%. If there is no fourth band, tolerance is understood to be +20%. **Tolerance means the possible variation from the marked value. For example**, a 1000Ω resistor with a tolerance of ±10% will have an actual resistance anywhere between 900Ω and 1100Ω.

Q.9 What is Rheostat? Also describe rheostat as:

(i) Variable resistor (ii) Potential divider

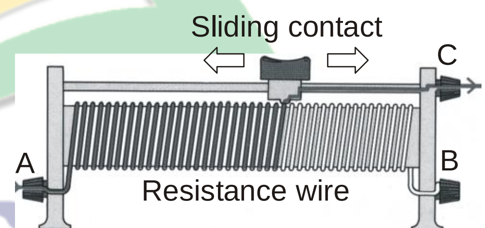
Ans. RHEOSTAT

It is a wire wound variable resistance. It consist of a bare manganin wire wound over an insulating cylinder. The ends of the wire are connected to two fixed terminals A and B. A third terminal C is attached to a sliding contact which can be moved over the wire at shown in figure (a).

A rheostat can be used as

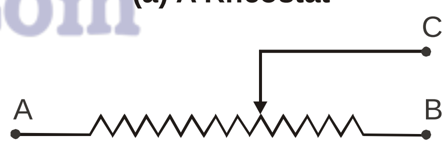
(i) Variable Resistor (ii) Potential Divider

(i) Rheostat as Variable Resistor



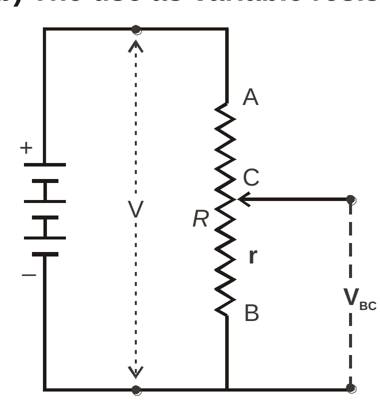
(a) A Rheostat

In order to use rheostat as a variable resistor, one of the fixed terminal say A and the sliding contact C are inserted in the circuit as shown in figure (b). In this way the resistance of the wire between A and C is used. If the sliding contact is shifted away from terminal A, the length and hence the resistance included in the circuit increases (because $R \propto L$) and if the sliding contact is moved towards A, the resistance decreases.



(b) The use as variable resistor

(ii) Rheostat as Potential Divider



Use of rheostat as potential divider

A potential difference V is applied across the fixed ends A and B with the help of the battery. If R is the resistance of the wire AB, the current passing through it is

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

The potential difference between the portion BC of the wire is given by

$$V_{BC} = Ir$$

Putting value of I

$$\therefore \quad V_{BC} = \frac{V}{R} r$$

$$V_{BC} = \frac{r}{R} V \quad \ldots\ldots \text{(i)}$$

where r is the resistance of the portion BC of the wire. The circuit shown in figure is known as potential divider. Eq. (i) shows that this circuit can provide at its output terminals a potential difference varying from zero to the full potential difference of the battery depending upon the position of the sliding contact. As the sliding contact C is moved towards B, the length and hence the resistance r of the portion of the wire decreases which decreases V_{BC}. If the sliding contact C is moved towards the end A, r increases hence V_{BC} increases.

Q.10 What is thermistors? How they made?

Ans. **THERMISTORS**

A thermistor is a heat sensitive resistor.

Most thermistors have negative temperature coefficient of resistance i.e., the resistance of such thermistor decreases when their temperature is increased. Thermistors with positive temperature coefficient are also available.

Thermistors are made by heating under high pressure semiconductor ceramic made from mixtures of metallic oxides of manganese, nickel, cobalt, copper, iron etc. These are pressed into desired shapes and then baked at high temperature. Different types of thermistors are shown in figure. They may be in the form of beads, rods or washers.

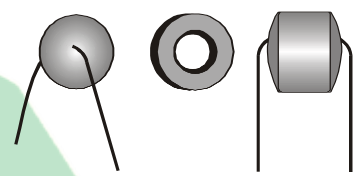


Fig Thermistors of different shapes

Interesting Information

A zero ohm resistor is indicated by a single black color band around the body of the resistor

Thermistors with high negative temperature coefficient are very accurate for measuring low temperature especially near 10 K (−263°C). The higher resistance at low temperature enables more accurate measurement possible.

Uses

(i) In fire alarms.

(ii) Thermistors with high negative temperature coefficient are very accurate for measuring low temperature especially near 10 kelvin.

(iii) Thermistors have wide range of application as temperature sensor i.e., they convert changes of temperature into electrical voltage which is duly processed.

Q.11 Describe electrical power and power dissipation in resistors.

Ans. **ELECTRICAL POWER AND POWER DISSIPATION IN RESISTORS**

Consider a circuit consisting of battery connected in series with R, as shown in fgure. A steady current I flows through the circuit and a potential difference V exists between the terminals A and B of resistance R. Terminal A connected to +ve pole of battery is at a higher potential than the terminal B.

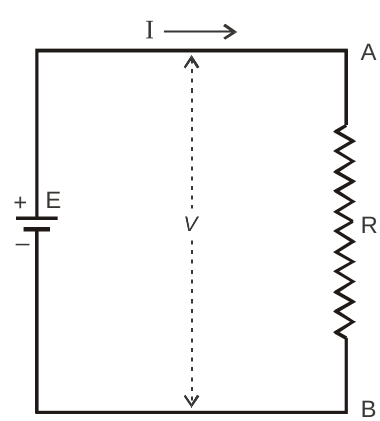


Fig. The power of a battery appears as the power dissipated in the resistor R.

By the definition of potential difference

$$V = \frac{\Delta W}{\Delta Q}$$

$$\text{Work done} = \Delta W = V\Delta Q$$

This is the work done supplied by the battery to move charge ΔQ from A to B.

Definition

"The rate at which the battery is supplying electrical energy is the electrical power of the battery" or power output i.e.,

As

$$\text{Electrical power} = \frac{\text{Electrical energy}}{\text{Time}}$$

$$P = \frac{V\Delta Q}{\Delta t}$$

$$P = V\left(\frac{\Delta Q}{\Delta t}\right)$$

$$\boxed{P = VI} \quad \ldots\ldots \text{(i)} \quad \left(\therefore\ I = \frac{\Delta Q}{\Delta t}\right)$$

In the circuit shown, the power supplied by the battery is dissipated in the resistor R. The principal of conservation of energy tells us that the power dissipated in the resistor is also VI.

$\therefore$ Power dissipated (P) = VI

From ohm's law

$$V = IR$$

Putting value of V in eq. (i), we get

$$P = IR \times I$$

$$\boxed{P = I^2R}$$

also from ohm's law

$$I = \underline{V}$$

Putting in eq. (i)

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

$$\boxed{P = \frac{V^2}{R}}$$

$$P = VI = I^2R = \frac{V^2}{R}$$

SI Unit

The SI unit of electrical power is watt.

Q.12 *Define electromotive force and terminal potential difference. Also describe its relation.*

Ans. **ELECTROMOTIVE FORCE (emf) AND TERMINAL POTENTIAL DIFFERENCE**

Suppose a steady current I has been established in the circuit, due to charge Δq passes through any cross section in time Δt. During motion, this charge enter the cell at its low potential end and leaves at high potential. The source must supply energy ΔW to the +ve charge to force it to go to the point of high potential.

The emf (E) of the source is defined as the energy supplied to a unit positive charge by the cell in moving from negative terminal to the positive terminal of the battery.

i.e., $$E = \frac{\Delta W}{\Delta q}$$

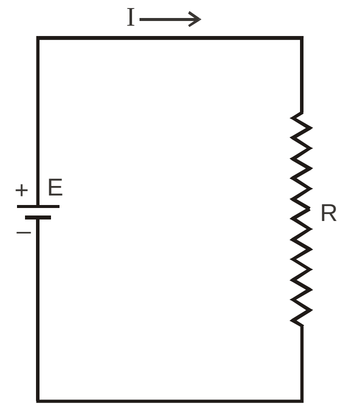


Fig. Electromotive force of a cell.

(OR)

It is the potential difference between the terminals of the battery when no current is flowing through an external circuit or when the circuit is open.

Terminal Potential Difference

The P.D between the two points in the circuit is the energy dissipated when one coulomb of charge flows from one point to another.

The electromotive force is not a force and do not measure in Newton.

Unit of emf

The unit of emf is joule/coulomb which is called volt.

Internal Resistance

The opposition offered by the electrolyte, present between the two electrodes of the cell to the flow of current is known as internal resistance 'r' of the cell. Internal resistance is due to the resistance of chemicals in the cells.

Fig. An equivalent circuit of a cell of emf E and internal resistance r.

A cell of emf E having an internal resistance r is equivalent to a source of pure emf E with r in series as shown in figure.

Relation between emf and Terminal Potential Difference

Consider a cell of emf E and internal resistance r as shown in figure. A voltmeter of infinite resistance measures the potential difference across the external resistance R.

When switch S is closed, the current I flowing through the circuit is given by

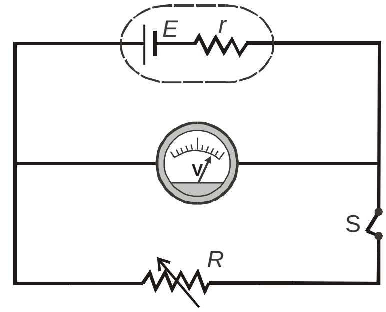


Fig. The terminal potential difference V of a cell is E – Ir.

$$I = \frac{E}{R + r}$$

$$E = I(R + r)$$

$$E = IR + Ir \qquad \ldots\ldots (i)$$

$$E = V_t + Ir$$

$$V_t = E - Ir$$

where V_t = IR is the terminal potential difference of the cell in the presence of current I.

When circuit is open then, I = 0. Therefore, voltmeter reads the emf E as terminal voltage when switch S is open. Thus terminal potential difference in the presence of current would be less than emf E by Ir.

Now we discuss eq. (i) on energy considerations. The left side of this equation is emf E which is equal to the energy gained by unit positive charge as it passes through the cell from its negative to positive terminal. The right side of this equation gives an account of the utilization of this energy as the current passes through the circuit. A part of this energy equal to Ir, is dissipated into the cell. The rest of the energy is dissipated into R which is in accordance with energy conservation.

(OR)

The emf gives the energy supplied to a unit charge by the cell and potential drop across various elements account for the dissipation of this energy into other forms as the unit charge passes through these element.

Also the emf is the "cause" and the potential difference is its "effect". The emf is always present even when no current is drawn through the battery or the cell but the potential difference across the conductor is zero when no current flows through it.

Condition for which emf (E) equal to terminal P.D V_t i.e.,

As $E = V_t - Ir$

$E = V_t$

If $I = 0$

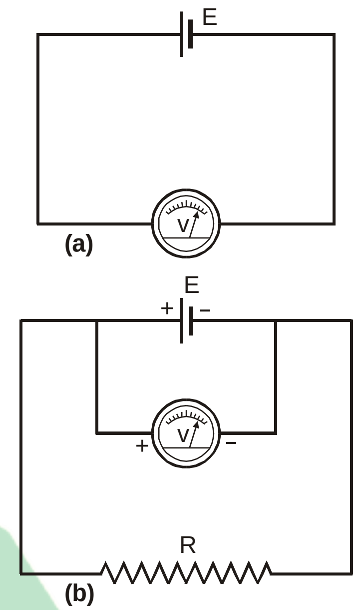
i.e., circuit is open.

Q.13 Calculate the maximum power output.

Ans. MAXIMUM POWER OUTPUT

In the circuit shown, as the current I flows through R, the charges flow from a point of higher potential to a point of lower potential and they loose potential energy. If V is the potential difference across R, the loss of P.E per second is VI. This loss of potential energy per second appears in other forms of energy and is known as **power delivered** to R by current I.

Do You Know?



A voltmeter connected across the terminals of a cell measures (a) the emf of the cell on open circuit, (b) the terminal potential difference on a closed circuit.

Power delivered to R = P_{out} = VI

$$P = I^2R$$

$$I = \frac{E}{R + r} \qquad (\therefore V = IR)$$

$$I = \frac{E^2R}{(R + r)^2}$$

$$P_{out} = \frac{E^2R}{R^2 + r^2 + 2Rr}$$

$$P_{out} = \frac{E^2R}{R^2 + r^2 - 2Rr + 4Rr}$$

$$= \frac{E^2R}{(R^2 + r^2 - 2Rr) + 4Rr}$$

$$= \frac{E^2R}{(R - r)^2 + 4Rr}$$

when R = r, the denominator is least and so P_{out} is maximum. Thus we see that maximum power is delivered to a resistance (load) when the internal resistance of the source equals the load resistance. The value of this maximum output power

$$P_{out} = \frac{E^2R}{4Rr}$$

$$P_{out} = \frac{E^2}{4R}$$

KIRCHHOFF'S RULE

Introduction

Ohm's law and rules of series and parallel combination of resistances are quite useful to analyze simple electrical circuits consisting of more than one resistance. However such a method fails in the case of complex networks consisting of a number of resistors, and a number of voltage sources. Problems of such networks can be solved by a system of analysis which is based upon two rules, known as Kirchhoff's rules.

Q.14 State and explain Kirchhoff's first rule.

Ans. KIRCHHOFF'S FIRST RULE

Statement

It states that "the sum of all the currents flowing towards a point is equal to the sum of all the currents flowing away from the point".

(OR)

"The sum of all the currents meeting at a point in the circuit is zero".

Mathematically

i.e., $\sum I = 0$ …… (i)

It is a convention that current flowing towards a point is taken as positive and that flowing away from the point is taken as negative.

Explanation

Consider a situation where four wires meet at a point A. The current flowing into the point A are I_1 and I_2. Currents flowing away from point A are I_3 and I_4. According to conventions I_1 and I_2 are +ve whereas I_3 and I_4 are –ve.

Apply eq. (i)

$$I_1 + I_2 + (-I_3) + (-I_4) = 0$$

or $$I_1 + I_2 = I_3 + I_4$$

Kirchhoff's 1st rule is also called as **Kirchhoff's point rule** is a manifestation of **law of conservation of charge**. If there is no sink and source of charge at the point, the total charge flowing towards the point must be equal to the total charge flowing away from the point.

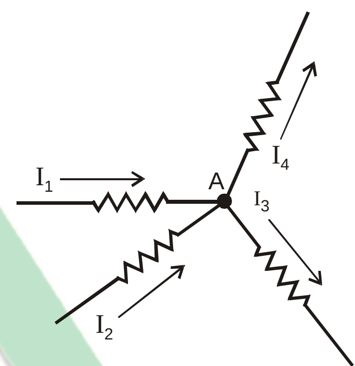


Fig. According to Kirchhoff's 1st rule $I_1 + I_2 = I_3 + I_4$.

Q.15 State and explain Kirchhoff's second rule.

Ans. **KIRCHHOFF'S SECOND RULE**

Statement

This rule states that the algebraic sum of potential changes for a closed loop (closed circuit) is zero.

Explanation

Consider a closed circuit as shown in figure. Let E_1 is greater than E_2, ($E_1 > E_2$) so the current flows in counter clockwise direction as shown in figure. By the definition of P.D

$$V = \frac{W}{\Delta Q}$$

$$W = V\Delta Q$$

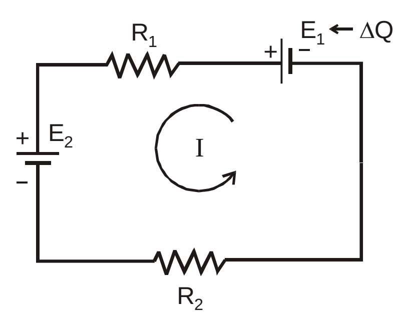


Fig. According to Kirchhoff's 2nd rule $E_1 - IR_1 - E_2 - IR_2 = 0$.

when a positive charge ΔQ due to current I, passes through cell E_1 from negative to positive terminal, it gains energy equal to $E_1\Delta Q$. When the current passes through the cell E_2, it looses energy equal to $-E_2\Delta Q$, because here the charge passes from high to low potential. In going through R_1, the charge ΔQ looses energy equal to $-IR_1\Delta Q$ where IR_1 is the potential difference across R_1. The negative sign shows that the charge is passing from high to low potential. Similarly the loss of energy while passing through R_2 is $-IR_2\Delta Q$. Finally the charge reaches the negative of cell E_1 from where we started. According to the **law of conservation of energy** the total change in energy of the system is zero.

$$\therefore \quad E_1\Delta Q - IR_1\Delta Q - E_2\Delta Q - IR_2\Delta Q = 0$$

$$\Delta Q(E_1 - IR_1 - E_2 - IR_2) = 0$$

Divide by ΔQ on both sides

So $$E_1 - IR_1 - E_2 - IR_2 = 0$$

which is Kirchhoff's second rule.

Note: This rule is simply a particular way of stating the law of conservation of energy in electrical problems.

Convention

- If a source of emf is traversed from –ve to positive terminal, the potential change is +ve, it is negative in opposite direction.
- If a resistor is transversed in the direction of current, the change in potential is negative, it is +ve in the opposite direction.

Procedure of Solution of Circuit Problems

After solving the above problem we are in a position to apply the same procedure to analyse other direct current complex networks. While using Kirchhoff's rules in other problems, it is worthwhile to follow the approach given below:

(i) Draw the circuit diagram.

(ii) The choice of loops should be such that each resistance is included at least once in the selected loops.

(iii) Assume a loop current in each loop, all the loop currents should be in the same sense. It may be either clockwise or anticlockwise.

(iv) Write the loop equations for all the selected loops. For writing each loop equation the voltage change across any component is positive if traversed from low to high potential and it is negative if traversed from high to low potential.

(v) Solve these equations for the unknown quantities.

Q.16 What is Wheatstone Bridge? Describe its construction and working.

Ans. **WHEATSTONE BRIDGE**

It is a device which is used to determine the unknown resistance of a material.

Construction

It consists of four resistances R_1, R_2, R_3 and R_4 connected in such a way so as to form a mash ABCDA. A battery is connected between points A and C. A sensitive galvanometer of resistance R_g is connected between points B and D.

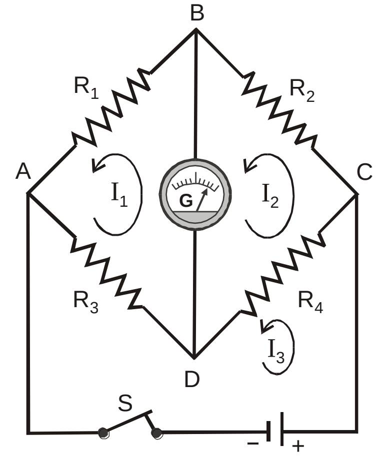


Fig. Wheatstone bridge circuit.

Working

If the switch S is closed, the current will flow through galvanometer. We are to determine the condition under which no current flows through the galvanometer even after the switch is closed. For this purpose we analysis this circuit using Kirchhoff's 2nd rule. We consider the loops ADBA, DCBD and CDAC and assume anticlockwise loop currents I_1, I_2 and I_3 through the loops respectively.

The Kirchhoff's 2nd rule applied to loop ADBA gives

$$-(I_1 - I_3)R_3 - (I_1 - I_2)R_g - I_1R_1 = 0 \quad \text{...... (i)}$$

Similarly applying Kirchhoff's 2nd rule to loop DCBD

$$-(I_2 - I_3)R_4 - I_2R_2 - (I_2 - I_1)R_g = 0 \quad \text{...... (ii)}$$

The current flowing through galvanometer is 0 if,

$$I_1 - I_2 = 0 \quad \text{or} \quad I_2 - I_1 = 0$$

$$\therefore \quad I_1 = I_2 \qquad I_2 = I_1$$

Putting this in eq. (i) and (ii) we get

$$-(I_1 - I_3)R_3 - I_1R_1 = 0 \quad \text{...... (iii)}$$

$$-(I_2 - I_3)R_4 - I_2R_2 = 0 \quad \text{...... (iv)}$$

$$-I_1R_1 = (I_1 - I_3)R_3 \quad \text{...... (v)}$$

$$-I_2R_2 = (I_2 - I_3)R_4 \quad \text{...... (vi)}$$

Dividing (v) by (vi)

$$\frac{-I_1R_1}{-I_2R_2} = \frac{(I_1 - I_3)R_3}{(I - I)R}$$

$$\frac{I_1R_1}{I_2R_2} = \frac{(I_1 - I_3)R_3}{(I_2 - I_3)R_4}$$

Since $I_1 = I_2$

$$\frac{I_1R_1}{I_1R_2} = \frac{(I_1 - I_3)R_3}{(I_1 - I_3)R_4}$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{...... (A)}$$

Thus whenever the condition of eq. (A) is satisfied, no current flows through galvanometer i.e., it shows no deflection or conversely when galvanometer shows no deflection, eq. (A) is satisfied. If we connect three resistances R_1, R_2 and R_3 of known value and a fourth resistance R_4 of unknown value and R_1, R_2 and R_3 are so adjusted that galvanometer shows no deflection then using eq. (A), R_4 can be determined.

Q.17 Describe potentiometer with its uses.

Ans. POTENTIOMETER

Introduction

Potential difference is usually measured by an instrument called a voltmeter. The voltmeter is connected across the two points in a circuit between which potential difference is to be measured. It is necessary that the resistance of the voltmeter must be large as compare to the circuit resistance across which the voltmeter is connected. Otherwise an appreciable current will flow through the voltmeter which will alter the circuit current and the potential difference to be measured. Thus the voltmeter can read the correct potential difference only when it does not draw any current from the circuit across which it is connected. An ideal voltmeter would have an infinite resistance.

However, there are some potential measuring instruments such as digital voltmeter and cathode ray oscilloscope which practically do not draw any current from the circuit because of their large resistance and are very accurate potential measuring instruments. But these instruments are very expensive and are difficult to use. A very simple instrument which can measure and compare potential differences accurately is a potentiometer.

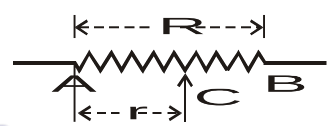
Definition

A very simple electrical instrument which can measure and compare potential differences without drawing any current from the circuit is called potentiometer.

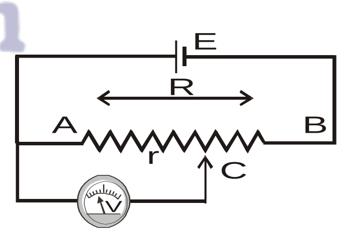
Principle

The potential difference across any wire of length L and uniform area of cross section A, is directly proportional to its length when constant current flows through it.

$$\therefore \quad E \propto L$$



A potentiometer is consist of a resistor R in the form of a wire, on which a terminal C can slide shown in figure.



Function

(i) As Potential Divider

The resistance between A and C can be varied from zero to R as the sliding contact C is moved from A to B. If a battery of emf E is connected across R. The current flowing through it is

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

If the resistance between A and C is r, the potential drop across these points will be

$$V_{AC} = Ir$$

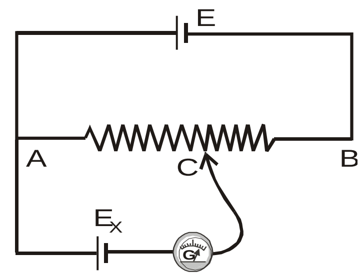
Putting the value of I, we get

$$V_{AC} = \frac{E}{R} r$$

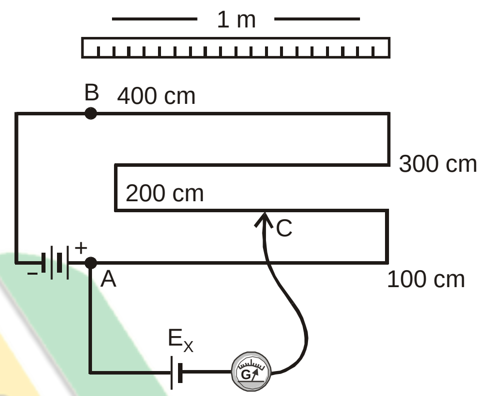
$$V_{AC} = \frac{r}{R} E$$

Hence as C is moved from A to B, r varies from 0 to R and V_{AC} changes from O to E.

(ii) To Measure Unknown emf of a Cell



To measure the unknown emf of a source by using a circuit shown in figure. Here R is in the form of a straight wire of uniform area of cross-section A. A cell whose emf E_x is to be measured is connected between A and C through a galvanometer G. It should be noted that +ve terminal of E_x and that of the potential divider are connected to the same point A. If in the loop AGCA, the point C and the –ve terminal of E_x are at the same potential then the two terminals of the galvanometer will be at same potential and no current will flow through the galvanometer. Therefore to measure the potential E_x, the position of C is so adjusted that the galvanometer shows no deflection. Under this condition $E_x = \frac{r}{R}E$.



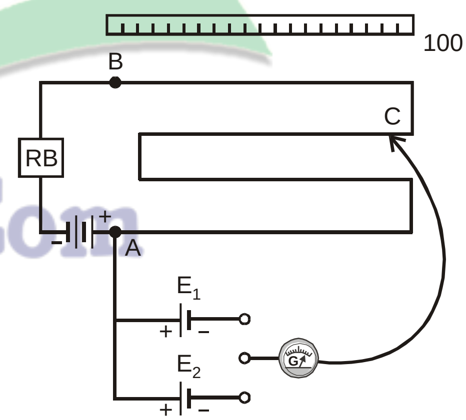
If L, is total length from A to B and '*l*' is length of wire between AC.

Therefore unknown emf is given by

$$E_x = \frac{l}{L}E$$

It can be seen that the unknown emf E_x is determined when no current is drawn from it and therefore, potentiometer is one of the most accurate methods for measuring potential.

To Compare the emf of Two Cells



To compare the emfs E_1 and E_2 of two cells we use the circuit diagram as shown. the balancing lengths l_1 and l_2 are found separately for the two cells, then

$$E_1 = \frac{l_1}{L}E \quad \text{...... (i)}$$

$$E_2 = \frac{l_2}{L}E \quad \text{...... (ii)}$$

Dividing (i) by (ii)

$$\frac{E_1}{E_2} \quad \frac{l\ E/L}{l_2E/L}$$

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

So the ratio of the emfs is equal to the ratio of the balancing lengths.

SOLVED EXAMPLES

EXAMPLE 13.1

1.0×10^7 electrons pass through a conductor in 1.0 μs. Find the current in ampere flowing through the conductor. Electronic charge is 1.6×10^{-19} C.

Data

Number of electrons = N = 1.0×10^7

Time = Δt = 1.0 μs = 1.0×10^{-6} C

Charge = q = 1.6×10^{-19} C

To Find

Current = I = ?

SOLUTION

By formula

$$I = \frac{\Delta Q}{\Delta t}$$

But $\Delta Q = N \times q$

$$= 1.0 \times 10^7 \times 1.6 \times 10^{-19}$$

$$= 1.6 \times 10^{-12}\ C$$

So $I = \frac{1.6 \times 10^{-12}}{1.0 \times 10^{-6}}$

$$= 1.6 \times 10^{-6}\ A$$

Result

Current = I = 1.6×10^{-6} A

EXAMPLE 13.2

0.75 A current flows through an iron wire when a battery of 1.5 V is connected across its ends. The length of the wire is 5.0 m and its cross sectional area is 2.5×10^{-7} m^2. Compute the resistivity of iron.

Data

Current = I = 0.75 A

Potential difference = V = 1.5 V

Length of wire = L = 5.0 m

Area of wire = A = 2.5×10^{-7} m^2

To Find

Resitivity of iron = ρ = ?

SOLUTION

By formula

$$R = \rho \frac{L}{A}$$

$$\rho = \frac{R \times A}{L} \qquad \ldots\ldots \text{(i)}$$

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

$$= \frac{1.5}{0.75} = 2.0\ \Omega$$

So $\rho = \frac{2.0 \times 2.5 \times 10^{-7}}{5.0}$

$$\rho = 1.0 \times 10^{-7}\ \Omega.m$$

Result

Resitivity = $\rho = 1.0 \times 10^{-7}\ \Omega.m$

EXAMPLE 13.3

A platinum wire has resistance of 10 Ω at 0°C and 20 Ω at 273°C. Find the value of temperature coefficient of resistance of platinum.

Data

Resistance at 0°C = R_o = 10 Ω

Resistance at 273°C = R_t = 20 Ω

Temperature = t_o = 0°C + 273

= 273 K

Temperature = t = 273°C + 273

= 546 K

Difference = $t - t_o$ = 546 – 273

= 273 K

To Find

Temperature coefficient = α = ?

SOLUTION

By formula

$$\alpha = \frac{R_t - R_o}{R_o t}$$

$$= \frac{20 - 10}{10 \times 273}$$

$$= \frac{1}{273\text{ K}}$$

$$= 3.66 \times 10^{-3}\text{ K}^{-1}$$

Result

Temperature coefficient $= \alpha = 3.66 \times 10^{-3}\text{ K}^{-1}$

EXAMPLE 13.4

The potential difference between the terminals of a battery in open circuit is 2.2 V. When it is connected across a resistance of 5.0 Ω, the potential falls to 1.8 V. Calculate the current and the internal resistance of the battery.

Data

Voltage $= E = 2.2$ volt

Resistance $= R = 5.0\ \Omega$

Potential difference $= V = 1.8$ V

To Find

Current $= I = ?$

Internal resistance $= r = ?$

SOLUTION

For current

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

$$= \frac{1.8}{5.0}$$

$$= 0.36\text{ A}$$

For internal resistance

$$E = V + Ir$$

$$E - V = Ir$$

$$r = \frac{E - V}{I}$$

$$= \frac{2.2 - 1.8}{0.36}$$

$$= 1.11\ \Omega$$

Result

Current $= I = 0.36$ A

Internal resistance $= r = 1.11\ \Omega$

EXAMPLE 13.5

Calculate the currents in the three resistances of the circuit shown in figure.

Data

The given resistance are

$R_1 = 10\,\Omega \quad , \quad R_2 = 30\,\Omega$

$R_3 = 15\,\Omega$

and voltages are

$E_1 = 40\text{ V} \quad , \quad E_2 = 60\text{ V}$

$E_3 = 50\text{ V}$

To Find

Current from $R_1 = I_1 = ?$

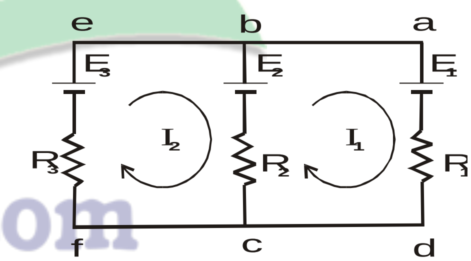
Current from $R_2 = I_2 = ?$

Current from $R_3 = I_3 = ?$

SOLUTION

By formula

Now applying the Kirchhoff's 2^{nd} rule on the loop adcba



$$-E_1 - I_1R_1 - (I_1 - I_2)R_2 + E_2 = 0$$

$$-40 - I_1 \times 10 - (I_1 - I_2) \times 30 + 60 = 0$$

$$-40 - 10I_1 - 30I_1 + 30I_2 + 60 = 0$$

$$20 - 40I_1 + 30I_2 = 0$$

$$2 - 4I_1 + 3I_2 = 0 \quad \ldots\ldots \text{(i)}$$

cfeb

Applying Kirchoof's 2^{nd}

$$-E_2 - (I_2 - I_1)R_2 - I_2R_3 + E_3 = 0$$

$$-60 - (I_2 - I_1) \times 30 - I_2 \times 15 + 50 = 0$$

$$-60 - 30I_2 + 30I_1 - 15I_2 + 50 = 0$$

$$-10 - 45I_2 + 30I_1 = 0$$

Divide by 5

$$-2 - 9I_2 + 6I_1 = 0 \quad \ldots\ldots \text{(ii)}$$

Multiply eq. (i) by 3 and add in (ii)

$$-2 - 9I_1 + 6I_1 = 0$$

$$6 - 12I_1 + 9I_2 = 0$$

$$6I_1 = 4$$

$$I_1 = \frac{4}{6}$$

$$I_1 = \frac{2}{3}\text{ A} = 0.66\text{ A}$$

Put in eq. (ii) for I_2

$$-2 - 9 \times I_2 + 6 \times \frac{2}{3} = 0$$

$$-2 - 9I_2 + 4 = 0$$

$$2 - 9I_2 = 0$$

$$2 = 9I_2$$

$$\boxed{I_2 = \frac{2}{9}} = 0.22\text{ A}$$

So the current from R_1 $= I_1 = \frac{2}{3} = 0.66$ A

Current from R_2 $= I_1 - I_2 = 0.66 - 0.22$

$= 0.44$ A

Current from R_3 $= I_2 = 0.22$ A

Result

Current from R_1 $= I_1 = 0.66$ A

Current from R_2 $= I_2 = 0.44$ A

Current from R_3 $= I_3 = 0.22$ A