

CHAPTER 18

CURRENT ELECTRICITY

Chapter Objectives

Electric current, flow of electric charges in a metallic conductor, drift velocity, mobility and their relation with electric current; Ohm's law, electrical resistance, V-I characteristics (linear and non-linear), electrical energy and power, electrical resistivity and conductivity, Carbon resistors, colour code for carbon resistors; series and parallel combinations of resistors; temperature dependence of resistance.

Internal resistance of a cell, potential difference and emf of a cell, combination of cells in series and in parallel, Kirchhoff's laws and simple applications, Wheatstone bridge, metre bridge.

Potentiometer - principle and its applications to measure potential difference and for comparing EMF of two cells; measurement of internal resistance of a cell.

STUDY MATERIAL

Concept Clarified

➤ Electric Current :

Flow of charge in a definite direction can be defined as electric current and the time rate of flow of charge through any cross section of a conductor is the measure of current.

$$\text{Electric Current, } I = \frac{\text{Net Charge Flown}}{\text{Time taken}} = \frac{q}{t} = \frac{dq}{dt}$$

- (a) It represents the direction of flow of positive charge.
- (b) It is a Scalar Quantity hence follows Law of Scalar Addition.

Note : The Angle between the current carrying wires does not affect the total current of the circuit.

➤ Current Carriers

(a) Current Carriers in Solid Conductors :

Valence Electrons are the usual current carriers in solids. For Example : In case of metals *i.e.*, Solid Conductor valence electron of atom do not remain attached to the individual atoms and remain free to move throughout the space (volume of the conductor). This valence electron activates because of an external electric field due to which valence electron move in a definite direction causing electric current in the conductor.

(b) Current Carriers in Liquid

Positively and negatively charged ions are the current carriers in liquids. For Example : In case of Electrolytes like CuSO_4 , NaCl etc., there exist positively and negatively charged ions (Cu^{++} , SO_4^-). These ions are forced to move in a definite direction under the effect of an external electric field causing electric current.

(c) Current Carriers in Gases

Usually Gases are insulators but can be ionized by application of high potential difference at low pressure. Positive Ions and Electrons currents carriers in Gases.

➤ Drift Velocity :

"Drift velocity can be defined as average velocity with which the free electrons get drifted towards the positive end of the conductor under the influence of an external electric field applied." Drift Velocity of an electron is of the order 10^{-4} m/s.

If $\vec{u}_1, \vec{u}_2, \vec{u}_3, \vec{u}_4, \vec{u}_5 \dots \vec{u}_n$ are the random velocities of n free electrons in metal conductor, then the average thermal velocity of electron is

$$\frac{\vec{u}_1 + \vec{u}_2 + \vec{u}_3 + \vec{u}_4 + \vec{u}_5 + \dots + \vec{u}_n}{n} = \vec{0}$$

Note : There will be no current as a result of no net flow of electrons or charge in one direction.

$$E = \frac{\text{Potential Difference}}{\text{Length}} = \frac{V}{l}$$

1. Each electron in the conductor experience a force : $\vec{F} = -e\vec{E}$

2. Each electron is accelerated with $\vec{a} = \frac{e\vec{E}}{m}$

3. Instant velocity of an electron having thermal velocity \vec{u}_1 will be

$$\vec{v}_1 = \vec{u}_1 + a\tau_1 \quad (\text{Here } \tau_1 - \text{elapsed time as it suffers collision with atoms of conductor})$$

4. The average velocity of all free electrons in conductor under the effect of external field is drift velocity \vec{v}_d of free electron.

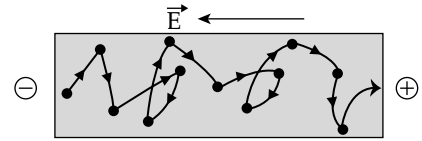
5. Hence,
$$v_d = \frac{\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + \vec{v}_4 + \vec{v}_5 + \dots + \vec{v}_n}{n} = \frac{(\vec{u}_1 + a\tau_1) + (\vec{u}_2 + a\tau_2) + (\vec{u}_3 + a\tau_3) + (\vec{u}_4 + a\tau_4) \dots + (\vec{u}_n + a\tau_n)}{n}$$

$$\Rightarrow \left(\frac{\vec{u}_1 + \vec{u}_2 + \vec{u}_3 + \vec{u}_4 + \vec{u}_5 + \dots + \vec{u}_n}{n} \right) + \vec{a} \frac{(\tau_1 + \tau_2 + \tau_3 + \tau_4 \dots + \tau_n)}{n} = 0 + \vec{a}\tau = \vec{a}\tau$$

Here $\tau = \frac{(\tau_1 + \tau_2 + \tau_3 + \tau_4 \dots + \tau_n)}{n}$, it is defined as the time elapsed since each electron suffered last collision with atom of conductor and is called average relaxation time. Value varies from 10^{-14} s. We get, $\vec{v}_d = \frac{-e\vec{E}\tau}{m}$

$$\Rightarrow \text{Average Drift Speed } \vec{v}_d = \frac{e\vec{E}\tau}{m}$$

**Here negative sign indicates that the direction of \vec{v}_d & \vec{E} is opposite.



➤ **Relaxation Time :**

Relaxation time is the time between two successive collision of electrons with positive ions in metallic lattice.

$$\tau = \frac{\text{Mean Free Path}}{\text{rms velocity of electrons}} = \frac{\lambda}{v_{\text{rms}}}$$

Note : Increase in temperature will increase the v_{rms} which result in decrement of τ .

There exists a direct proportional relation of τ and λ , both increases interdependently.

Mobility :

Mobility of Electron defines the Drift velocity per unit electric field. SI unit is $\text{m}^2/\text{volt-s}$

Mathematically,
$$\mu = \frac{v_d}{E}$$

- If Cross section is constant, $I \propto J$ i.e., for the given cross-sectional area, along with direct proportionality between current density and current.
- Drift velocity of electron is diminished as a result of frequent collision suffered by electrons.
- The small value of drift velocity produces a large amount of electric current due to presence of high number of free electrons in conductor. Current propagates at speed of light i.e., Electromagnetic process. Electric bulb glows suddenly and fan start movement suddenly when switch is ON due to this effect only.
- The path of electrons between successive collisions are straight line in the absence of electric field and path remain curved in case of presence of electric field.
- Free electron density in a metal is given by, $n = \frac{N_A x d}{A}$

(Here N_A = Avogadro Number, x = number of free electrons, d = density of metal, A = Atomic weight)

Mobility of Charge carriers (μ) the magnitude of the drift velocity of charge per unit electric field applied. Mathematically,

$$\mu = \frac{\text{Drift Velocity}}{\text{Electric Field}} = \frac{v_d}{E} = \frac{qE\tau / m}{E} = q\tau / m$$

Mobility of Electron : $\mu_e = q\tau_e / m_e$

Net current is the sum of the net current carried by positive and negative charge carriers. Mathematically,

$$v_d = \mu_e E$$

Relation between Current and Drift Velocity :

Let there be a conductor of length l and uniform cross section A , Volume of conductor = Al . If n is the number of free electrons per unit volume, then total number of free electrons = Aln

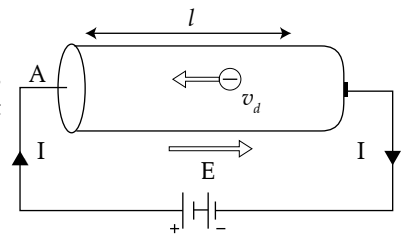
Then net charge of all electrons in conductor, $q = Alne$

Net electric field set up across the conductor is given by $E = V/l$. Due to this field, the free electron will start moving with a drift velocity v_d towards left hand side.

Time taken by free electron to cross the conductor, $t = l/v_d$

Hence current, $dI = \frac{q}{t} = \frac{Alne}{t = l/v_d} = I = Anev_d$

Putting value of $v_d = eE\tau / m$, we have $I = \frac{Ane^2E\tau}{m}$



➤ **Ohm's Law**

It states that "Current flowing through a conductor is directly proportional to the potential difference (V) across its ends provided all physical condition are remain same".

$I \propto V$ or $V = RI$ or $V/I = R = \text{Constant}$

Deduction of Ohm's Law

We know that, $v_d = \frac{eE}{m}\tau$ but $E = V/l$ hence $v_d = \frac{eV}{ml}\tau$

Also, $I = Anev_d$ and $I = Ane\left(\frac{eV}{ml}\tau\right) = \left(\frac{Ane^2\tau}{ml}\right)V$

$\Rightarrow \frac{V}{I} = \frac{ml}{Ane^2\tau} = R = a$ constant i.e., known as Resistance.

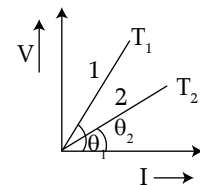
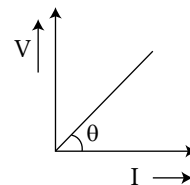
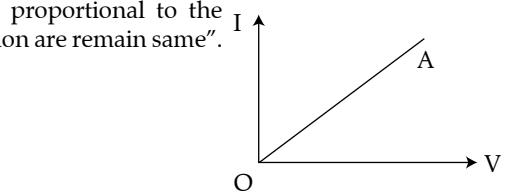
This is $V = IR$ (This is called Ohm's Law).

- Ohm's Law is not a Universal law and those substance obey Ohm's Law are called Ohmic substance. Graphic between V & I for a metallic conductor is a straight-line V & I curve are different.

- Non-Ohmic or Non-linear substance conductors are those device and substance which don't obey ohm's law e.g. Gases, Crystal rectifiers etc.

Static Resistance, $R_{st} = \frac{V}{i} = \frac{1}{\tan\theta}$

Dynamic Resistance $R_{dyn} = \frac{\Delta V}{\Delta I} = \frac{1}{\tan\phi}$

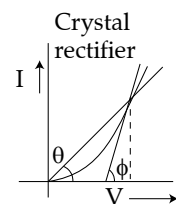


(A) Slope of the line

(B) Here $\tan\theta_1 > \tan\theta_2$

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

So, $R_1 > R_2$ i.e., $T_1 > T_2$



➤ **Electrical Resistance :**

The obstacle posed by the conductor to the flow of electric current is called the Electrical Resistance. Measured in Ohm or Volt/ampere.

Dimensions : Pot. Diff. / Current = $\frac{ML^2T^{-2}/AT}{A} = [M^1L^2T^{-3}A^{-2}]$

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

Resistance of a conductor depends on :

- (a) **Length (l) :** Resistance shows a directly proportional relation with Length. i.e., $R \propto l$
- (b) **Area of Cross-Section (A) :** Resistance shows an inversely proportional relation with Area of Cross Section i.e., $R \propto 1/A$
- (c) Resistance also shows dependency on the nature of material and temperature of the conductor.

$R \propto \frac{l}{A}$ or $R = \frac{\rho l}{A}$

➤ **Resistivity (ρ) :**

Resistivity ρ is constant of proportionality and defines the Specific Resistance or Electrical Resistivity of that conductor. It is defined as the resistance of a unit length with unit area of the material of conductor.

Unit – Ohm/m and Dimension $[ML^3T^{-3}A^{-2}]$. Mathematically $\rightarrow \rho = \frac{m}{ne^2\tau}$

It is intrinsic in nature and Independent of shape and size of the body.

Example : $\rho_{\text{silver}}(\text{minimum}) = 1.6 \times 10^{-8} \Omega\text{m}$ and $\rho_{\text{fused quartz}}(\text{max}) = 10^{16} \Omega\text{m}$

$$\rho_{\text{insulator}} \propto \rho_{\text{alloy}} \propto \rho_{\text{semi-conductor}} \propto \rho_{\text{conductor}}$$

- It depends on temperature *i.e.*, $\rho_i = \rho_0(1 + a\Delta t)$ resistivity increase with temperature.
- Impurity and Mechanical Stress also increases resistivity.
- It increases with magnetic field for all metal except iron, cobalt and nickel.
- Resistivity also shows a inverse proportionality with Intensity of light for certain material like Selenium, cadmium, sulphides etc.

We have, $R = \frac{V}{I} = \frac{ml}{Ane^2\tau} = \frac{m}{ne^2\tau} \times \frac{l}{A}$, comparing the above relation we get $\rho = \frac{m}{ne^2\tau}$

➤ **Conductivity :**

Reciprocal of Resistivity is called Conductivity (σ) *i.e.*, $\sigma = 1/\rho$. Unit – mho/m and dimensions $[M^{-1}L^{-3}T^3A^2]$

Conductance

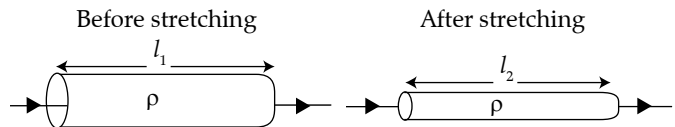
Reciprocal of Resistance is called Conductance $C = 1/R$. Unit $-1/\Omega$ or Ω^{-1} or Siemen.

Concept of Wire Stretching

If a conductor is stretched along its length, length increases, and area of cross section decreases as a result resistance increases but the net volume remain constant.

Let the initial Resistance be : $R_1 = \rho \frac{l_1}{A_1}$

Volume remain constant *i.e.*, $A_1 l_1 = A_2 l_2$



After Stretching, New Volume = $A_2 l_2$ and Resistance = $R_2 = \rho \frac{l_2}{A_2}$

Ratio of resistance, $\frac{R_1}{R_2} = \frac{l_1}{l_2} \times \frac{A_2}{A_1} = \left(\frac{l_1}{l_2}\right)^2 = \left(\frac{A_2}{A_1}\right)^2 = \left(\frac{r_2}{r_1}\right)^4 = \left(\frac{d_2}{d_1}\right)^4$

(i) If length is given, then $R \propto l^2$ and $\frac{R_1}{R_2} = \left(\frac{l_1}{l_2}\right)^2$

(ii) If radius is given, then $R \propto 1/r^4$ and $\frac{R_1}{R_2} = \left(\frac{r_2}{r_1}\right)^4$

Relation between Current Density, Conductance and Electrical Conductivity

We know : $I = nAev_d = nAe \left(\frac{eE}{m} \tau \right) = \frac{nAe^2 E \tau}{m} = \frac{I}{A} = \frac{ne^2 E \tau}{m}$ or $J = \frac{1}{\rho} E = \sigma E$

Here, I - current, E - Magnitude of electric field, J - current density, σ - conductivity, A - area, l - length, ρ = resistivity,

Types of material (based on current carrying capacity) :

- Insulator :** Material with zero or infinitesimal electric conductivity. Example : Wood, Rubber etc.
- Conductors :** Material with high electric conductivity. When a small potential difference is applied across two ends and a strong current flow through the conductor.
- Super Conductor :** Material with infinite electric conductivity.
- Semiconductor :** Material with electrical conductivity value between insulator and conductor.

Semiconductors can conduct electricity but not very easily, low current arises as the result of potential difference created across conductors. Motion of electrons and holes are the reason behind the electric conduction in semiconductors.

In Semiconductors, Resistance increases with increase in temperature.

$$\alpha = \frac{R_t - R_0}{R_0 \times t} = \frac{\text{Increase in resistance}}{\text{Original Resistance} \times \text{Rise in Temp.}}$$

Temperature Coefficient of Resistance is the increment in resistance per unit original resistance of a metal that increases with rise in temperature. Unit is K^{-1} or $^{\circ}C^{-1}$.

(a) **For Metals** : Direct Proportionality can be seen, value of α is positive.

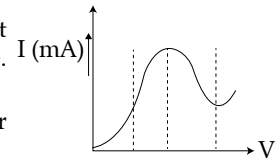
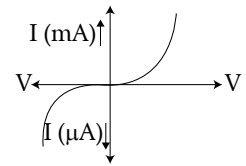
(b) **For Insulators and Semiconductor** : Usually, value of α is negative, hence resistance decreases with rise in temperature.

Non Ohmic Device

Device which do not obey Ohm's law is called Non Ohmic Device. **Example** : Vacuum Tube, semiconductor etc. Non ohmic devices show changing trends when plotted in VI graph, characteristics are as follows :

(a) The relation between V and I depend on sign of V. It means that if I is the current at a certain value of V and then reverse the direction of V keeping the magnitude same. The current produced will not have magnitude I but in opposite direction.

(b) The relation between V and I is not unique, there is more than one value of V for same value of I



Colour Code for Carbon Resistors

Colour	Letter as an Aid	Number	Multiplier	Colour	Tolerance
Black	B	0	10^0	Golden	5%
Brown	B	1	10^1	Silver	10%
Red	R	2	10^2	No Colour	20%
Orange	O	3	10^3		
Yellow	Y	4	10^4		
Green	G	5	10^5		
Blue	B	6	10^6		
Violet	V	7	10^7		
Grey	G	8	10^8		
White	W	9	10^9		

Colour coding can be remembered for the carbon resistor using a simple sentence :

"BB ROY Green Britain Very Good Wife Gold Silver"

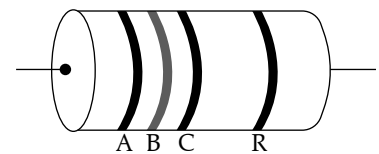
In the system of colour coding, strips of different colours are given on the body of the resistor. The colours are noted from left to right.

(a) First strip A colour shows the first significant of resistance in ohm.

(b) Second Strip B colour shows the second figure of resistance in ohm

(c) Colour of the third strip C indicates multiplier *i.e.*, the number of zeros will follow two significant figures.

(d) Fourth Strip R indicates the tolerance limit of the resistance value of percentage accuracy of resistance.



Combination of Resistors

I. Resistances in Series

In case of Series Combination of Resistances, it should be noted that :

(a) Current entering each resistor is same.

(b) Relative Position of Resistor doesn't have any effect on Current in circuit.

(c) $V \propto R$

(d) Net Value of Resistance = Sum of individual resistances used in combination.

(e) R_s (Net Resistance) > Resistance having highest magnitude

II. Resistances in Parallel

In case of Parallel Combination of Resistances, it should be noted that :

(a) Potential difference across each resistor is same across the system.

(b) $I \propto 1/R$.

(c) Net current in system is sum of net current flowing through the resistors.

(d) $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

➤ **Cells :**

Cell can be defined as the device which converts chemical energy into electrical energy is known as Electrical Cell. Cell is a source of constant emf (not constant current).

I. EMF of Cell (E) : EMF is defined as the potential difference across the terminal of the cell while not supplying any current.

II. Potential Difference : Potential difference across terminal of a cell when it is supplying current to external resistance or terminal voltage. It is equal to the product of current and resistance *i.e.*,

$$V = IR$$

III. Internal Resistance : The opposition of electrolyte to the flow of current through it is called Internal Resistance. The internal resistance of a cell depends on :

- (a) The distance between electrodes ($r \propto d$)
- (b) The area of electrode ($r \propto 1/A$)
- (c) Nature, Concentration ($r \propto C$)
- (d) Temperature of Electrolyte ($r \propto 1/\text{temp}$)

Note : A cell is said to be ideal, if it has zero internal resistance.

Cell in various positions :

1. Closed Circuit : Constant Current is supplied in the circuit by cell. Current in cell is given by $i = \frac{E}{r + R}$

- (i) Potential difference across the resistance, $V = iR$,
- (ii) potential drop inside the cell = ir
- (iii) Equation of cell, $E = V + ir$ ($E > V$),
- (iv) Internal resistance of the cell, $r = \left(\frac{E}{V} - 1\right)R$

(v) Power dissipated in external resistance, $P = Vi = i^2R = \frac{V^2}{R} = \left(\frac{E}{R+r}\right)^2 R$

Maximises when, $R = r$ So, $P_{max} = \frac{E^2}{4r}$

Maximum Power transfer theorem :

Statement - "To obtain maximum external power from a source with a finite internal resistance, the resistance of the load must equal the resistance of the source as viewed from its output."

Statement is also known as "Maximum Power Transfer Theorem".

If cell is continuously charged, then $E = V + ir$ and $E < V$

2. Open Circuit : When no current is supplied from the cell. Current through the circuit is given by :

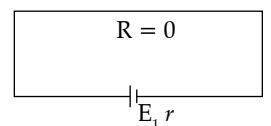
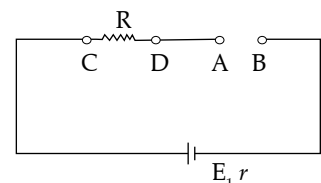
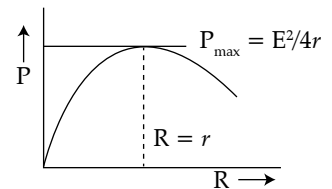
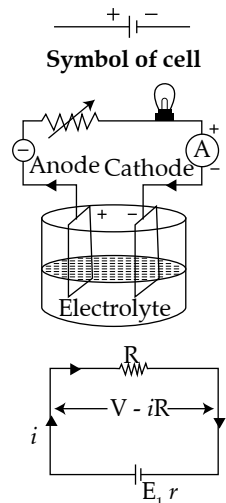
- (i) Current through circuit, $i = 0$
- (ii) Potential difference between A and B, $V_{AB} = E$
- (iii) Potential difference between C and D, $V_{CD} = 0$

3. Short Circuit : When two terminals of a cell are connected by a thick conducting wire.

- (i) Maximum Current (momentarily) : $i_{sc} = \frac{E}{r}$
- (ii) Potential Difference, $V = 0$

Difference between EMF and Potential Difference :

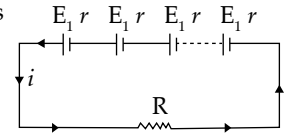
EMF of a Cell	Potential Difference
Maximum potential difference between two electrodes of a cell when cell is in open circuit is called EMF of Cell.	Potential difference between two points is the difference of potential between those two points.
EMF depends on nature of electrodes and electrolyte of the cell.	Potential difference is interdependent on nature of electrodes and electrolyte of the cell.



EMF is independent of the resistance of circuit.	Potential difference depends on the Current flowing through the circuit.
EMF is used for Source of Electric Current.	PD is measured between any two points of electric circuit.
It is a cause.	It is an effect.

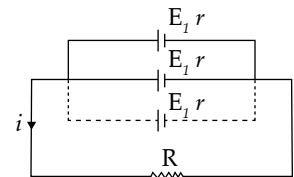
➤ **Combination of Cells**

A. Series Combination : If n identical cells are connected in series, anode of one cell is connected to cathode of another cell and so on.



- (i) Equivalent emf of combination, $E_{eq} = nE$
- (ii) Equivalent Internal resistance, $r_{eq} = nr$
- (iii) Main current = Current from each cell = $i = \frac{nE}{R + nr}$
- (iv) Potential Difference across external resistance, $V = iR$
- (v) Potential difference across each cell, $V' = \frac{V}{n}$
- (vi) Power dissipated in external circuit = $\left(\frac{nE}{R + nr}\right)^2 R$
- (vii) Condition for Maximum power, $R = nr$ and $P_{max} = n\left(\frac{E^2}{4r}\right)$
- (viii) This type of combination is used when $nr \ll R$

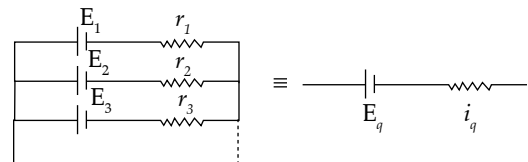
B. Parallel Combination : If n cells are connected in parallel, all anodes are connected at a point and all cathodes are connected at another point.



- (i) Equivalent emf of combination, $E_{eq} = E$
- (ii) Equivalent Internal resistance, $R_{eq} = r/n$
- (iii) Main current = Current from each cell = $i = \frac{E}{R + \frac{r}{n}}$
- (iv) Potential Difference across external resistance, $V = iR$
- (v) Potential difference across each cell, $i' = \frac{i}{n}$
- (vi) Power dissipated in external circuit = $\left(\frac{E}{R + \frac{r}{n}}\right)^2 R$
- (vii) Condition for Maximum power, $R = r/n$ and $P_{max} = n\left(\frac{E^2}{4r}\right)$
- (viii) This type of combination is used when $nr \gg R$

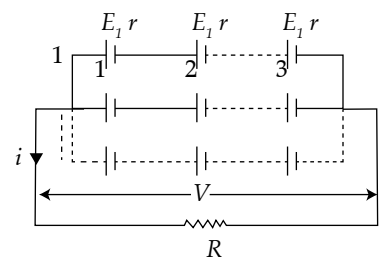
Generalised Parallel Battery

$$E_{eq} = \frac{\frac{E_1}{r_1} + \frac{E_2}{r_2} + \dots + \frac{E_n}{r_n}}{\frac{1}{r_1} + \frac{1}{r_2} + \dots + \frac{1}{r_n}} \text{ and } \frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \dots + \frac{1}{r_n}$$



C. Mixed Combination : If n identical cells are connected in series or row and much rows are connected in parallel then :

- (i) Equivalent emf of combination, $E_{eq} = nE$
- (ii) Equivalent resistance of combination, $r_{eq} = nr/m$
- (iii) Main current flowing through load, $i = \frac{nE}{R + \frac{nr}{m}} = \frac{mnE}{mR + nr}$
- (iv) Potential difference across load, $V = iR$



(v) Potential difference across each cell, $V = \frac{V}{n}$

(vi) Current from each cell, $i' = \frac{i}{n}$

(vii) Condition for maximum power, $R = \frac{nr}{m}$ and $P_{\max} = (mn) \frac{E^2}{4r}$

(viii) Total number of cells = mn

Note :

(i) If two cells are connected in parallel are of same emf's and same internal resistance r , then

$$E_{\text{eq}} = \frac{E_r + E_r}{r + r} = E \Rightarrow \frac{1}{r_{\text{eq}}} = \frac{1}{r} + \frac{1}{r} = \frac{2}{r} \quad r_{\text{eq}} = \frac{r}{2}$$

(ii) If n identical cells are connected in parallel, then equivalent emf of all cells is equal to the emf of one cell.

$$\frac{1}{r_{\text{eq}}} = \frac{1}{r} + \frac{1}{r} + \dots + n \text{ terms} = \frac{n}{r} \quad \text{or} \quad r_{\text{eq}} = \frac{r}{n}$$

➤ **Electric Current :**

(a) Current can be defined as the time rate of flow of charge through any cross section *i.e.*, $i = \lim_{\Delta t \rightarrow 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$. If

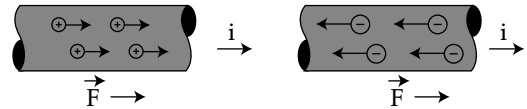
flow is uniform, then $i = Q/t$. It is a scalar quantity and measured in ampere (A) and CGS unit – emu also called Biot (Bi) or ab ampere. $1 \text{ A} = (1/10) \text{ Bi}$ (ab amp).

(b) 1 Amp of current is defined as the flow of 6.25×10^{18} electrons through any cross-section of the conductor.

(c) Direction of flow of positive charge can be taken as the conventional flow of current.

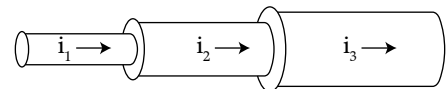
(d) Net charge on current carrying conductor is nil

(e) Current is independent of cross-sectional area *i.e.*, $i_1 = i_2 = i_3$



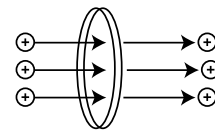
(f) **Current due to translational motion :** Let there be n particles having charge q moving through a given area in time t then :
If there is n particles with q charge, then Current associated per unit area is $i = nqA$

If there are n particles per unit volume with charge q , moving with velocity v then $i = nqvA$



(g) **Current due to Rotational Motion of Charge :** If a point charge q is moving in a circle with radius r with speed v then

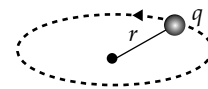
– current $i = qv = \frac{q}{T} = \frac{qv}{2\pi r} = \frac{q\omega}{2\pi}$



(h) **Current Carriers :** The accumulation of the charged particles that flow in a definite direction are called Current Carriers.

Note : The amount of charge flowing through a cross-section of a conductor from $t = t_i$ to $t = t_f$ is given by :

$$q = \int_{t_i}^{t_f} I dt$$



➤ **Kirchhoff's Law**

A. Kirchhoff's First Law/Kirchhoff's Junction Law/Kirchhoff's Current Law : It states that the algebraic sum of currents meeting at a junction in a closed electric circuit is zero *i.e.*, $\sum I = 0$. It is based on conservation of Charge.

Note : Current cannot be stored at the junction *i.e.*, No point junction in the circuit can act as a sink or source of charge.

B. Kirchhoff's Second Law / Kirchhoff's Loop Law/Kirchhoff's Voltage Law : It states that algebraic sum of difference in potential around any closed path of electric circuit in the loop is zero. *i.e.*, $\sum \Delta V = 0$. We also get, $\sum E + \sum IR = 0$

Few General Observations

A. Galvanometer : Galvanometer is a device used to detect passing by small current. Usually it is of following types: 1. Moving Coil Galvanometer 2. Moving Magnet Galvanometer 3. Hot wire Galvanometer.

Symbol : $\text{---}\textcircled{G}\text{---}$; where G is the total internal resistance of Galvanometer. When maximum deflection is achieved in galvanometer, the current flowing in the circuit is known as **Full scale deflection current** represented by i_g .

- Small resistance connected in parallel with Galvanometer coil is known as Shunt. This usually controls the net current passing through the device.

Pros of Shunt	Cons of Shunt
Protection of Galvanometer from Burning.	Shunt Resistance influences sensitivity of device.
Shunt is used to convert Galvanometer to Ammeter.	

B. Ammeter : Device used to measure current is called ammeter. Usually it is connected in series with the element through which the current passes.

Ammeter is said to be ideal if the value of resistance is zero or infinitesimal. The actual value of current will always be less than the real value of current.

Principle of Conversion of Galvanometer to Ammeter : We can convert an ammeter to galvanometer by adding a shunt (Low resistor) parallel to galvanometer.

$$\text{Combination Resistance, } R_c = \frac{GS}{G+S}$$

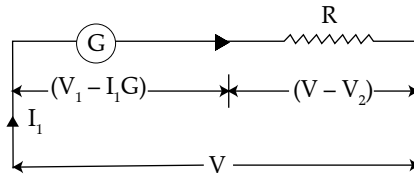
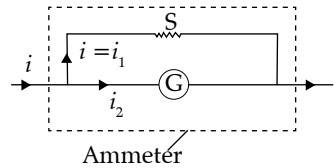
Both S and G are parallel attached hence both will have equal potential difference *i.e.*,

$$i_g G = (i - i_g) S \Rightarrow S = \frac{i_g}{i - i_g} G$$

C. Voltmeter : Voltmeter is a device used to measure potential difference and is attached in parallel with 'circuit element' across which the potential difference is to be measured.

Conversion of Galvanometer to Voltmeter :

Galvanometer can be converted into a voltmeter by connecting a large resistance R in series with Galvanometer.



Equivalent Resistance, $R_{eq} = G + R$

As per Ohm's Law, maximum reading of V which can be taken, $V = i_g (G+R)$ which gives

$$R = \frac{V}{i_g} - G = \left(\frac{V}{V_g} - 1 \right) G$$

Note : If nth part of the partial voltage appeared across galvanometer (*i.e.*, $V_g = \frac{V}{n}$) then required resistance $R = (n - 1) G$

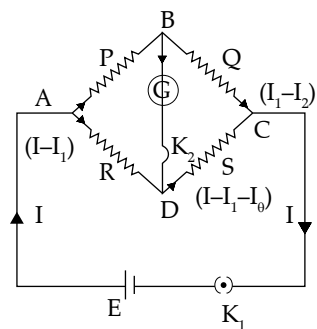
D. Wheatstone Bridge : Principle : As per the principle, if four resistances P, Q, R and S are arranged in form of a bridge and a galvanometer if attached shows no deflection then the system is said to be in Equilibrium or Balanced State. Mathematically,

$$\frac{P}{Q} = \frac{R}{S}$$

Note : In Wheatstone bridge circuit, arm AB and BC having resistance P and Q form ratio arm. The arm AD having a resistance R is known as **variable resistance** arm and arm DC having resistance S is **unknown resistance arm**.

A. Balanced Bridge : When Galvanometer reads zero, it is said to be balanced *i.e.* the current flows through Galvanometer only $\Rightarrow V_B = V_D$. In balanced condition $\frac{P}{Q} = \frac{R}{S}$, mutually changing the position of cell and Galvanometer this condition will not change.

B. Unbalanced Bridge : If the bridge is not balanced, current will flow from D to B if $V_B < V_D$ *i.e.*, $(V_A - V_D) < (V_A - V_B)$ which gives $PS > RQ$.



Application of Wheatstone Bridge :

Principle of Wheatstone bridge are used to measure unknown resistance and in instruments like meter bridge, post office box and Carey Foster bridge.

E. Meter Bridge or Slide Wire Bridge

A meter bridge or Slide wire bridge is the practical form of Wheatstone bridge.

Working : At B, adjust the position of Jockey where Galvanometer shows no deflection.

As per the Wheat Stone Bridge Principle :

$$\frac{P}{Q} = \frac{R}{S}$$

where, τ = resistance per cm per length, P = resistance of length l of wire $AB = l\tau$

Q = resistance of length $(100 - l)$ of wire $BC = (100 - l)\tau$

$$\frac{l\tau}{(100-l)\tau} = \frac{R}{S} \text{ or } S = \left(\frac{100-l}{l}\right)R$$

Knowing l and R , we can calculate S .

F. Potentiometer :

Potentiometer is a device used to measure EMF of a cell or potential difference between two points in an electric circuit. It consists of a long uniform wire generally made of constant. Stretched on a wooden board.

Principle : "The potential across any portion of the wire is directly proportional to the length of the portion, wire should be of uniform area of cross section and a constant current is flowing through it".

Let there be, A – Area of Cross section, ρ = Specific Resistance of material, V = Potential Difference across the length of wire with resistance R , I = Current Flowing.

As per Ohm's Law :

$$V = IR, R = \rho l/A$$

$$V = I\rho \frac{l}{A} = \frac{Kl}{A} \text{ (here } K = I\rho/A)$$

$$V \propto l \text{ (If } I \text{ and } A \text{ are constant)}$$

i.e., Potential difference across any potentiometer wire is directly proportional to length of the wire. Here $V/l = K$ is called Potential gradient *i.e.*, the fall of potential per unit length of wire.

Determination of Potential Difference :

Working and Theory :

Close key K and select a value on resistance box such that the fall of potential difference across the wire is greater than the potential difference. Usually it can be check by pushing the Jockey J along the potentiometer wire at various points *i.e.*, on A then B . Both will show opposite directional deflection on Galvanometer.

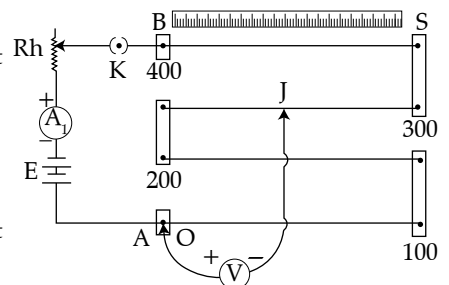
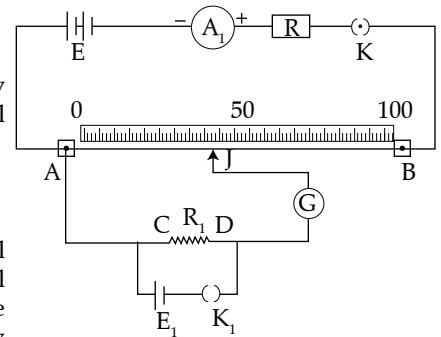
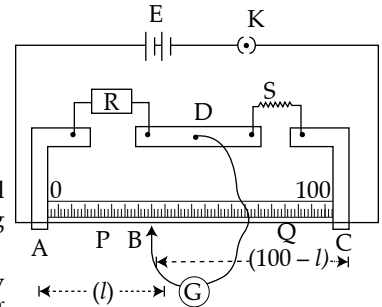
Close key K_1 , current flows through R_1 . A potential develops through R_1 . Adjust the position of jockey on potentiometer wire if pressed shows no deflection. Follow the same pattern when jockey is at J . Note the length $AJ (= l)$ of potentiometer wire. This would happen when potential difference across R_1 is equal to fall of potential across potentiometer wire of length l . If K is the potential gradient, then potential difference across R_1 *i.e.*, $V = Kl$

If r is the resistance of potentiometer wire of length L , then current through potentiometer wire, $I = \frac{E}{R+r}$

$$\text{Potential drop across potentiometer wire} = Ir = \left(\frac{E}{R+r}\right)r$$

Potential gradient of potentiometer wire *i.e.*, fall of potential per unit length is :

$$K = \left(\frac{E}{R+r}\right)\frac{r}{L}, \text{ hence } V = \left(\frac{E}{R+r}\right)\frac{r}{L}l$$



➤ **Comparison of EMF's of two cells using Potentiometer :**

Setup : A battery with emf E is connected between end terminal A and B of potentiometer with rheostat R_h , ammeter A_1 and key K in series.

The positive terminal of both is connected at A and the negative terminals are connected at 1 and 2 of two-way keys. The common terminal 3 is connected at Jockey J through Galvanometer G.

Working : Insert the plug in the gap between terminal 1 and 3 of two-way key so that the cell of emf ε_1 develops in circuit. Adjust the position of the jockey on potentiometer wire, where if pressed, the galvanometer shows no deflection. Let it be when jockey be at J_1 . Length of wire is AJ_1 .

There will be no current in arm AJ_1 . It means that,

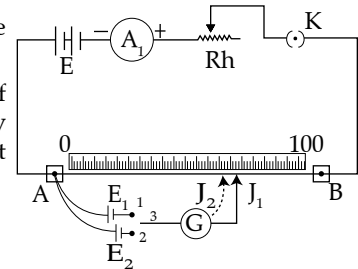
Potential of positive terminal of cell = potential of point A

Potential of negative terminal of cell = potential of point J_1 .

EMF of the cell will be equal to potential difference between points A and J_1 of the potentiometer wire *i.e.*, $E_1 = KJ_1$

Now remove the plug from gap between 1 and 3 insert in gap between 2 and 3 of two way so that calls of EMF comes into the circuit. Now repeating the activity find the position of jockey on wire, where Galvanometer shows no deflection. Let it be at J_2 . Length of wire is AJ_2 then, $E_2 = KJ_2$

Using both equations we get, $\frac{E_1}{E_2} = \frac{l_1}{l_2}$



Precautions :

1. The current in potentiometer wire must be kept constant.
2. The edge of the jockey should not be rubbed on the wire while adjusting the position of jockey on potentiometer wire, such that the area of cross section will remain same.
3. Heating effect should be controlled by managing the time of current flow in the system as this will change the resistance of wire.

Determination of Internal Resistance of Cell by Potentiometer :

In this we will find the internal resistance r of a cell of emf E using potentiometer, the setup is as shown below:

Close key K and constant current is maintained in potentiometer with the help of Rheostat R_h . Adjust the position of the jockey on potentiometer wire where we get zero deflection on Galvanometer. When jockey is at J_1 , length is $AJ_1(l_1)$, we know that,

$$E = KJ_1$$

Close key K_1 and take suitable resistance R from the resistance box in cell circuit. Now find the position of jockey on potentiometer wire where galvanometer shows no deflection. Let it be J_2 . Length is AJ_2 . As current is being drawn from the cell, its terminal potential difference V is balanced. Now the $V =$ potential difference across length l_2 of the potentiometer wire,

$$V = KJ_2$$

Now we get, $\frac{E}{V} = \frac{l_1}{l_2}$, we know that internal resistance r of the cell of EMF E when a resistance R is connected in its circuit is given by :

$$r = \frac{E - V}{V} \times R = \left(\frac{E}{V} - 1\right)R$$

Putting the value, we get : $r = \left(\frac{l_1}{l_2} - 1\right)R = \frac{(l_1 - l_2)}{l_2} \times R$

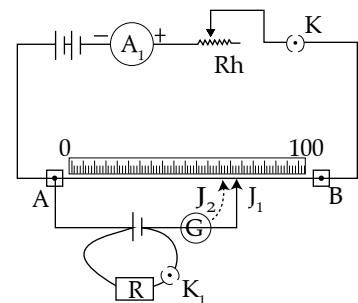
Knowing the values of l_1 , l_2 and R , internal resistance r of the cell can be determined.

➤ **Sensitiveness of Potentiometer :**

The smallest potential difference that can be measured using the potentiometer is called its "Sensitiveness". It can be increased by decreasing the potential gradient. Ways to decrease potential gradient are as follows :

A. Increasing the length of Potentiometer wire.

B. If the wire is of fixed length, potential gradient can be decreased by reducing the current in circuit with Rheostat and a single cell.



➤ **Heating Effect of Current :**

When some potential difference V is applied across a resistance then work done by electric field on charge q to flow through the circuit in time t will be :

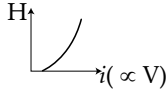
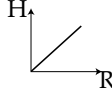

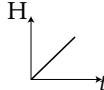
$$W = qV = Vit = i^2R = \frac{V^2t}{R} \text{ Joule}$$


Heat produced in the resistor gives the work., heat produced is given by :

$$H = \frac{W}{J} = \frac{Vit}{4.2} = \frac{i^2Rt}{4.2} = \frac{V^2t}{4.2R} \text{ Cal.}$$

This relation is called **Joule Heating**.

Some important relations are as follows :

Condition	Graph
If R and t is constant, $H \propto i^2$ and $H \propto V^2$	
If I and t are constant (Series), $H \propto R$	
If V and t are constant (Parallel), $H \propto 1/R$	
If V, I and R are constant, $H \propto t$	

➤ **Electric Power :**

The rate at which the electric energy is dissipated into other forms of energy, is called **Electric power**.

$$P = W/t = Vi = i^2R = V^2/R$$

Unit : SI – Joule /s or Watt, Other units : kW, MW (1 HP = 746 Watt)

A. Calculating Resistance of Electric Appliance : Neglecting the variance of resistance with temperature, resistance can be calculated by rated power and voltage *i.e.*, by using $R = \frac{V_R^2}{P_R}$ **For Example :** Power of 50 W , 220 Volt bulb,

$$R = \frac{220 \times 220}{50} = 968\Omega$$

B. Calculating Power Consumption : An electric appliance consumes rated power only if applied voltage (V_A) matched rated voltage (V_R).

If $V_A = V_R$ hence $P_{\text{consumed}} = P_R$,

If $V_A < V_R$ then $P_{\text{consumed}} = \frac{V_A^2}{R}$, also we have $R = \frac{V_R^2}{P_R}$

Using both we get $P_{\text{consumed}}(\text{Brightness}) = \left(\frac{V_A^2}{V_R^2}\right) \times P_R$
 $P_{\text{consumed}} \propto \text{Brightness}$

For Example : If 50 W, 220 V bulb operates on 110 V supply then $P_{\text{cons.}} = \left(\frac{110}{220}\right)^2 \times 100 = 25 \text{ W}$

Note : If $V_A < V_R$ then % drop in output power is $\frac{P_R - P_{\text{consumed}}}{P_R} \times 100$

Also, the $P_{\text{consumed}} < P_R < \text{Thickness} \propto \frac{1}{R}$ (Voltage should be Constant)

Long distance power transmission :

Power loss will be i^2R if the current moves through a power line of resistance R . Now if power P is transmitted to voltage V . then :

$$P = Vi \Rightarrow i = P/V \text{ such that Power loss} = \frac{P^2}{V^2} \times R.$$

$$\text{Hence, we can say that : Power loss} \propto \frac{1}{V^2}$$

Time taken by heater to boil water :

We know the relation that heat required to raise the temperature $\Delta\theta$ of mass m and specific heat S ,
 $H = mS\Delta\theta$

Now Heat produced by heater = heat produced to raise the temp $\Delta\theta$

$$\text{i.e., } p \times t = J \times ms\Delta\theta \Rightarrow t = \frac{J(ms\Delta\theta)}{P}$$

$$\text{Hence for 'm' kg water } t = \frac{4180m\Delta\theta}{P}$$

➤ Electric Energy :

The net electric work done or energy supplied by the source in maintaining the current in electric circuit for a given time is called Electric energy consumed.

Electric Energy :

$$W = VI \times t = Pt$$

Electric Energy = Electric Power \times time

SI unit of electric energy is Joule and the commercial unit used is kWh where :

$$1 \text{ kWh} = 1 \text{ kilo watt} \times 1 \text{ Hour} = 1000 \text{ watt} \times 1 \text{ Hour}$$

$$1 \text{ kWh} = 1000 \text{ Wh} = 1000 \text{ W} \times (60 \times 60 \text{ s}) = 3.6 \times 10^6 \text{ J}$$

$$\text{Unit of Electricity consumed} = \text{No. of kWh} = \frac{\text{watt} \times \text{hour}}{1000}$$

$$\text{Electric Energy} = VI t = I^2 R t = V^2 t / R$$

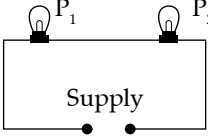
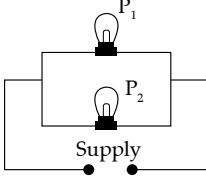
Electricity Consumption

The price of electrical consumption is based on electrical energy. Joule is a very small unit and cannot be used for practical purpose.

$$1 \text{ kWh} = 1000 \text{ W} \times 3600 \text{ sec} = 3.6 \times 10^6 \text{ J}$$

$$\text{No. of Consumed Units, } n = \frac{\text{Total Watt} \times \text{Total Hours}}{1000}$$

Combination of Bulbs / Heater :

Connected in Series	Connected in Parallel
<p>Power Consumed</p> $= \frac{1}{P_{\text{total}}} = \frac{1}{P_1} + \frac{1}{P_2} + \dots + \frac{1}{P_n}$ 	<p>Power Consumption</p> $= P_{\text{total}} = P_1 + P_2 + \dots + P_n$ 
<p>If n bulbs are identical then, $P_{\text{total}} = \frac{P}{N}$</p> <p>$P_{\text{consumed}}$ (Brightness) $\propto V \propto R \propto 1/P_{\text{rated}}$</p> <p><i>i.e., in series bulb with less wattage will be bright and pd across will be more.</i></p>	<p>If n bulbs are identical then, $P_{\text{total}} = nP$</p> <p>P_{consumed} (Brightness) $\propto i \propto 1/R \propto P_{\text{rated}}$</p> <p><i>i.e., in parallel bulb of greater wattage will be bright and more current will pass through it.</i></p>

➤ Electrical Conducting Material for Specific Use

A. Filament of Electric Bulb : Material having Properties like high resistance and high melting point such as Tungsten is used for it.

- B. **Element of Heating devices** : It is usually made up of nichrome which have high resistivity and high melting point.
- C. **Resistance of Resistance Box** : It is usually made up of alloy of Manganin, Constantan and Nichrome. This material pursues moderate resistivity which is practically independent of temperature.
- D. **Fuse Wire** : It is usually made up of tin – 63% lead – 37% alloy. The material should pursue low melting point and high resistivity. It is used in series as a safety device in an electric circuit. The function of fuse is to open the circuit when the heat level increases up to a certain level. It is independent of its length.
- E. **Thermistors** : A thermistor is a heat sensitive device usually prepared from oxides of various metals such as nickel, cobalt, iron etc. For thermistors α is very high which might be positive or negative. The resistance can change rapidly with change in temperature. This device is usually used to measure very small temperature changes.

II. Important Formula

1. Electric Current, $I = \frac{\text{Net Force Flown}}{\text{Time taken}} = \frac{q}{t} = \frac{dq}{dt}$
2. $E = \frac{\text{Potential Difference}}{\text{Length}} = \frac{V}{l}$
3. Average Drift Speed, $\bar{v}_d = \frac{e\bar{E}\tau}{m}$
4. Relaxation Time, $\tau = \frac{\text{mean Free Path}}{\text{rms velocity of electrons}} = \frac{\lambda}{v_{rms}}$
5. Mobility, $\mu = \frac{v_d}{E}$
6. Mobility of Charge Carriers, $\mu = \frac{\text{Drift Velocity}}{\text{Electric Field}} = \frac{v_d}{E} = \frac{qE\tau / m}{E} = q\tau / m$
7. Resistivity, $\rho = \frac{m}{ne^2\tau}$
8. Relation between Current Density, Conductance and Electrical Conductivity, $J = \frac{1}{\rho}E = \sigma E$
9. Maximum Power Transfer theorem, $P_{max} = \frac{E^2}{4\tau}$
10. Maximum Reading of V as per Ohm's Law, $V = i_g(G+R)$
11. Time taken by heater to boil water, $t = \frac{J(ms\Delta\theta)}{P}$