CHAPTER-3

Current Electricity

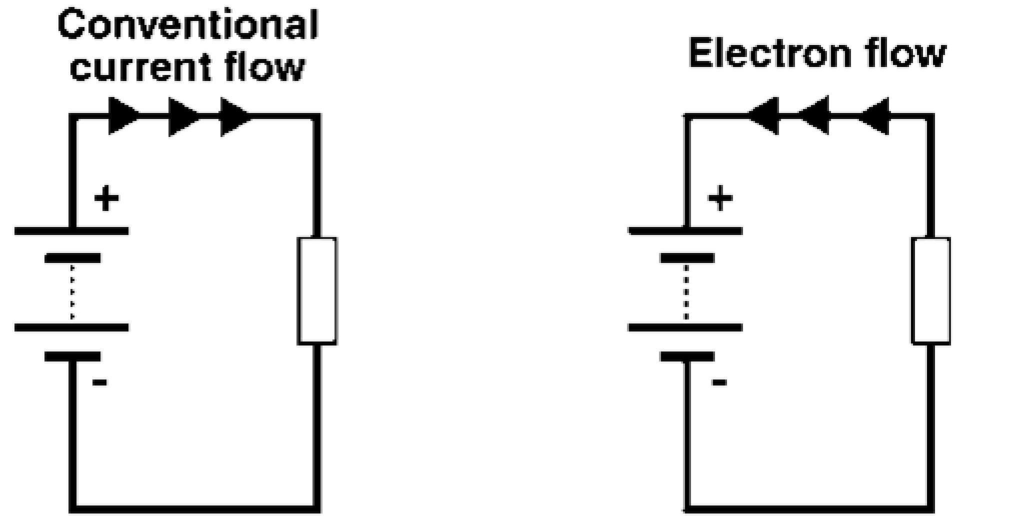
TOPICS INCLUDE

- Electric current,
- flow of electric charges in a metallic conductor,
- drift velocity, mobility and their relation with electric current,
- Ohm's law,
- V-I characteristics (linear and non-linear),
- electrical energy and power,
- electrical resistivity and conductivity,
- 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 rules,
- Wheatstone bridge

ELECTRIC CURRENT

Electric current is defined as the rate of flow of electric charge in a conductor. The SI Unit of electric current is the Ampere(A).

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



Electron and conventional current flow

FLOW OF ELECTRIC CHARGES IN A METALLIC CONDUCTOR

- Electric charge in motion, due to the force experienced by an applied electric field, constitutes electric current.
- In solid conductors the current is carried by negatively charged electrons.
- In electrolytic solution the current is carried by the motion of positive and negative ions.
- When no electric field is applied ,the electrons are in random motion and the average velocity of charges is zero .Therefore there will be no net current.

DRIFT VELOCITY

Drift velocity: The average velocity attained by charged particles, (eg. electrons) in a material due to an electric field.

Consider a section of wire of length *l*.

The volume of wire in this section will be V = A*l*

If **n** be the no. of charge carriers per unit volume in the wire and the charge on each charge carrier is e, the quantity of charge within the section will be

Q = nVe = nA*l*e

We have, I $= \frac{Q}{t} = \frac{nAel}{t} = \boldsymbol{nAev_d}$

CURRENT DENSITY AND MOBILITY

Drift velocity: Current density is defined as the amount of electric current flowing per unit cross-sectional area of a conductor, expressed in amperes per square meter (A/m²).

$$\text{Current Density, } J = \frac{\mathrm{I}}{\mathrm{A}} = \frac{Current}{cross\ sectional\ area}$$

$$\text{We have, } \mathrm{I} = \boldsymbol{nAev_d}$$

$$J = \frac{\mathrm{I}}{\mathrm{A}} = \boldsymbol{nev_d}$$

Mobility: The drift velocity of an electron for a unit electric field is known as *mobility of the electron*.

$$\text{Mobility, } \mu = \frac{v_d}{E} = \frac{drift\ velocity}{electric\ field}$$

RELATION BETWEEN CURRENT DENSITY AND ELECTRIC FIELD

We have, from Ohm's law

V = IR

Also the relations,

$R = \rho \frac{l}{A}$, $V = \frac{E}{l}$, $J = \frac{I}{A}$, $\sigma = \frac{1}{\rho}$

From these relations,

$$\Longrightarrow V = I.\rho\frac{l}{A} = J.\rho.l$$

$$\frac{V}{l}.\frac{1}{\rho} = I.\rho\frac{l}{A} = J$$

$$\therefore \boldsymbol{J = \sigma E}$$

ELECTRON MOBILITY, CONDUCTIVITY & RESISTIVITY

Let an electron of mass 'm' and charge 'e' is placed in an electric field E. The electric force experienced by it is **F= eE**

Also from Newton's law, F = ma

Hence, ma = eE

$$\Longrightarrow a = \frac{eE}{m}$$

The average drift speed of electron is, $v_d = a\tau$, where τ is average time collision called mean free time or relaxation time.

Therefore, $v_d = \frac{eE\tau}{m}$ ……….(i)

Continued $\Rightarrow$

ELECTRON MOBILITY, CONDUCTIVITY & RESISTIVITY

Electron mobility, $\mu = \frac{v_d}{E} = \frac{e\tau}{m}$ ……….(ii)

Since current density, $J = nev_d = ne\frac{eE\tau}{m} = \frac{ne^2\tau}{m}E$ ……….(iii)

Also, $J = \sigma E$ ……….(iv)

Comparing equations (iii) and (iv), we get

Electron Conductivity, $\sigma = \frac{ne^2\tau}{m}$ ……….(v)

Resistivity, $\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$

Also, from (iii), $\sigma = ne.\frac{e\tau}{m} = ne\mu$

OHM'S LAW

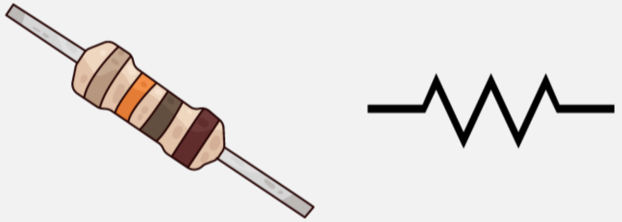
The electric current flowing through a conductor is directly proportional to the potential difference across the two ends of the conductor when physical conditions such as temperature, mechanical strain, etc. remain the same.

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

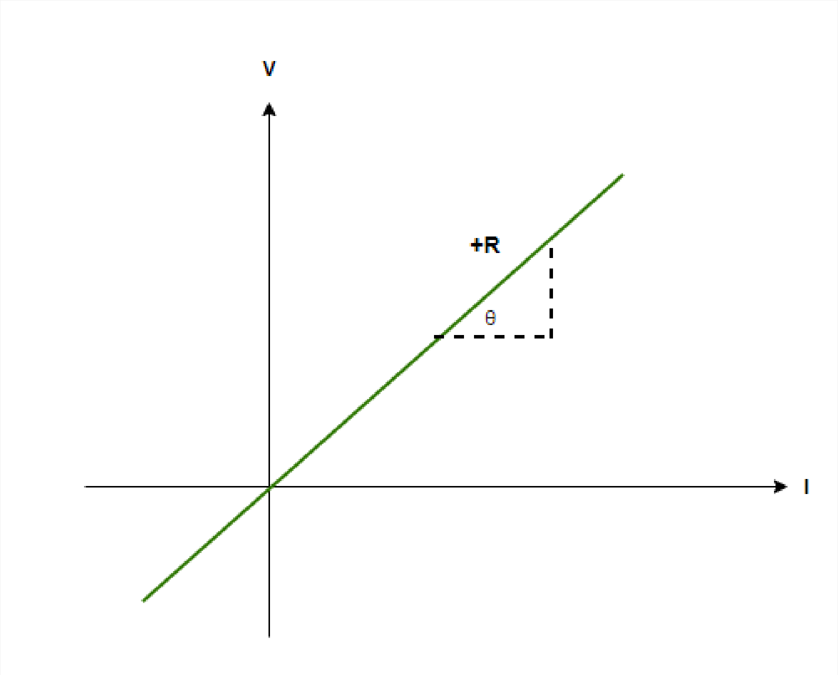
$$\text{or,} \quad V = R\,I$$

Where, R = Resistance

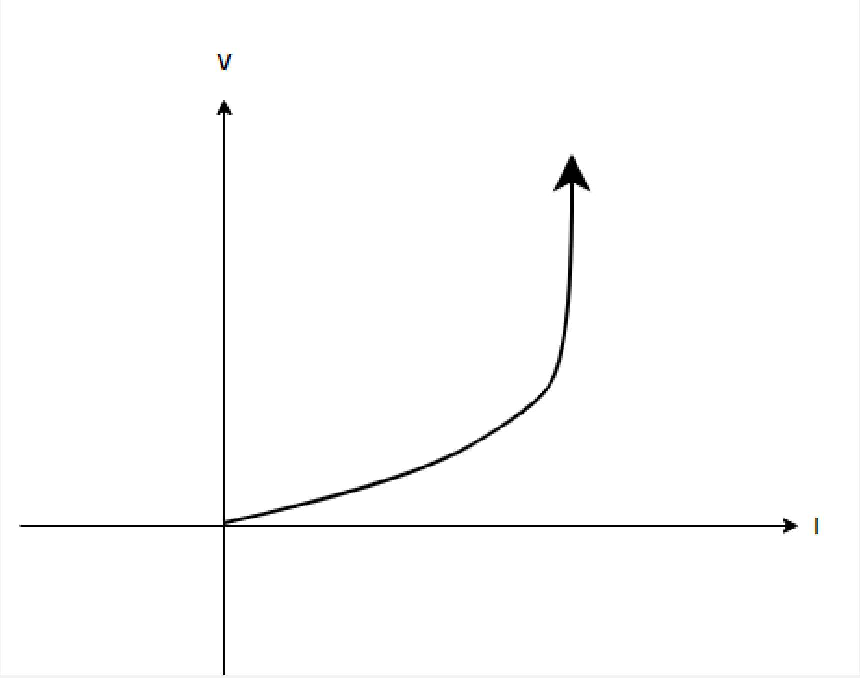
Resistance is the property of a substance by virtue of which it opposes the flow of current or charge. Its unit is Ω. Factors affecting resistance are length of the conductor, area of the cross-section of the conductor, temperature of the conductor and nature of material of the conductor



V-I CHARACTERISTICS (LINEAR AND NON-LINEAR)



Linear V-I characteristics are shown by ohmic resistors. The slope of the line gives resistance. Higher the slope, the higher will be the resistance.



Examples of non-ohmic resistances are diodes, SCRs (Silicon controlled resistors), transistors, etc. Voltage is no more proportional to current. The relationship between V and I is not unique, which means, more than one value of voltage is obtained for one value of current.

ELECTRICAL ENERGY AND POWER

- **Electrical energy** is the energy derived from electric potential energy or kinetic energy of the charged particles.

  Energy = QV

  where, Q is charge
  V is the potential difference

- **Electric power** is the rate at which work is done or energy is transformed in an electrical circuit. Simply put, it is a measure of how much energy is used in a span of time.

$$P = I^2R = VI$$

ELECTRICAL RESISTIVITY & CONDUCTIVITY

- Resistivity or specific resistance is the property of the material of the conducting substance and is defined as the resistance of a conductor of unit length and unit area of cross-section. Its unit is Ωm. Factors affecting resistivity are temperature, number density of free electrons, type of conductor and relaxation time.

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

- Conductance is the reciprocal of resistance. Its S.I unit is mho.
- Conductivity is the reciprocal of resistivity. Its S.I unit is mho / m.

INTERNAL RESISTANCE OF A CELL

Internal resistance refers to the opposition to the flow of current offered by the cells and batteries themselves resulting in the generation of heat. Internal resistance is measured in Ohms. The relationship between internal resistance (r) and emf (e) of cell s given by.

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

where, e = EMF i.e. electromotive force (Volts), I = current (A), R = Load resistance, and r is the internal resistance of cell measured in ohms.
On rearranging the above equation we get;

$$E = IR + Ir$$
$$\text{or, } E = V + Ir$$

Note: The emf (e) of a cell is always greater than the potential difference (terminal) across the cell

EMF & POTENTIAL DIFFERENCE

EMF

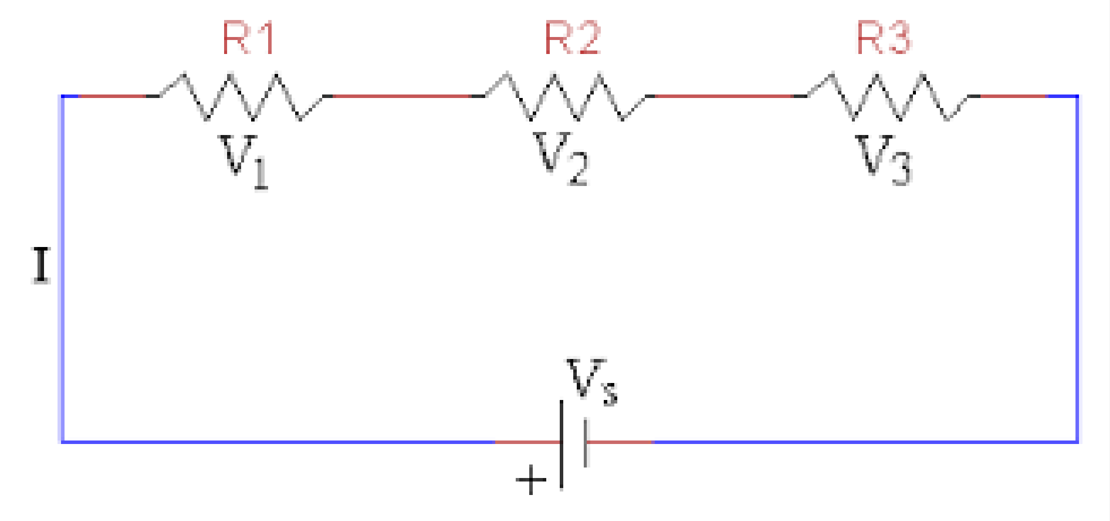
1. EMF is the maximum potential difference between the two electrodes of the cell when no current is drawn from the cell, i.e, when the circuit is open.
2. It is independent of the resistance of the circuit.
3. The term emf is used only for the source of the emf.
4. It is greater than the potential difference between any two points in a circuit.

Potential Difference

1. P.D is the difference of potentials between any two points in a closed circuit.
2. It is proportional to the resistance between the given points.
3. It is measured between any two points of the circuit.
4. However, P.D is greater than emf when the cell is being charged.

COMBINATION OF CELLS IN SERIES

If three resistors of resistances R_1, R_2 and R_3 are combined in series,



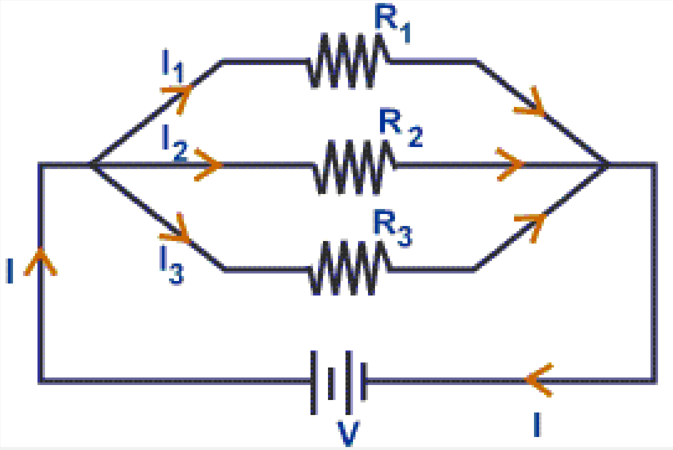
Effective resistance, R = $R_1 + R_2 + R_3$

The potential drop across the combination, V = $V_1 + V_2 + V_3$

The current remains same.

COMBINATION OF CELLS IN PARALLEL

If three resistors of resistances R_1, R_2 and R_3 are combined in parallel,



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

The current through the combination, I = $I_1 + I_2 + I_3$

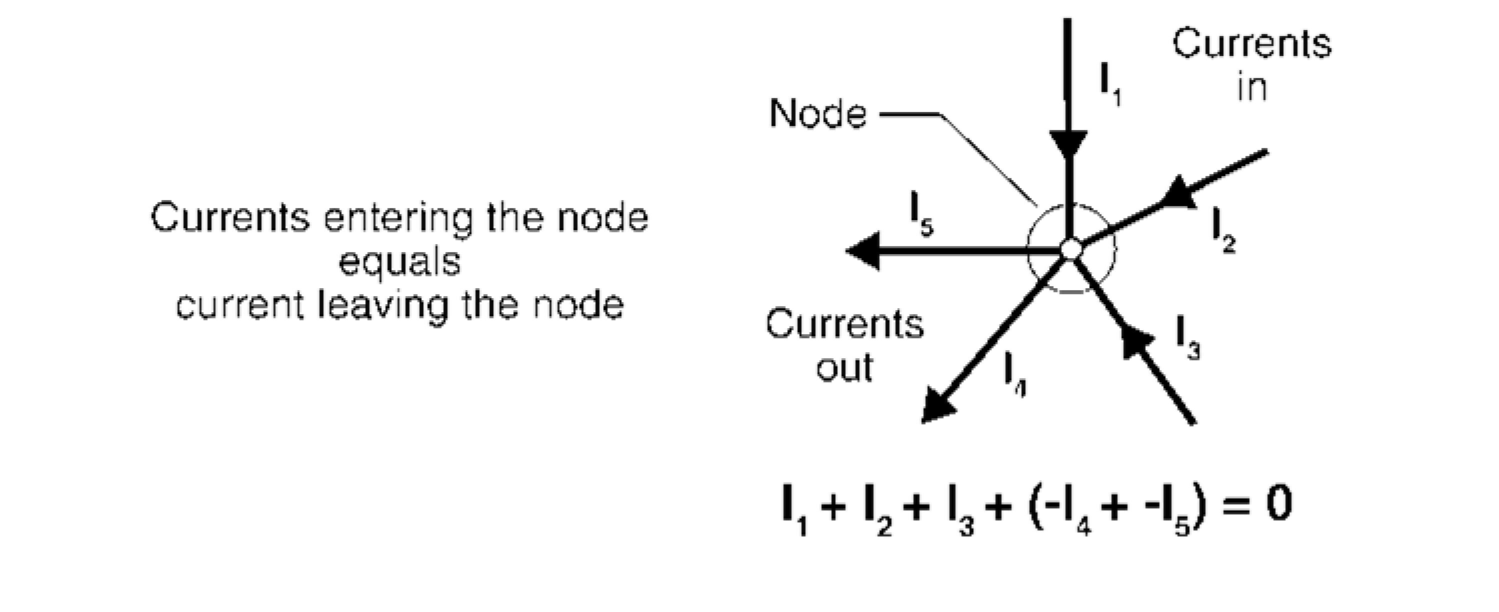
The voltage remains same.

KIRCHHOFF'S RULES

- In 1845, a German physicist, Gustav Kirchhoff, developed a pair of laws that deal with the conservation of current and energy within electrical circuits. These two laws are commonly known as Kirchhoff's Voltage and Current Law.
- Kirchhoff's Current Law goes by several names: Kirchhoff's First Law and Kirchhoff's Junction Rule. According to the Junction rule, the total of the currents in a junction is equal to the sum of currents outside the junction in a circuit.
- Kirchhoff's Voltage Law goes by several names: Kirchhoff's Second Law and Kirchhoff's Loop Rule. According to the loop rule, the sum of the voltages around the closed loop is equal to null.

KIRCHHOFF’S CURRENT LAW

According to Kirchhoff’s Current Law, The total current entering a junction or a node is equal to the charge leaving the node as no charge is lost.



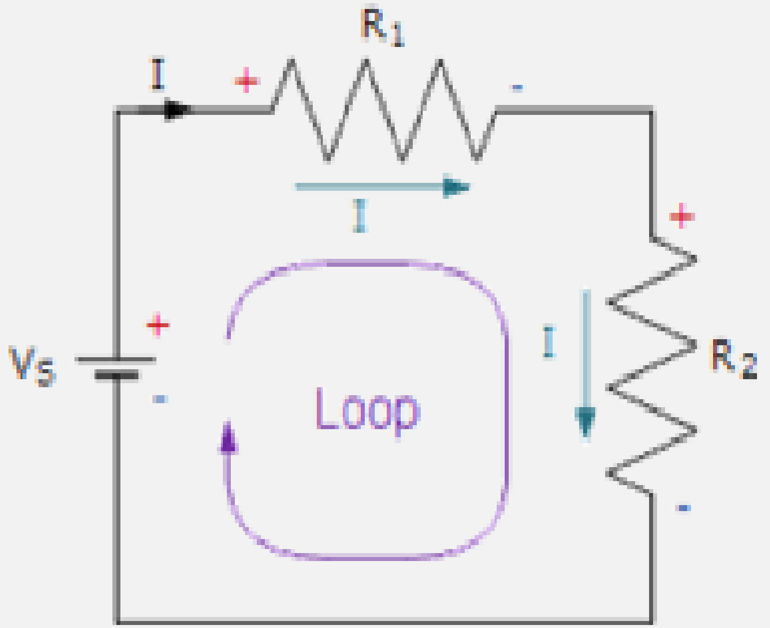
KIRCHHOFF'S CURRENT LAW

According to Kirchhoff's Voltage Law, The voltage around a loop equals the sum of every voltage drop in the same loop for any closed network and equals zero.

Hints:

If you are taking loop direction in the direction of current flowing,

- the voltage in resistor is taken as **negative** (drop) i.e −IR
- If moving from the **negative to the positive** terminal of a voltage source (battery), it is taken as **positive** (gain) i.e +V
- If moving from **positive to negative** terminal of a voltage source, it is taken as **negative** (drop) i.e –V

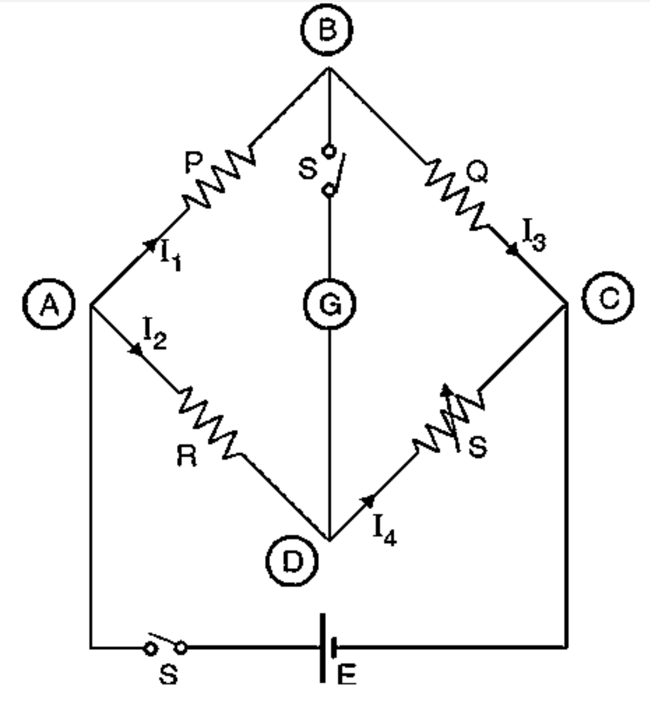


$$V_S + (-IR_1) + (-IR_2) = 0$$

WHEATSTONE BRIDGE

Wheatstone bridge, also known as the resistance bridge, calculates the unknown resistance by balancing two legs of the bridge circuit. One leg includes the component of unknown resistance.

The Wheatstone Bridge Circuit comprises two known resistors, one unknown resistor and one variable resistor connected in the form of a bridge. This bridge is very reliable as it gives accurate measurements.



In balanced condition,

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