ELECTRICTY AND MAGNETISM

CURRENT ELECTRICITY

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Applied – I: Electricty and magnetism (20UPH3AC5)

UNIT II: Current Electricity

Biot Savart's law-Magnetic induction at a Point due to a straight conductor carrying current-Ampere's circuital law-#Kirchhoff's Laws#– Application of Kirchhoff's laws to Wheatstone's bridge–Carey Foster's Bridge–Potentiometer– Calibration of Ammeter and Voltmeter (Low range) - Comparison of capacitances of two capacitors.

Text Book:

R. Murugeshan, Electricity and Magnetism, S. Chand & Company Ltd, New Delhi (2006)

Current Electricity

- Many inventions and discoveries have been made in order to facilitate human life smoothly. The discovery of current electricity is one such discovery that we are highly dependent on to make our life easier. Benjamin Franklin is credited with the discovery of electricity.

- What is Current Electricity?

Current electricity is defined as the flow of electrons from one section of the circuit to another.

When two bodies at different potentials are linked with a wire, free electrons stream from Point 1 to Point 2, until both the objects reach the same potential, after which the current stops flowing. Until a potential difference is present throughout a conductor, current runs.

- From the above analogy, we can define electromotive force and voltage as follows:

- Electromotive Force Definition: Electromotive force is defined as the electric potential produced by either an electrochemical cell or by changing the magnetic field.

- Voltage Definition: Voltage is defined as the electric potential difference between two points.

Types of Current Electricity

There are two types of current electricity as follows:

- Direct Current (DC)
- Alternating Current (AC)

Direct Current

The current electricity whose direction remains the same is known as direct current. Direct current is defined by the constant flow of electrons from a region of high electron density to a region of low electron density. DC is used in many household appliance and applications that involve a battery.

Alternating Current

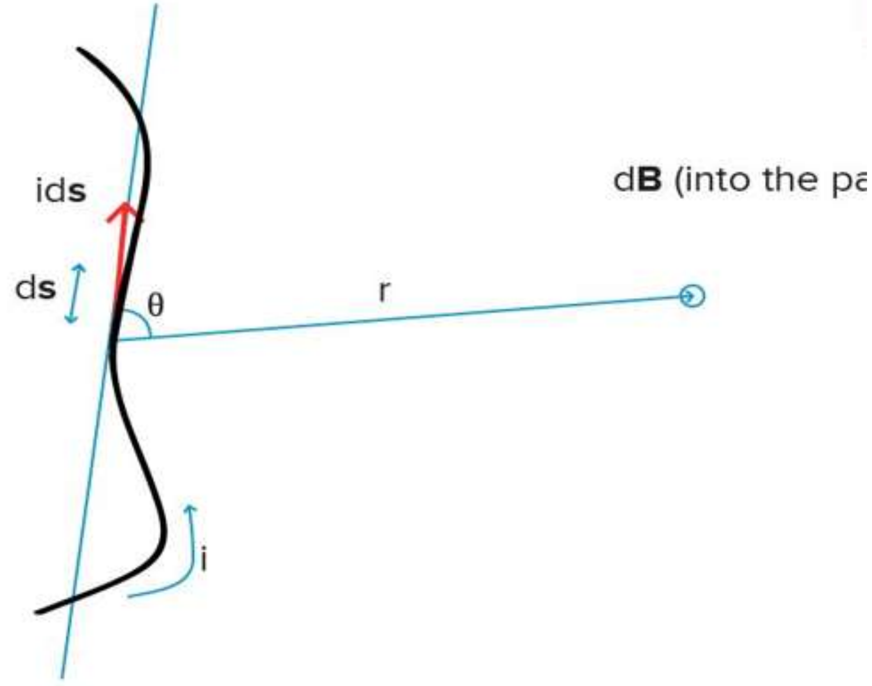
The current electricity that is bidirectional and keeps changing the direction of the charge flow is known as alternating current. The bidirectionality is caused by a sinusoidally varying current and voltage that reverses directions, creating a periodic back and forth motion for the current. The electrical outlets at our home and industries are supplied with alternating current.

What is Biot-Savart Law?

Biot-Savart's law is an equation that gives the magnetic field produced due to a current carrying segment. This segment is taken as a vector quantity known as the current element

The Biot-Savart law states " **how the value of the magnetic field at a specific point in space from one short segment of current-carrying conductor depends on each factor that influences the field**"

Consider a current carrying wire '**i**' in a specific direction as shown in the above figure. Take a small element of the wire of length **ds**. The direction of this element is along that of the current so that it forms a vector **i ds**.



To know the magnetic field produced at a point due to this small element, one can apply Biot-Savart's Law. Let the position vector of the point in question drawn from the current element be **r** and the angle between the two be **θ**. Then,

then the intensity of field dB is:

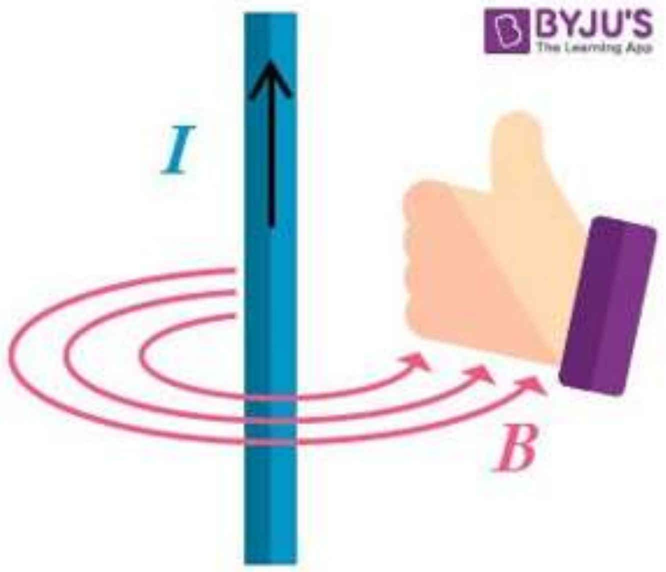
- Directly proportional to the current I, **$dB \propto I$**
- Directly proportional to the length of the conductor. **$dB \propto dl$**
- Directly proportional to the sine of the angle between the line joining the point and dl, **$dB \propto \sin\theta$**
- Inversely proportional to the square of the distance of the point P from the line **dB∝ 1/r2**

Combining all the four

$$dB = \left(\frac{\mu_0}{4\pi}\right)\left(\frac{I\,dl\,\sin\theta}{r^2}\right)$$

Where, μ_0 is the permeability of free space and is equal to $4\pi \times 10^{-7}$ N/A^2.

- We can use Biot–Savart law to calculate magnetic responses even at the atomic or molecular level
- It is also used in aerodynamic theory to calculate the velocity induced by vortex lines.



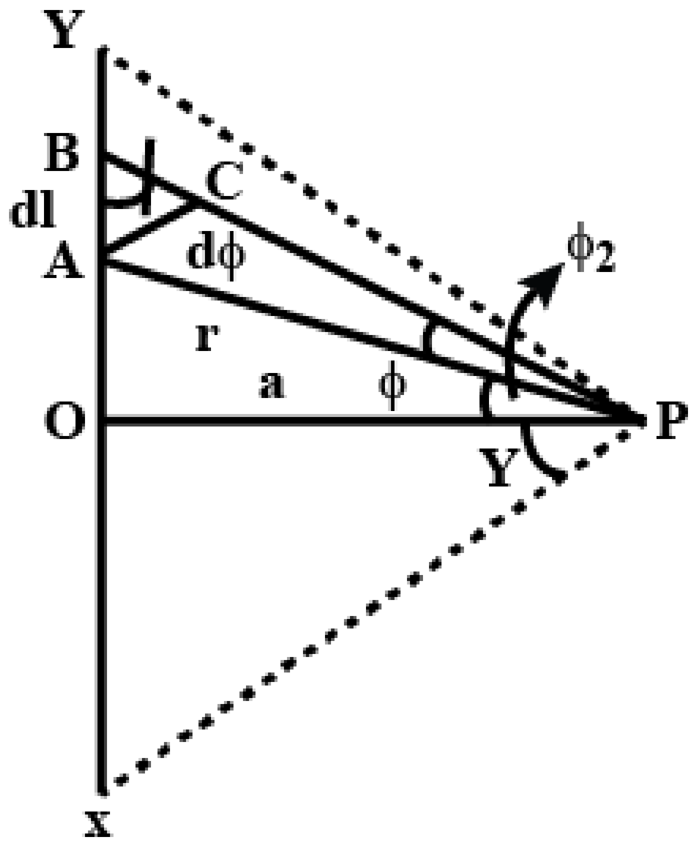
The direction of the magnetic field is always in a plane perpendicular to the line of element and position vector. It is given by the right-hand thumb rule where the thumb points to the direction of conventional current and the other fingers show the magnetic field’s direction.

Magnetic induction at a Point due to a straight conductor carrying current

- Magnetic induction due to infinitely long straight conductor carrying current: XY, is an infinitely long straight conductor carrying a current I(Figure).

- P is a point at a distance a from the conductor. AB is a small element of length dl. θ is the angle between the current element Idl and the line joining the element dl and the point P.

- According to Biot-Savart law, the magnetic induction at the point P due to the current element Idl is.



Straight conductor

$$dB = \frac{\mu_o}{4\pi} \frac{Idl \cdot \sin\theta}{r^2} \quad ......(1)$$

AC is drawn perpendicular to BP from A.

$\angle OPA = \phi, \angle APB = d\phi$

In ΔABC, $\sin\theta = \frac{AC}{AB} = \frac{AC}{dl}$

$\therefore AC = dl\sin\theta \quad ....(2)$

From ΔAPC, AC$= rd\phi \quad ....(3)$

From equations (2) and (3),

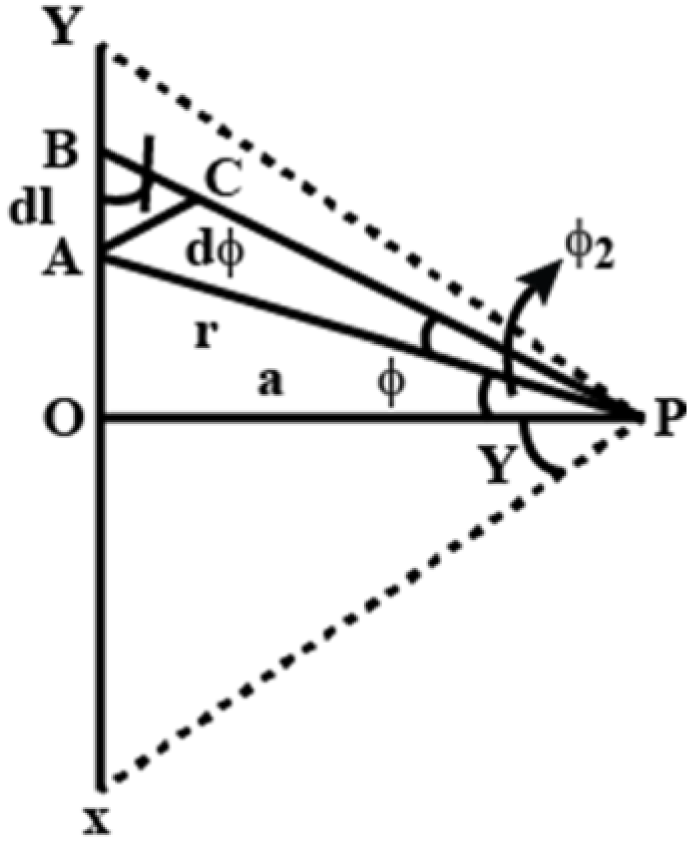
$rd\phi = dl\sin\theta \quad ....(4)$

Substituting equation (4) in equation (1)

$$dB = \frac{\mu_o}{4\pi} \frac{Ird\phi}{r^2} = \frac{\mu_o}{4\pi} \frac{Id\phi}{r} \quad ....(5)$$

In ΔOPA, $\cos\phi = \frac{a}{r}$

$$\therefore r = \frac{a}{\cos\phi} \quad ....(6)$$



Straight conductor

Substituting equation (6) in equation (5)

$$dB = \frac{\mu_o}{4\pi}\frac{1}{a}\cos\phi d\phi$$

The total magnetic induction at P due to the conductor XY is

$$B = \int_{-\phi_1}^{\phi_2} dB = \int_{-\phi_1}^{\phi_2} \frac{\mu_o I}{4\pi a}\cos\phi d\phi$$

$$B = \frac{\mu_o I}{4\pi a}[\sin\phi_1 + \sin\phi_2]$$

For infinitely long conductor,

$$\phi_1 = \phi_2 = 90^o$$

$$\therefore B = \frac{\mu_o I}{2\pi a}$$

If the conductor is places in a medium of permeability μ_0, $B = \frac{\mu I}{2\pi a}$.

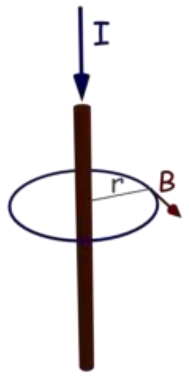
Ampere's circuital law

Ampere's circuital law states that the **line integral of magnetic field** represented by B, around a closed path is equal to the **product of the magnetic permeability of that space and the total current** through the area bounded by that path.

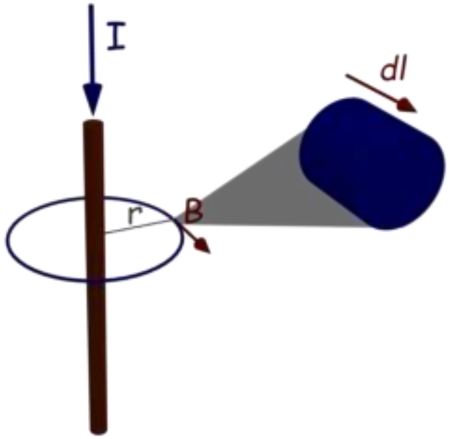
$$\oint B.dl = \mu_0 I$$

- ✓ Let us take an electrical conductor, carrying a current of I ampere, downward as shown in the figure

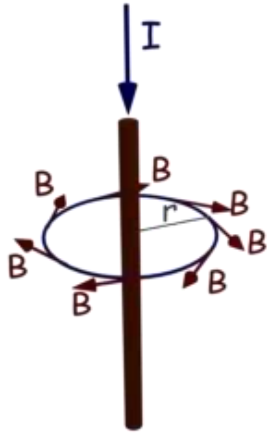
- ✓ Let us take an imaginary loop around the conductor which is radius is **r** and the flux density created at any point on the loop due to current through the conductor is **B**



- ✓ Let us consider an infinitesimal length dl of the amperian loop at the same point



- ✓ At each point on the amperian loop, the value of B is constant since the perpendicular distance of that point from the axis of conductor is fixed, but the direction will be along the tangent on the loop at that point



$$\oint \mathbf{B.dl} = \mu_0 \mathbf{I}$$

Kirchhoff’s Laws

- Kirchhoff’s Laws, or circuit laws, are two mathematical equality equations that deal with electricity, current and voltage (potential difference) in the lumped element model of electrical circuits.

- Kirchhoff’s Laws are also known as Kirchhoff's Voltage Law and Kirchhoff's Laws For Current And Voltage.

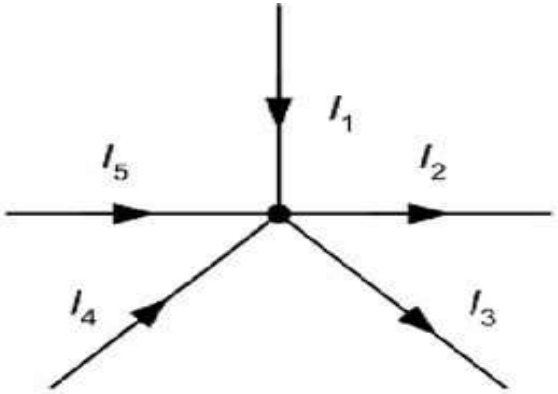
- Kirchhoff’s laws are fundamental laws used in electrical engineering and related fields, as well as in formulating proper circuits. There are two laws, as follows:

➢ Kirchhoff's first Law or Current Law (KCL):

It states that the **amount of current flowing into a node or junction is equal to the sum of the currents flowing out of it**. This is used in conjunction with Ohm's law in performing nodal analysis.

From the circuit, $i_1 - i_2 - i_3 + i_4 + i_5 = 0$

ie., , $i_1 + i_4 + i_5 = i_2 + i_3$



$$I_1 - I_2 - I_3 + I_4 + I_5 = 0$$

Convention:
Current flowing towards the junction is positive (+)
Current flowing away from the junction is negative (–)

So **currents entering to a node = currents leaving the node**

➢ Kirchhoff's Voltage Law (KVL):

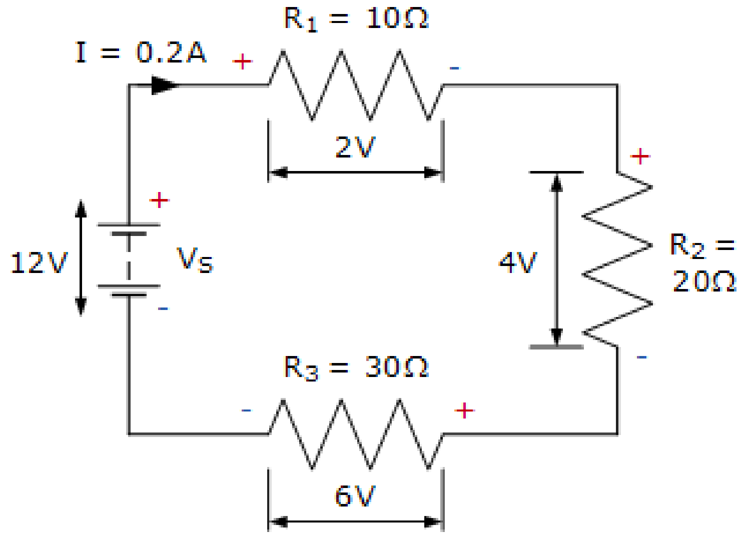
This is also known as the second law, loop rule or mesh rule and is based on the principle of conservation of energy. It states that the **sum of the voltages or electrical potential differences in a closed network is zero**. Thus the algebraic sum of all voltages within the loop will be equal to zero. The total amount of energy gained must equal the amount of energy lost per unit charge. **$\Sigma V = 0$**

$$V_S + (-IR_1) + (-IR_2) + (-IR_3) = 0$$

$$12 + (-0.2\times10) + (-0.2\times20) + (-0.2\times30) = 0$$

$$12 + (-2) + (-4) + (-6) = 0$$

$$\therefore 12 - 2 - 4 - 6 = 0$$



Thus Kirchhoff's voltage law holds true as the individual voltage drops around the closed loop add up to the total

Application of Kirchhoff's laws to Wheatstone's bridge

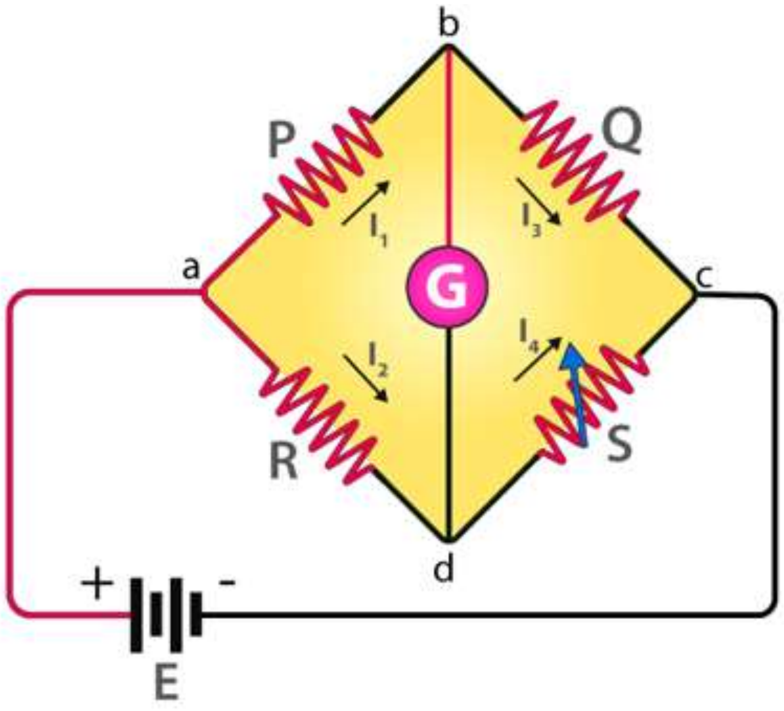
- ✓ Wheatstone bridge, also known as the **resistance bridge**, calculates the unknown resistance by balancing two legs of the bridge circuit. One leg includes the component of unknown resistance.

- ✓ 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.

- ✓ The Wheatstone bridge works on the principle of **null deflection**, i.e. the ratio of their resistances are equal and no current flows through the circuit.

- ✓ Under normal conditions, the bridge is in the unbalanced condition where current flows through the galvanometer. The bridge is said to be in a balanced condition when no current flows through the galvanometer. This condition can be achieved by adjusting the known resistance and variable resistance.

Construction of Wheatstone Bridge

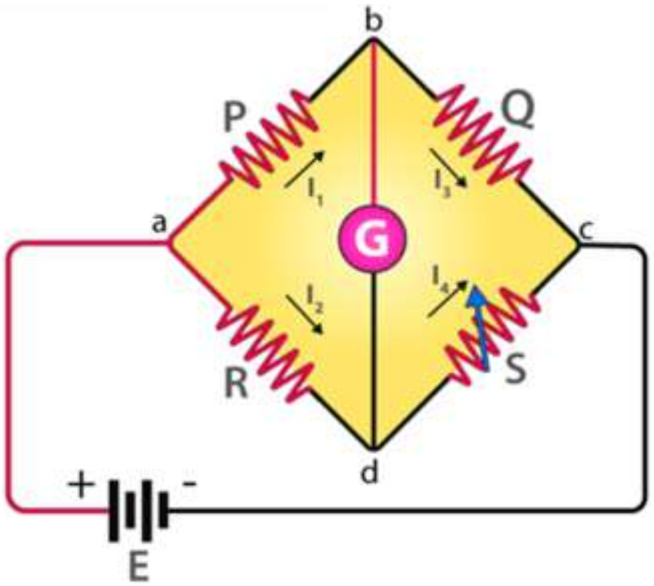


- ✓ A Wheatstone bridge circuit consists of four arms of which two arms consist of known resistances while the other two arms consist of an unknown resistance and a variable resistance.

- ✓ The circuit also consists of a galvanometer and an electromotive force source

- ✓ The emf source is attached between points *a* and *b* while the galvanometer is connected between the points *c* and *d*. The current that flows through the galvanometer depends on the potential difference across it.

Wheatstone Bridge Derivation



- ✓ The current enters the galvanometer and divides into two equal magnitude currents as I_1 and I_2. The following condition exists when the current through a galvanometer is zero

$$I_1 P = I_2 R \quad \text{---------------} \quad (1)$$

- ✓ The currents in the bridge, in a balanced condition, is expressed as follows:

$I_1 = I_3 = E / P+Q$ And $I_2 = I_4 = E / R+S$

Here, *E* is the emf of the battery.

By substituting the value of I_1 and I_2 in equation (1), we get

$$\frac{P\,E}{P+Q} = \frac{R\,E}{R+S} \Rightarrow \frac{P}{P+Q} = \frac{R}{R+S} \Rightarrow P\,(R+S) = R\,(P+Q) \Rightarrow PR + PS = RP + RQ$$

$$PS = RQ \quad \text{----------------} \quad (2)$$

$$\text{Therefore , } R = \frac{P}{Q}\,S \quad \text{--------------------}(3)$$

Equation (2) shows the **balanced condition of the bridge** while (3) determines the **value of the unknown resistance**