

Unit-1

Electromagnetic Theory

→ Scalar field :- Eg: Temperature gradient

→ Vector field :- which have both magnitude and direction
 $[\vec{E}, \vec{B}]$

Ex :- Direction Magnitude

$\frac{d\vec{B}}{dt}, \frac{d\vec{E}}{dt}$ → Maxwell Equation

→ charge density :-

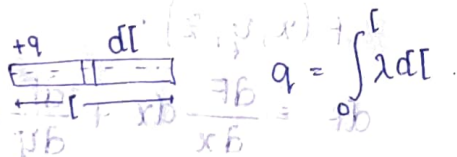
There are 3 types of charge density's.

i. Linear (λ)

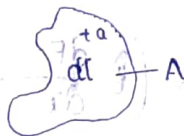
ii. Surface (σ)

iii. Volume (ρ)

i. Linear (λ) :- $\lambda = \frac{q}{l}$

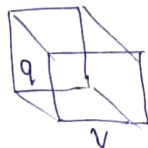

$$q = \int \lambda dl$$

ii. Surface (σ) :- $\sigma = \frac{q}{A}$



$$q = \int \sigma dA$$

iii. Volume (ρ) :- $\rho = \frac{q}{V}$



$$q = \int \rho dv$$

Del Operator ($\vec{\nabla}$) :-

It is also known as differential operator.

$$\frac{d}{dx} f(x) \quad \vec{\nabla} = \hat{i} \frac{d}{dx} + \hat{j} \frac{d}{dy} + \hat{k} \frac{d}{dz}$$

* $F(x, y, z) \rightarrow$ Scalar field, $\vec{A}(x, y, z) \rightarrow$ vector field.

* $\vec{\nabla} \cdot \vec{\nabla} = \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \rightarrow$ These is called

Laplacian operator.

* $\vec{\nabla} \cdot F(x, y, z) \rightarrow$ Gradient of F [vector quantity]

* $\vec{\nabla} \cdot \vec{A}(x, y, z) \rightarrow$ Divergence of $\vec{A} \rightarrow$ divergence \vec{A} .

* $\vec{\nabla} \times \vec{A}(x, y, z) \rightarrow$ Curl of $\vec{A} = \text{Curl } \vec{A}$ [vector].

Gradient of field F :-

$$\frac{dy}{dx}$$

* Rate of change of these quantity with distance (or) length.

$$F(x, y, z)$$

$$dF = \frac{\partial F}{\partial x} dx + \frac{\partial F}{\partial y} dy + \frac{\partial F}{\partial z} dz$$

$$= \left(\hat{i} \frac{\partial F}{\partial x} + \hat{j} \frac{\partial F}{\partial y} + \hat{k} \frac{\partial F}{\partial z} \right) \cdot (\hat{i} dx + \hat{j} dy + \hat{k} dz)$$

$$= (\vec{\nabla} F) \cdot d\vec{l} \quad \text{where } d\vec{l} = \hat{i} dx + \hat{j} dy + \hat{k} dz$$

$$dF = |\vec{\nabla} F| |\vec{\mu}| \cos \alpha$$

$\alpha = 0$. Then dF will be max.

1) $\phi = 3x^2y - yz^2$ find gradient of ϕ at $(1, 2, -1)$.

$$\vec{\nabla} \phi = \left(\hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z} \right) \phi$$

$$= \hat{i} \frac{\partial \phi}{\partial x} + \hat{j} \frac{\partial \phi}{\partial y} + \hat{k} \frac{\partial \phi}{\partial z}$$

$$= \hat{i} \frac{\partial}{\partial x} (3x^2y - yz^2) + \hat{j} \frac{\partial}{\partial y} (3x^2y - yz^2) +$$

$$+ \hat{k} \frac{\partial}{\partial z} [3x^2y - yz^2]$$

$$\hat{i}(6xy) + \hat{j}(3x^2 - z^2) + \hat{k}(-2yz)$$

$$(x, y, z) = 1, 2, -1$$

$$\bar{\nabla} \phi = 12\hat{i} + 2\hat{j} + 4\hat{k}$$

Divergence :-

→ Gauss Theorem :-

$$\int_V (\bar{\nabla} \cdot \bar{A}) dV = \oint_S \bar{A} \cdot d\bar{s}$$

+ This is used to volume integral to surface.
with vice versa.

→ Stoke's Theorem :-

+ This is used to surface integral to circulation

$$\int_S (\bar{\nabla} \times \bar{A}) \cdot d\bar{s} = \oint_C \bar{A} \cdot d\bar{l}$$

Divergence :-

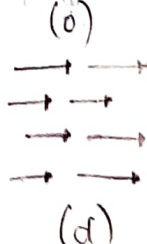
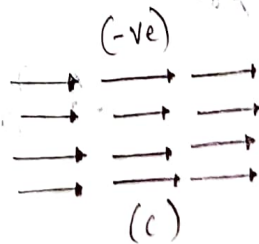
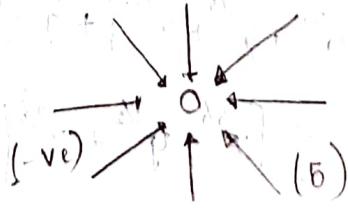
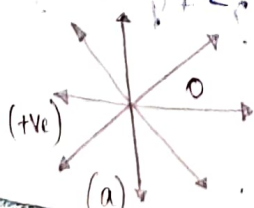
$$\bar{A}(x, y, z) = A_x \hat{i} + A_y \hat{j} + A_z \hat{k}$$

$$\bar{\nabla} \cdot \bar{A} = \text{div } \bar{A} = \left(\hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z} \right) \cdot (A_x \hat{i} + A_y \hat{j} + A_z \hat{k})$$

$$= \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

+ Divergence of \bar{A} is defined as net outward flux per unit volume over a closed surface.

[\bar{A} = vector surface]



* In which the divergence will take place at positive, negative and zero?

→ Divergence of \vec{A} at given point is a measure of how much a vector \vec{A} spread out from that point [i.e., divergence].

→ Curl :-

$$\oint_S (\nabla \times \vec{A}) \cdot d\vec{s} = \oint_C \vec{A} \cdot d\vec{l}$$

→ Circulation

• Single line integral says that Circulation.

$$\vec{A} = A_x \hat{i} + A_y \hat{j} + A_z \hat{k}$$

$$\nabla \times \vec{A} = ?$$

* Curl of \vec{A} at some point O is a measure of how much the vector \vec{A} curves around point O .

$$\nabla = \hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z}$$

$$\vec{A} = A_x \hat{i} + A_y \hat{j} + A_z \hat{k}$$

$$\nabla \times \vec{A} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$$

$$\oint \vec{E} \cdot d\vec{s} = \frac{q}{\epsilon_0}$$

$$\oint \vec{B} \cdot d\vec{s} = 0$$

$$e = \frac{d\phi}{dt}$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$$

Q.) $\phi = x^{3/2} + y^{3/2} + z^{3/2}$ find gradient of $\nabla \phi$.

$$\text{Sol.} \quad \nabla \phi = \left(\hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z} \right) \phi$$

$$= \hat{i} \frac{\partial \phi}{\partial x} + \hat{j} \frac{\partial \phi}{\partial y} + \hat{k} \frac{\partial \phi}{\partial z}$$

$$= \hat{i} \frac{\partial}{\partial x} [x^{3/2} + y^{3/2} + z^{3/2}] + \hat{j} \frac{\partial}{\partial y} [x^{3/2} + y^{3/2} + z^{3/2}] +$$

$$\hat{k} \frac{\partial}{\partial z} [x^{3/2} + y^{3/2} + z^{3/2}]$$

$$= \frac{3}{2} \left[x^{1/2} \hat{i} + y^{1/2} \hat{j} + z^{1/2} \hat{k} \right]$$

Q) Prove that $\vec{A} = 3y^2 z^2 \hat{i} + 3x^2 z^2 \hat{j} + 3x^2 y^2 \hat{k}$ is a Solenoidal vector?

$\boxed{\nabla \cdot \vec{A} = 0} \rightarrow \text{Solenoidal field}$

$\nabla \cdot \vec{A} = ?$

$$\nabla \cdot \vec{A} = \left(\hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z} \right) \vec{A}$$

$$\frac{\partial}{\partial x} (3y^2 z^2) + \frac{\partial}{\partial y} (3x^2 z^2) + \frac{\partial}{\partial z} (3x^2 y^2) = 0 + 0 + 0 = 0$$

∴ These is a Solenoidal field.

Q) The $\vec{A} = x^2 \hat{i} + y^2 \hat{j} + z^2 \hat{k}$ (a) Is the field Solenoidal?
(b) Is the field irrotational?

Sol. (a) $\vec{A} = x^2 \hat{i} + y^2 \hat{j} + z^2 \hat{k}$

$$\nabla \cdot \vec{A} = \left(\hat{i} \frac{\partial}{\partial x} + \hat{j} \frac{\partial}{\partial y} + \hat{k} \frac{\partial}{\partial z} \right) \vec{A}$$

It is also a Solenoid field.

(b) $\nabla \times \vec{A} = 0$

Q) $\vec{A} = yz \hat{i} + xz \hat{j} + xy \hat{k}$

i. $\nabla \cdot \vec{A} = ?$ ii. $\nabla \times \vec{A} = ?$

Sol. $\nabla \cdot \vec{A} = \text{Solenoid}$

$$\begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ yz & xz & xy \end{vmatrix} = \hat{i}(x - x) - \hat{j}(y - y) + \hat{k}(z - z) = 0$$

Q.) $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$ find $\nabla r^n = ?$

a) $n r^{n-1} \vec{r}$

b) $n r^{n-2} \vec{r}$

Sol.) $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$

$|r| = r = (x^2 + y^2 + z^2)^{1/2}$

$\phi = r^n = (x^2 + y^2 + z^2)^{n/2}$

$\nabla \phi = \hat{i} \frac{\partial \phi}{\partial x} + \hat{j} \frac{\partial \phi}{\partial y} + \hat{k} \frac{\partial \phi}{\partial z}$

$= \frac{n}{2} \cdot 2x (x^2 + y^2 + z^2)^{n/2-1} \hat{i}$

+ Gauss's Law of Electricity :-

Flux is emerging out from the closed surface is equal to charge enclosed by the surface per ϵ_0

$\phi_e = \oint_S \vec{E} \cdot d\vec{s} = \frac{q}{\epsilon_0}$

Differential form of Gauss Law :-

$\nabla \cdot \vec{D} = \rho$ $\vec{D} = \text{Electric displacement vector}$

$\vec{D} = \epsilon_0 \vec{E}$

charge & charge density are related.

$q = \int_V \rho dv \rightarrow (1)$

+ Gauss's Law in Electricity :-

$\oint_S \vec{E} \cdot d\vec{s} = \frac{q}{\epsilon_0}$

$\oint_S \vec{E} \cdot d\vec{s} = \frac{1}{\epsilon_0} \int_V \rho dv$

$\oint_S (\epsilon_0 \vec{E}) \cdot d\vec{s} = \int_V \rho dv$

$$\oint_C \vec{D} \cdot d\vec{s} = \int_V \rho dv$$

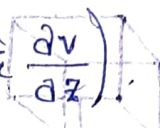
By using Gauss law divergence theorem in left hand side.

$$\int_V (\vec{\nabla} \cdot \vec{D}) dv = \int_V \rho dv$$

for an arbitrary volume

$$\boxed{\vec{\nabla} \cdot \vec{D} = \rho} \rightarrow 1^{st} \text{ max. equation}$$

Relation b/w electric field & Potential :- $[\vec{E} \text{ \& } v]$

$$\vec{E} = -\frac{\partial v}{\partial x} \hat{i} - \frac{\partial v}{\partial y} \hat{j} - \frac{\partial v}{\partial z} \hat{k} \quad \vec{E} = \left(\hat{i} \frac{\partial v}{\partial x} + \hat{j} \frac{\partial v}{\partial y} + \hat{k} \frac{\partial v}{\partial z} \right)$$


$$\boxed{\vec{E} = -\vec{\nabla} \cdot v}$$

Poisson's Equation and Laplace Equation :-

Gauss's law in electricity is given by

$$(\vec{\nabla} \cdot \vec{D} = \rho)$$

where, $\vec{D} = \epsilon_0 \vec{E}$

$$\vec{\nabla} (\epsilon_0 \vec{E}) = \rho$$

$$\vec{\nabla} (\vec{\nabla} \cdot v) = \frac{-\rho}{\epsilon_0}$$

$$\boxed{\nabla^2 v = \frac{-\rho}{\epsilon_0}}$$

→ These is called Poisson Equation.

For charge free region $\rho = 0$

$$\boxed{\nabla^2 v = 0}$$

→ These is called Laplace eqⁿ.

Maxwell's Eqⁿ in Differential form :-

1. $\vec{\nabla} \cdot \vec{D} = \rho$ Gauss law in electricity. $\left\{ \begin{array}{l} \text{div } \vec{D} \\ \text{div } \vec{E} \end{array} \right\}$

2. $\vec{\nabla} \cdot \vec{B} = 0$ Gauss law in Magnetism.

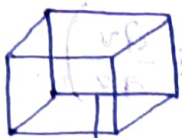
3. $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ Faraday's Law of electric magnetic induction.

4. $\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$ Modified ampere's Law $\vec{\nabla} = \text{del operator}$

→ Continuity Equation :-

$$\mathcal{P} = \frac{-dq}{dt} \rightarrow \textcircled{1}$$

$$\left\{ \begin{array}{l} \vec{\nabla} f(x, y, z) \rightarrow \text{gradient of } f \\ \vec{\nabla} \cdot \vec{A}(x, y, z) = \text{divergence of } \vec{A} \\ \vec{\nabla} \times \vec{A}(x, y, z) = \text{curl of } \vec{A} \end{array} \right.$$



$$\mathcal{P} = \frac{-dq}{dt}$$

charge is leaving the volume.

we know that $q = \int_V \rho dv \rightarrow \textcircled{2}$

$$\mathcal{P} = \frac{-d}{dt} \int_V \rho dv \rightarrow \textcircled{3}$$

Current & Current density are related with,

$$\vec{\nabla} \cdot \vec{J} = \frac{\partial \rho}{\partial t} = 0$$

Conservation of charge,

$$\mathcal{P} = \oint_S \vec{J} \cdot d\vec{s} \rightarrow \textcircled{4}$$

from $\textcircled{3}$ & $\textcircled{4}$ Equations

$$\frac{-dq}{dt} = \mathcal{P}$$

$$\oint_S \vec{J} \cdot d\vec{s} = \frac{-d}{dt} \int_V \rho dv$$

$$\oint_S \vec{J} \cdot d\vec{s} = - \int_V \frac{\partial \rho}{\partial t} dv$$

Only depends on time.

Use Gauss law divergence theorem in left hand theorem

$$\int_V (\vec{\nabla} \cdot \vec{J}) dv = - \int_V \frac{\partial \rho}{\partial t} dv$$

for any arbitrary volume

$$\boxed{\vec{\nabla} \cdot \vec{J} = -\frac{\partial \rho}{\partial t}}$$

Continuity Eqⁿ

(Conservation of charge)

If there is Stationary Current $\frac{d\rho}{dt} = 0$.

$$\vec{\nabla} \cdot \vec{J} = 0$$

• Derivation of 2nd Maxwell Equation :-

$$\vec{\nabla} \cdot \vec{B} = 0$$

proof : Gauss law in magnetism.

$$\oint_S \vec{B} \cdot d\vec{s} = 0$$

use Gauss's law divergence theorem,

$$\int (\vec{\nabla} \cdot \vec{B}) dV = 0$$

form an arbitrary volume, $\vec{\nabla} \cdot \vec{B} = 0$

Magnetic monopoles do not exist $\text{div } \vec{B} = 0$

• Derivation of 3rd Maxwell Equation :-

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt}$$

proof : According to Faraday's law, induced emf in closed loop is given by

$$E_{\text{emf}} = -\frac{d\phi_B}{dt} \quad \phi_B = \oint_S \vec{B} \cdot d\vec{s}$$

$$E_{\text{emf}} = -\frac{d}{dt} \oint_S \vec{B} \cdot d\vec{s} \rightarrow (1)$$

* Induced emf can also be calculated :

E_{emf} = work done in carrying out a unit charge around a closed loop.

$$E_{\text{emf}} = \oint_C \vec{E} \cdot d\vec{l} \rightarrow (2)$$

from (1) & (2) eqⁿs.

$$\oint_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \oint_S \vec{B} \cdot d\vec{s}$$

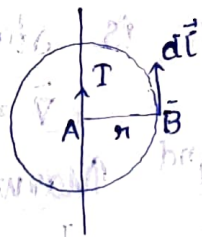
use Stoke's theorem,

$$\oint_S (\vec{\nabla} \times \vec{E}) \cdot d\vec{s} = -\oint_S \frac{d\vec{B}}{dt} \cdot d\vec{s}$$

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt}$$

Ampere's Circuit Law

$$\Rightarrow \oint_C \vec{B} \cdot d\vec{l} = \mu_0 I$$



Proof : use Biot's Savarts Law.

$$\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{2I}{r}$$

$$LHS = \oint \vec{B} \cdot d\vec{l}$$

$$= \oint B dl \cos 0 = B \oint dl = B \cdot 2\pi r$$

$$= \frac{\mu_0}{4\pi} \cdot \frac{2I}{r} \cdot 2\pi r = \mu_0 I$$

$$\frac{B}{\mu_0 I} = 1 = RHS.$$

$$\Rightarrow \oint \vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad \left[\vec{D} = \epsilon_0 \vec{E} \right]$$

Proof of 4th Maxwell Eqn:

According to Ampere's Circuit Law

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$$

$$\Rightarrow \oint \frac{\vec{B}}{\mu_0} \cdot d\vec{l} = I = \oint \vec{J} \cdot d\vec{s}$$

$$\oint_C \vec{H} \cdot d\vec{l} = \oint_S \vec{J} \cdot d\vec{s}$$

Use Stoke's theorem, Magnetic field Strength.

$$\oint_S (\vec{\nabla} \times \vec{H}) \cdot d\vec{s} = \oint_S \vec{J} \cdot d\vec{s}$$

For an arbitrary surface,

① $\left[\vec{\nabla} \times \vec{H} = \vec{J} \right]$ → accepts only for the Stationary Current.

Take div. Both Sides of ①

$$\text{div}(\nabla \times \vec{H}) = \text{div} \vec{J}$$

$$0 = \text{div} \vec{J} \Rightarrow \boxed{\nabla \cdot \vec{J} = 0}$$

Continuity equation is given by, $\vec{J} = \vec{H} \times \vec{V}$

$$\nabla \cdot \vec{J} + \frac{d\rho}{dt} = 0$$

$$\boxed{\nabla \cdot \vec{J} = 0} \text{ if } \frac{d\rho}{dt} = 0$$

Stationary Current.

For changing electric field :

According to Maxwell,

$$\textcircled{2} \rightarrow \boxed{\nabla \times \vec{H} = \vec{J} + \vec{J}'} \leftarrow \text{because of } \vec{J}_d$$

Because of Current (\vec{J})

Take div. of Both sides of eq ②

$$\text{div}(\nabla \times \vec{H}) = \text{div} \vec{J} + \text{div} \vec{J}'$$

$$0 = \frac{-d\rho}{dt} (\nabla \cdot \vec{D})$$

$$\nabla \cdot \vec{J}' = \nabla \cdot \left(\frac{d\vec{D}}{dt} \right) \Rightarrow \vec{J}' = \frac{d\vec{D}}{dt}$$

* The rate of change of electric field is known as displacement Current

$$\Rightarrow \nabla \times \vec{H} = \vec{J} + \frac{d\vec{D}}{dt}$$

⇒ Integral form of Maxwell's Eqⁿ :

Gauss's Law in electricity

$$1. \nabla \cdot \vec{D} = \rho$$

$$\oint_S \vec{D} \cdot d\vec{s} = q$$

$$2. \nabla \cdot \vec{B} = 0$$

$$\oint_S \vec{B} \cdot d\vec{s} = 0$$

$$\left(\nabla \cdot \vec{D} \right)$$

$$3. \quad \nabla \times \vec{E} = - \frac{\partial \vec{B}}{\partial t} \quad \oint \vec{E} \cdot d\vec{l} = - \frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{s}$$

$$4. \quad \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad \oint \vec{H} \cdot d\vec{l} = \oint \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \cdot d\vec{s}$$

Proof of 1st Maxwell's Eqn

$$\nabla \cdot \vec{D} = \rho$$

Take volume integration both sides.

$$\int_V (\nabla \cdot \vec{D}) dV = \int_V \rho dV$$

$$q = \int \rho dV$$

$$\boxed{\oint \vec{D} \cdot d\vec{s} = q}$$

$$\int (\nabla \cdot \vec{A}) dV = \oint \vec{A} \cdot d\vec{s}$$

Gauss div.

theorem

$$\nabla \cdot \vec{B} = 0$$

Take volume integration both sides.

$$\int_V (\nabla \cdot \vec{B}) dV = 0$$

$$\boxed{\oint \vec{B} \cdot d\vec{s} = 0}$$

Proof of 3rd Maxwell Eqn

$$\nabla \times \vec{E} = - \frac{\partial \vec{B}}{\partial t}$$

Take the surface integration b.s.

$$\oint_S (\nabla \times \vec{E}) \cdot d\vec{s} = - \frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{s}$$

$$\oint_V (\nabla \cdot \vec{B}) dV = 0 \Rightarrow \boxed{\oint \vec{B} \cdot d\vec{s} = 0}$$

$$\oint_S (\nabla \times \vec{E}) \cdot d\vec{s} = -\frac{d}{dt} \oint_S \vec{B} \cdot d\vec{s}$$

$$\boxed{\oint_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \oint_S \vec{B} \cdot d\vec{s}}$$

Proof

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\int (\nabla \times \vec{H}) \cdot d\vec{s} = \int \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \cdot d\vec{s}$$

$$\Rightarrow \boxed{\oint_C \vec{H} \cdot d\vec{l} = \oint_S \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \cdot d\vec{s}}$$

→ Physical Significance of Maxwell Eqn :-

→ First, Maxwell eqn is Gauss law in electricity
it states that electric flux out of any closed surface is proportional to the charge enclosed by that surface.

→ Integral form of 1st Maxwell's equation is used to find electric field around charged objects.

→ $(\nabla \cdot \vec{B}) \rightarrow$ Net Magnetic flux out of any closed surface is Zero.

→ $(\nabla \cdot \vec{D}) \rightarrow$ Gauss law in electricity.

→ There are no magnetic monopoles.

→ By changing magnetic field ($d\vec{B}$) by time we can induce electric field.

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$

→ Line integral of the electric field around a closed loop is equal to negative rate of change of magnetic flux through the area enclosed by the loop. $\rightarrow \oint_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \oint_S \vec{B} \cdot d\vec{S}$

$$4. \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

By changing electric field with time we can induce magnetic field.

→ Line integral of the magnetic field around a closed loop is proportional to the current flowing through the loop.

→ application of EM waves

→ Role of EM waves