ELECTROMAGNETIC THEORY

INTRODUCTION

Electromagnetic theory is a discipline concerned with the study of charges at rest and in motion. Electromagnetic principles are fundamental to the study of electrical engineering and physics. Electromagnetic theory is also indispensable to the understanding, analysis and design of various electrical, electromechanical and electronic systems. Some of the branches of study where

Electromagnetic principles find applications are:

1. RF communication
2. Microwave Engineering
3. Antennas
4. Electrical Machines
5. Satellite Communication
6. Atomic and nuclear research
7. Radar Technology
8. Remote sensing
9. EMI EMC
10. Quantum Electronics
11. VLSI

Electromagnetic theory is a prerequisite for a wide spectrum of studies in the field of Electrical Sciences and Physics. Electromagnetic theory can be thought of as generalization of circuit theory. There are certain situations that can be handled exclusively in terms of field theory. In electromagnetic theory, the quantities involved can be categorized as **source quantities** and **field quantities**. Source of electromagnetic field is electric charges: either at rest or in motion. However an electromagnetic field may cause a redistribution of charges that in turn change the field and hence the separation of cause and effect is not always visible.

Sources of EMF:

- Current carrying conductors.

- Mobile phones.
- Microwave oven.
- Computer and Television screen.
- High voltage Power lines.

Effects of Electromagnetic fields:

- Plants and Animals.
- Humans.
- Electrical components.

Fields are classified as

- Scalar field
- Vector field.

Electric charge is a fundamental property of matter. Charge exist only in positive or negative integral multiple of **electronic charge**, -e, e= 1.60 × 10-19 coulombs. [It may be noted here that in 1962, Murray Gell-Mann hypothesized **Quarks** as the basic building blocks of matters. Quarks were predicted to carry a fraction of electronic charge and the existence of Quarks have been experimentally verified.] Principle of conservation of charge states that the total charge (algebraic sum of positive and negative charges) of an isolated system remains unchanged, though the charges may redistribute under the influence of electric field. Kirchhoff's Current Law (KCL) is an assertion of the conservative property of charges under the implicit assumption that there is no accumulation of charge at the junction.

Electromagnetic theory deals directly with the electric and magnetic field vectors where as circuit theory deals with the voltages and currents. Voltages and currents are integrated effects of electric and magnetic fields respectively. Electromagnetic field problems involve three space variables along with the time variable and hence the solution tends to become correspondingly complex. Vector analysis is a mathematical tool with which electromagnetic concepts are more conveniently expressed and best comprehended. Since use of vector analysis in the study of electromagnetic field theory results in real economy of time and thought, we first introduce the concept of vector analysis.

Vector Analysis:

The quantities that we deal in electromagnetic theory may be either **scalar** or **vectors** [There are other class of physical quantities called **Tensors**: where magnitude and direction vary with co ordinate axes]. Scalars are quantities characterized by magnitude only and algebraic sign. A quantity that has direction as well as magnitude is called a vector. Both scalar and vector quantities are function of *time* and *position* . A field is a function that specifies a particular quantity everywhere in a region. Depending upon the nature of the quantity under consideration, the field may be a vector or a scalar field. Example of scalar field is the electric potential in a region while electric or magnetic fields at any point is the example of vector field.

A vector $\vec{A}$ can be written as, $\vec{A} = \hat{a} A$,

where, $A = |\vec{A}|$ is the magnitude

and $\hat{a} = \frac{\vec{A}}{|A|}$ is the unit vector which has unit magnitude and same direction as that of $\vec{A}$.

Two vector $\vec{A}$ and $\vec{B}$ are added together to give another vector $\vec{C}$. We have

$$\vec{C} = \vec{A} + \vec{B} \quad \text{................(1.1)}$$

Let us see the animations in the next pages for the addition of two vectors, which has two rules:

1: Parallelogram law and **2: Head & tail rule**

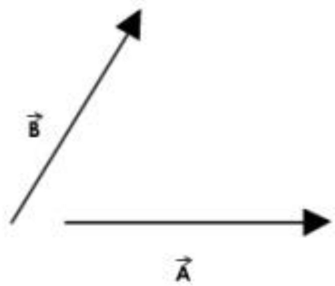

Fig 1.1(b): Vector Addition (Head & Tail Rule)

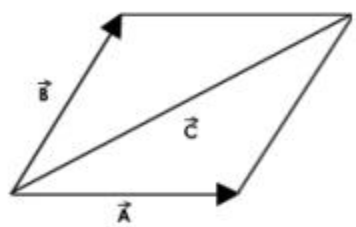

Fig 1.1(a):Vector Addition(Parallelogram Rule)

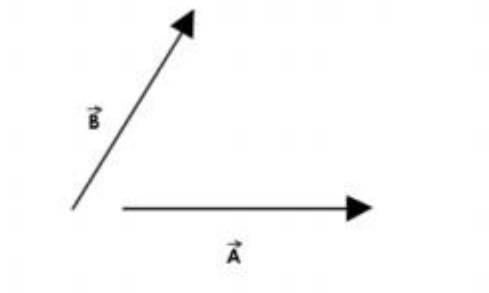

Fig 1.1(b): Vector Addition (Head & Tail Rule)

VECTOR ADDITION

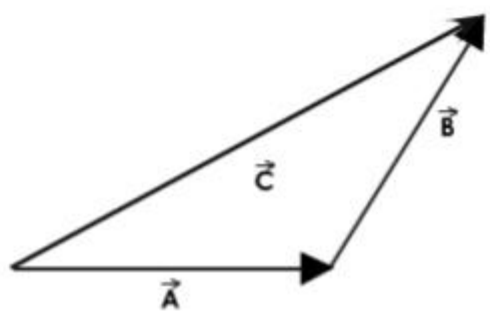

Fig 1.1(b): Vector Addition (Head & Tail Rule)

Vector Subtraction is similarly carried out: $\vec{D} = \vec{A} - \vec{B} = \vec{A} + (-\vec{B})$ ....(1.2)

VECTOR SUBTRACTION

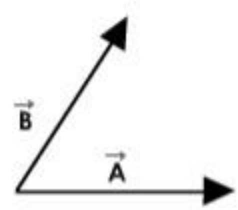

Fig 1.2: Vector subtraction

Vector Subtraction is similarly carried out: $\vec{D} = \vec{A} - \vec{B} = \vec{A} + (-\vec{B})$ ....(1.2)

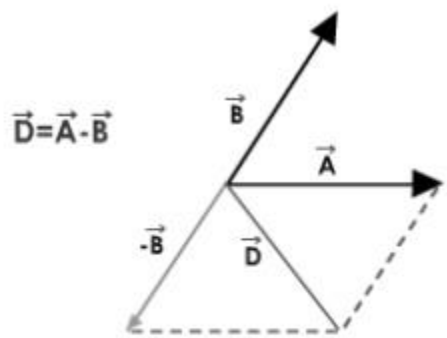

Fig 1.2: Vector subtraction

Scaling of a vector is defined as $\vec{C} = \alpha\vec{B}$, where $\vec{C}$ is scaled version of vector $\vec{B}$ and α is a scalar. Some important laws of vector algebra are:

$\vec{A} + \vec{B} = \vec{B} + \vec{A}$ Commutative Law..(1.3)

$\vec{A}+\left(\vec{B}+\vec{C}\right)=\left(\vec{A}+\vec{B}\right)+\vec{C}$ Associative Law..(1.4)

$\alpha(\vec{A}+\vec{B})=\alpha\vec{A}+\alpha\vec{B}$ Distributive Law ....(1.5)

The position vector $\vec{r_Q}$ of a point *P* is the directed distance from the origin (*O*) to *P*, i.e., $\vec{r_Q}=\overrightarrow{OP}$.

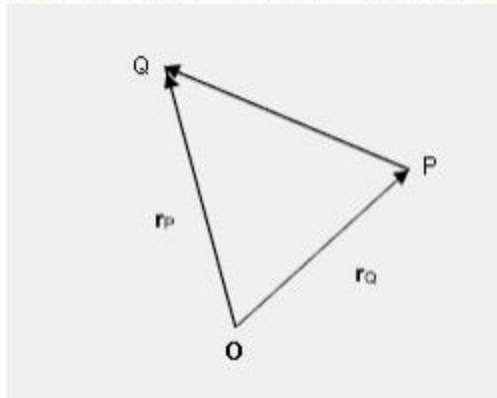

Fig 1.3: Distance Vector

If $\vec{r_Q}$ = OP and $\vec{r_P}$ = OQ are the position vectors of the points P and Q then the distance vector

$\overrightarrow{PQ}=\overrightarrow{OQ}-\overrightarrow{OP}=\vec{r_P}-\vec{r_Q}$

Product of Vectors

When two vectors $\vec{A}$ and $\vec{B}$ are multiplied, the result is either a scalar or a vector depending how the two vectors were multiplied. The two types of vector multiplication are:
Scalar product (or dot product) $\vec{A}\cdot\vec{B}$ gives a scalar.
Vector product (or cross product) $\vec{A}\times\vec{B}$ gives a vector.
The dot product between two vectors is defined as

$$\vec{A}\cdot\vec{B} = |A||B|\cos\vartheta_{AB}$$

Vector product

$$\vec{A}\times\vec{B} = |A||B|\sin\theta_{AB}\cdot\vec{n}$$

$\vec{n}$ is unit vector perpendicular to $\vec{A}$ and $\vec{B}$

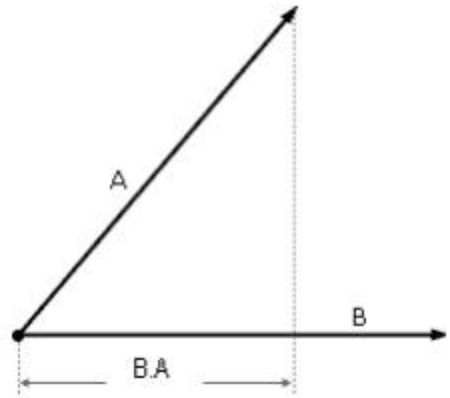

Fig 1.4: Vector dot product

The dot product is commutative i.e., $\vec{A}\cdot\vec{B}=\vec{B}\cdot\vec{A}$ and distributive i.e.,

$$\vec{A}\cdot\left(\vec{B}+\vec{C}\right)=\vec{A}\cdot\vec{B}+\vec{A}\cdot\vec{C}$$

Associative law does not apply to scalar product. The vector or cross product of two vectors $\vec{A}$ and $\vec{B}$ is denoted by

$\vec{A}\times\vec{B}$. $\vec{A}\times\vec{B}$ is a vector perpendicular to the plane containing $\vec{A}$ and $\vec{B}$, the magnitude is given by

$|A||B|\sin\theta_{AB}$

and direction is given by right hand rule as explained in Figure 1.5.

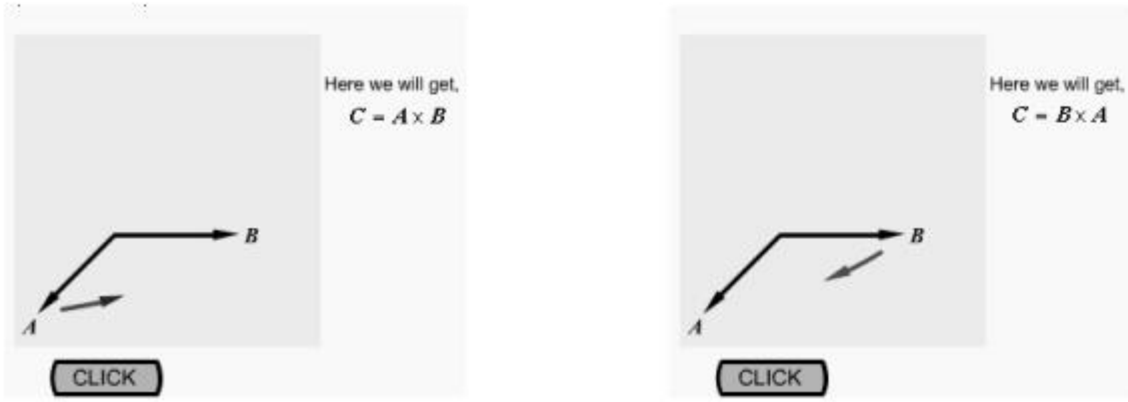

Fig 1.5 :Illustrating the left thumb rule for determining the vector cross product

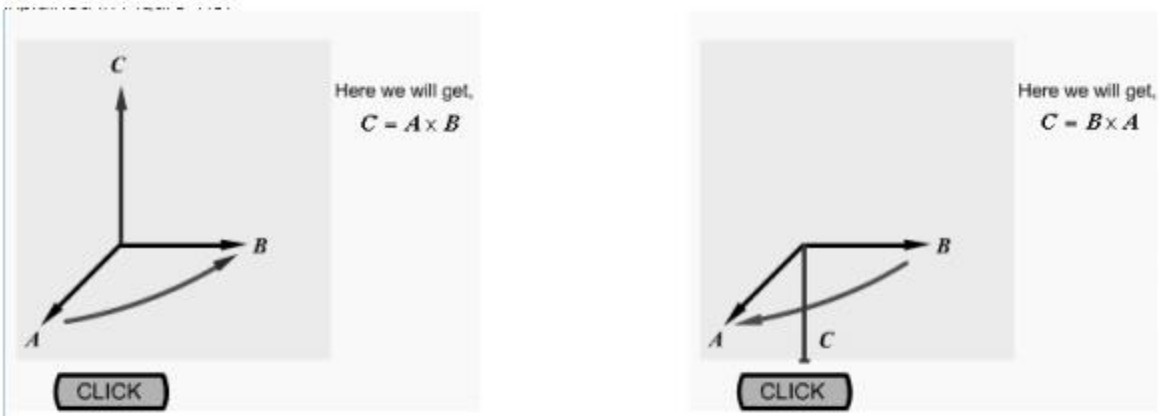

Fig 1.5 :Illustrating the left thumb rule for determining the vector cross product

$$\vec{A}\times\vec{B} = \hat{a}_n\, AB\sin\theta_{AB} \quad \text{.......(1.7)}$$

where $\hat{a}_n$ is the unit vector given by, $\hat{a}_n = \dfrac{\vec{A}\times\vec{B}}{|\vec{A}\times\vec{B}|}$.

The following relations hold for vector product.

$\vec{A}\times\vec{B} = -\vec{B}\times\vec{A}$ i.e., cross product is non commutative ....(1.8)

$\vec{A}\times\left(\vec{B} + \vec{C}\right) = \vec{A}\times\vec{B} + \vec{A}\times\vec{C}$ i.e., cross product is distributive.......................(1.9)

$\vec{A}\times\left(\vec{B} \times \vec{C}\right) \neq \left(\vec{A}\times\vec{B}\right)\times\vec{C}$ i.e., cross product is non associative.............(1.10)

Scalar and vector triple product :

Scalar triple product $\vec{A}\cdot\left(\vec{B} \times \vec{C}\right) = \vec{B}\cdot\left(\vec{C}\times\vec{A}\right) = \vec{C}\cdot\left(\vec{A}\times\vec{B}\right)$ ....(1.11)

Vector triple product $\vec{A}\times\left(\vec{B} \times \vec{C}\right) = \vec{B}\left(\vec{A}\cdot\vec{C}\right) - \vec{C}\left(\vec{A}\cdot\vec{B}\right)$ ....(1.12)