Electromagnetic Waves

Modification of Ampere's Circuital law by Maxwell and Concept of Displacement Current:

According to Ampere circuital law,

$$\oint \vec{B}.\,d\vec{l} = \mu_0 I \quad \text{---------- (1)}$$

Where I is the steady current passing through the closed loop (amperian loop).

If a capacitor is present in a circuit, Maxwell found that the Ampere's law gives contradictory results if is applied at two different points, one close to the connecting wires and another at the space between the plates of capacitor. Since the contradiction arises from our use of Ampere's circuital law, this law must be missing something.

So according to Maxwell the Ampere's Law should be modified to by considering I as sum of two types of currents – Conduction current and Displacement Current. The current carried by conductors due to flow of charges is called conduction current (I_C). The current generated due to changing electric field called displacement current (I_D)or Maxwell's displacement current.

$$\oint \vec{B}\,.\vec{dl} = \mu_0(I_C + I_D) \quad \text{---------- (2).}$$

Where I_D is the displacement current.

$$E = \frac{\varepsilon}{\varepsilon_0} = \frac{q/A}{\varepsilon_0}$$

$$q = \varepsilon_0(EA) = \varepsilon_0.\phi_E$$

$$I_D = \frac{dq}{dt} = \frac{\varepsilon_0 d\phi_E}{dt}$$

So from eq. (2) $$\oint \vec{B}.d\vec{l} = \mu_0\left(I_C + \frac{\varepsilon_o d\varphi_E}{dt}\right) \quad \text{------------(3)}$$

This equation is called modified equation of Ampere's Law.

NOTE: At any instant the value of conduction current is equal to the displacement current.

Maxwell's Equations of Electromagnetic Waves:

Maxwell used four fundamental equations of electricity and magnetism for development of the theory of electromagnetic waves.

1. Gauss's Law of Electrostatics:

$$\oint_s \vec{E}.d\vec{s} = \frac{q}{\varepsilon_0} \quad \text{------------------- (1)}$$

2. Gauss's Law of Magnetism

$$\oint_s \vec{B}.d\vec{s} = 0 \quad \text{----------------- (2)}$$

3. Modified eq. of Ampere's Law:

$$\oint \vec{B}.d\vec{l} = \mu_0 \left(I + \frac{\varepsilon_0 d\phi_E}{dt} \right) \qquad \text{------------ (3)}$$

4. Faraday's Law of electromagnetic induction

$$\varepsilon = -\frac{d\phi_B}{dt}$$

$$\Rightarrow \oint_c \vec{E}.d\vec{l} = -\frac{d\phi_B}{dt} \qquad [\ \varepsilon = \frac{W}{q_0} = \frac{1}{q_0}\oint_c \vec{F}.d\vec{l} = \frac{1}{q_0}\oint_c q_0\vec{E}.d\vec{l} = \oint_c \vec{E}.d\vec{l}\ ]$$

Maxwell solved the above four equations simultaneously using calculus. A part of the conclusion derived by him is the theory of electromagnetic wave.

NOTE: It is an important result of Maxwell's theory that accelerated charges radiate electromagnetic waves. Consider a charge oscillating with some frequency. (An oscillating charge is an example of accelerating charge.) This produces an oscillating electric field in space, which produces an oscillating magnetic field, which in turn, is a source of oscillating electric field, and so on. The oscillating electric and magnetic fields thus regenerate each other, so to speak, as the wave propagates through the space. The frequency of the electromagnetic wave naturally equals the frequency of oscillation of the charge. The energy associated with the propagating wave comes at the expense of the energy of the source – the accelerated charge.

- Since the experimental demonstration of generation of EM wave of visible range, due to oscillating charge, require alternating voltage of very high frequency, the experimental demonstration of electromagnetic radio waves or micro wave is only possible. This is the reason in Hertz's experiment wave had to come in the low frequency region (the radio wave region)(1887).
- Two important achievements in this connection deserve mention. Seven years after Hertz, Jagdish Chandra Bose, working at Calcutta (now Kolkata), succeeded in producing and observing electromagnetic waves of much shorter wavelength (25 mm to 5 mm). His experiment, like that of Hertz's, was confined to the laboratory.
- At around the same time, Guglielmo Marconi in Italy followed Hertz's work and succeeded in transmitting electromagnetic waves over distances of many kilometres. Marconi's experiment marks the beginning of the field of communication using electromagnetic waves.