# BASIC ELECTRICAL ENGINEERING UNIT II

#### **MODULE 2: Electromagnetism and Inductance**

### Outline

#### **Module 2: Electromagnetism and Inductance**

- Magnetic fields,
- Magnetic flux and Flux density,
- Magnetomotive force and Magnetic Field intensity,
- Permeability and magnetomotive force,
- Electromagnetic induction,
- Laws of magnetic force,
- Self and Mutual inductances.
- Inductances in series and parallel,
- Energy stored in an inductor;

## Magnetostatics



- Magnetostatics deals with the behaviour of stationary Magnetic fields.
- Hans Christian Oersted and André-Marie Ampère proved experimentally that the current carrying conductor produces a magnetic field around it.
- The origin of Magnetism is linked with current and magnetic quantities are measured in terms of current.

#### Magnetic dipole

- Any two opposite magnetic poles separated by a distance *d* constitute a magnetic dipole.
- Electromagnetism is a branch of Physics that describes the interactions involving electric charge.

## **Magnetic Fields**

- The primary source of magnetic field is a permanent magnet.
- It is a piece of ferromagnetic material (such as iron, nickel or cobalt) which has properties of attracting other pieces of these materials.
- A permanent magnet will position itself in a north and south direction when freely suspended.
- The north-seeking end of the magnet is called the north pole, N, and the south-seeking end the south pole, S.
- The area around a magnet is called the magnetic field and it is in this area that the effects of the magnetic force produced by the magnet can be detected.

### **Magnetic Fields**

- A magnetic field cannot be seen, felt, smelt or heard and therefore is difficult to represent. However, it exists in the region surrounding a permanent magnet.
- It can be represented by *magnetic flux lines* similar to electric flux lines. Magnetic flux lines, however, do not have origins or terminating points as do electric flux lines but exist in continuous loops, as shown in Fig. x.
- The strength of a magnetic field in a particular region is directly related to the density of flux lines in that region.
- If unlike poles of two permanent magnets are brought together, the magnets attract, and the flux distribution is as shown in Fig. y.
- If like poles are brought together, the magnets repel, and the flux distribution is as shown in Fig. z.







Flux distribution for two adjacent, opposite poles.





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### **Magnetic flux and flux density**



**Magnetic flux** is the amount of magnetic field (or the number of lines of force) produced by a magnetic source. The symbol for magnetic flux is  $\varphi$  (Greek letter 'phi'). The unit of magnetic flux is the weber, Wb

It can also be defined as the total number of lines of force emanating from North Pole.

**Magnetic flux density (or) Magnetic induction (B)** is the amount of flux passing through a defined area that is perpendicular to the direction of the flux:

$$B = \frac{\text{Magnetic Flux}}{\text{UnitArea}} = \frac{\varphi}{A} \quad \text{weber/m}^2(\text{or})\text{Tesla}$$



Magnetomotive force and magnetic field strength(intensity)



 Magnetomotive force (m.m.f.) is the cause of the existence of a magnetic flux in a magnetic circuit,

 $m.m.f.F_m$ =NI amperes-turns

Where: N is the number of conductors (or turns)

I is the current in amperes.

• Magnetic field strength (intensity) (or magnetising force),  $H = \frac{NI}{l}$  ampere – turns per meter

Where *l* is the mean length of the flux path in meters.

• Thus: 
$$m.m.f. = Hl \ ampere - turns$$

#### Magnetic Permeability (µ) and B–H curves

- For air, or any non-magnetic medium, the ratio of magnetic flux density to magnetizing force is a constant, i.e.  $\frac{B}{H} = \text{constant}$ .
- This constant  $\mu_0$  is the permeability of free space (or the magnetic space constant) and is equal to  $4\pi x \ 10^{-7} H/m$ , i.e.

$$\frac{B}{H} = \mu_0$$

• For all media other than free space,

$$\frac{B}{H} = \mu_0 \mu_r = \mu$$

Where  $\mu_r$  is the **relative permeability**,

 $\mu$  is the absolute permeability.



#### Magnetic Permeability (µ) and B–H curves

By plotting measured values of flux density B against magnetic field strength H, a magnetization curve (or B–H curve) is produced. For nonmagnetic materials this is a straight line. Typical curves for four magnetic materials are shown



Problem 2. The maximum working flux density of a lifting electromagnet is 1.8 T and the effective area of a pole face is circular in cross-section. If the total magnetic flux produced is 353 mWb, determine the radius of the pole face.

Problem 3. A magnetising force of 8000 A/m is applied to a circular magnetic circuit of mean diameter 30 cm by passing a current through a coil wound on the circuit. If the coil is uniformly wound around the circuit and has 750 turns, find the current in the coil. Flux density B = 1.8 T and flux  $\Phi = 353$  mWb =  $353 \times 10^{-3}$  Wb. Since  $B = \Phi/A$ , cross-sectional area  $A = \Phi/B$  $353 \times 10^{-3}$ 

$$=\frac{353\times10^{-3}}{1.8}\,\mathrm{m}^2=0.1961\,\mathrm{m}^2$$

The pole face is circular, hence area  $= \pi r^2$ , where r is the radius. Hence  $\pi r^2 = 0.1961$  from which,  $r^2 = 0.1961/\pi$  and radius  $r = \sqrt{(0.1961/\pi)} = 0.250$  m i.e. the radius of the pole face is 250 mm.

 $H = 8000 \text{ A/m}, l = \pi d = \pi \times 30 \times 10^{-2} \text{ m and } N = 750 \text{ turns}.$  Since H = NI/l, then

$$I = \frac{Hl}{N} = \frac{8000 \times \pi \times 30 \times 10^{-2}}{750}$$

Thus, current I = 10.05 A

(a) Magnetic field strength

Problem 6. A coil of 300 turns is wound  
uniformly on a ring of non-magnetic  
material. The ring has a mean circumference  
of 40 cm and a uniform cross-sectional area  
of 
$$4 \text{ cm}^2$$
. If the current in the coil is 5 A,  
calculate (a) the magnetic field strength, (b)  
the flux density and (c) the total magnetic  
flux in the ring.

$$H = \frac{NI}{l} = \frac{300 \times 5}{40 \times 10^{-2}}$$
$$= 3750 \,\text{A/m}$$

(b) For a non-magnetic material  $\mu_r = 1$ , thus flux density  $B = \mu_0 H$ 

i.e. 
$$B = 4\pi \times 10^{-7} \times 3750$$

 $= 4.712 \,\mathrm{mT}$ 

(c) Flux 
$$\Phi = BA = (4.712 \times 10^{-3})(4 \times 10^{-4})$$

 $= 1.885 \,\mu \text{Wb}$ 



#### **Class Work**



A magnetic field strength of 5000 A/m is applied to a circular magnetic circuit of mean diameter 250 mm. If the coil has 500 turns find the current in the coil.

Find the magnetic field strength and the magnetomotive force needed to produce a flux density of 0.33 T in an air-gap of length 15 mm.

#### **Electromagnetic induction**



- When a conductor is moved across a magnetic field so as to cut through the lines of force (or flux), an electromotive force (e.m.f.) is produced in the conductor.
- If the conductor forms part of a closed circuit then the e.m.f. produced causes an electric current to flow round the circuit. Hence an e.m.f. (and thus current) is 'induced' in the conductor as a result of its movement across the magnetic field. This effect is known as 'electromagnetic induction'.
- Figure below shows a coil of wire connected to a center-zero galvanometer, which is a sensitive ammeter with the zero-current position in the center of the scale.
- When the magnet is held stationary, even within the coil, no deflection is recorded.

#### **Electromagnetic induction**



- When the magnet is moved at constant speed towards and away from the coil, a deflection is noted on the galvanometer showing that a current has been produced in the coil.
- When a second coil is moved at the same speed towards and away from the stationary coil the same galvanometer deflection is noted.
- When the two coils are stationary, and current in the second coil is varied, the same galvanometer deflection is noted.

#### **Electromagnetic induction**





All these actions DO induce a current in the coil. What do they have in common? (They cause the magnetic field through the coil to *change*.)

• It is the relative movement of the magnetic flux and the coil that causes an e.m.f. and thus current, to be induced in the coil.

## **Laws of Electromagnetic Induction**



#### Faraday's laws of electromagnetic induction state:

- i. An induced e.m.f. is set up whenever the magnetic field linking that circuit changes.
- ii. The magnitude of the induced e.m.f. in any circuit is proportional to the rate of change of the magnetic flux linking the circuit.

#### Lenz's law states:

The direction of an induced e.m.f. is always such that it tends to set up a current opposing the motion or the change of flux responsible for inducing that e.m.f.

#### **Laws of Electromagnetic Induction**

An alternative method to Lenz's law is given by Fleming's Right-hand rule (often called the geneRator rule) which states:

Let the thumb, first finger and second finger of the right hand be extended such that they are all at right angles to each other (as shown in Fig. x).

If the first finger points in the direction of the magnetic field and the thumb points in the direction of motion of the conductor relative to the magnetic field, then the second finger will point in the direction of the induced e.m.f.

Note: First finger - Field

ThuMb - Motion

SEcond finger - E.m.f.





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#### Inductance



- Inductance is the property of a circuit whereby there is an e.m.f. induced into the circuit by the change of flux linkages produced by a current change.
- When the e.m.f. is induced in the same circuit as that in which the current is changing, the property is called *self inductance*, L.
- When the e.m.f. is induced in a circuit by a change of flux due to current changing in an adjacent circuit, the property is called *mutual inductance*, M.
- The unit of inductance is the henry, H.
- I henry is the inductance level that will establish a voltage of 1 volt across the coil due to a change in current of 1 A/s through the coil.

#### Inductance





- where  $d\varphi$  is the change in flux in Webers, and dt is the time taken for the flux to change in seconds.
- Induced e.m.f. in a coil of inductance L henrys,  $E = -L \frac{dI}{dt}$



Ferromagnetic core

Variable (permeability-tuned)

(d)

Air-con

Tapped

(c)

• where *dI* is the change in current in amperes and *dt* is the time taken for the current to change in seconds.

#### Inductor

A component called an inductor is used when the property of inductance is required in a circuit. The basic form of an Type: Air-core inductors (1-32 turns) Typical values: 2.5 nH-1 µH Applications: High-frequency applications: High-fre

#### Factors affecting the inductance of an inductor

- i. the number of turns of wire the more turns the higher the inductance
- ii. the cross-sectional area of the coil of wire the greater the cross-sectional area the higher the inductance
- iii. the presence of a magnetic core when the coil is wound on an iron core the same current sets up a more concentrated magnetic field and the inductance is increased
- iv. the way the turns are arranged a short thick coil of wire has a higher inductance than a long thin one.



Type: Toroid coil Typical values:  $10\mu$ H–30 mH Applications: Used as a choke in ac power line circuits to filter transient and reduce EMI interference. This coil is found in many electronic appliances.

Type: Common-mode choke coil Typical values: 0.6 mH-50 mH Applications: Used in ac line filters, switching power supplies, battery chargers, and other electronic equipment



#### Inductor

- If a current changing from 0 to I amperes, produces a flux change from 0 to  $\phi$  webers, then dI = I and  $d\phi = \phi$ .
- Then induced e.m.f.

$$E = -L\frac{l}{t}$$
$$E = \frac{N\varphi}{t} = \frac{LI}{t}$$

• from which, inductance of coil,

$$L = \frac{N\varphi}{I}$$

• Mutually induced e.m.f. in the second coil,

$$E_2 = -M\frac{dI_1}{dt}$$

where M is the mutual inductance between two coils, in henrys, and  $\frac{dI_1}{dt}$  is the rate of change of current in the first coil.

#### Inductors connected in series and parallel

- Inductors, like resistors and capacitors, can be placed in series or in parallel.
- Increasing levels of inductance can be obtained by placing inductors in series, while decreasing levels can be obtained by placing inductors in parallel.
- For inductors in series, the total inductance is found in the same manner as the total resistance of resistors in series given as

$$L_T = L_1 + L_2 + L_3 + \dots + L_N$$





#### Inductors connected in series and parallel

• For inductors in parallel, the total inductance is found in the same manner as the total resistance of resistors in parallel given as:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots + \frac{1}{L_N}$$



For two inductors in parallel,

$$L_T = \frac{L_1 L_2}{L_1 + L_2}$$

### **Energy Stored in a Inductor**



- An ideal capacitor does not dissipate any of the energy supplied to it. It stores the energy in the form of an electric field between the conducting surfaces.
- An ideal inductor possesses an ability to store energy and just like the ideal capacitor, it does not dissipate the electrical energy supplied to it. It stores the energy in the form of a magnetic field.
- The energy stored, W, in the magnetic field of an inductor is given by:

$$W = \frac{1}{2}LI^2 \text{ joules}$$

Problem 13. A flux of 25 mWb links with a 1500 turn coil when a current of 3 A passes through the coil. Calculate (a) the inductance of the coil, (b) the energy stored in the magnetic field, and (c) the average e.m.f. induced if the current falls to zero in 150 ms.

Inductance,

$$L = \frac{N\Phi}{I} = \frac{(1500)(25 \times 10^{-3})}{3} = 12.5 \,\mathrm{H}$$

Energy stored,

$$W = \frac{1}{2}LI^2 = \frac{1}{2}(12.5)(3)^2 = 56.25 \text{ J}$$

Induced emf,

$$E = -L\frac{dI}{dt} = -(12.5)\left(\frac{3-0}{150\times10^{-3}}\right)$$
$$= -250 \text{ V}$$

Alternatively,

$$E = -N \frac{d\Phi}{dt}$$
  
= -(1500)  $\left(\frac{25 \times 10^{-3}}{150 \times 10^{-3}}\right)$   
= -250 V

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Problem 18. Two coils have a mutual inductance of 0.2 H. If the current in one coil is changed from 10 A to 4 A in 10 ms, calculate (a) the average induced e.m.f. in the second coil, (b) the change of flux linked with the second coil if it is wound with 500 turns.

Induced e.m.f.

$$|E_2| = -M \frac{dI_1}{dt}$$
  
= -(0.2)  $\left(\frac{10-4}{10 \times 10^{-3}}\right) = -120 \text{ V}$ 

Induced e.m.f.

$$|E_2| = N \frac{\mathrm{d}\Phi}{\mathrm{d}t}$$
, hence  $\mathrm{d}\Phi = \frac{|E_2|\mathrm{d}t}{N}$ 

Thus the change of flux,

$$d\Phi = \frac{(120)(10 \times 10^{-3})}{500} = 2.4 \,\mathrm{mWb}$$





The mutual inductance between two coils is 240 mH. If the current in one coil changes from 15 A to 6 A in 12 ms, calculate (a) the average e.m.f. induced in the other coil, (b) the change of flux linked with the other coil if it is wound with 400 turns.



• Find the equivalent inductance of the circuit shown in Figure below.



#### Solution:

The 10-H, 12-H, and 20-H inductors are in series; thus, combining them gives a 42-H inductance. This 42-H inductor is in parallel with the 7-H inductor so that they are combined, to give

$$\frac{7 \times 42}{7 + 42} = 6 \text{ H}$$

This 6-H inductor is in series with the 4-H and 8-H inductors. Hence,

$$L_{\rm eq} = 4 + 6 + 8 = 18 \, {\rm H}$$

#### **Class work Problem**

Calculate the equivalent inductance for the inductive ladder network



The mutual inductance between two coils is 240 mH. If the current in one coil changes from 15 A to 6 A in 12 ms, calculate (a) the average e.m.f. induced in the other coil, (b) the change of flux linked with the other coil if it is wound with 400 turns.

### What does a capacitor look like?





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## Applications





# Thank You for Listening

