UNIT 7 MAGNETIC CIRCUIT, ELECTROMAGNETISM AND ELECTROMAGNETIC INDUCTION

7.1 Magnetism

7.1.1 The principles of magnetism and its characteristic

Magnetism is defined as the force produced by charge particles (electrons) of magnet. A magnet is a material that generates a magnetic field.

A permanent magnet 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 direction of a line of flux is from the north pole to the south pole on the outside of the magnet and is then assumed to continue through the magnet back to the point at which it emerged at the north pole. Thus such lines of flux always form complete closed loops or paths, they never intersect and always have a definite direction. The laws of magnetic attraction and repulsion can be demonstrated by using two bar magnets. In Figure 1(a), with unlike poles adjacent, attraction takes place. Lines of flux are imagined to contract and the magnets try to pull together. The magnetic field is strongest in between the two magnets, shown by the lines of flux being close together. In Figure 1(b), with similar poles adjacent (i.e. two north poles), repulsion occurs, i.e. the two north poles try to push each other apart, since magnetic flux lines running side by side in the same direction repel.
7.1.2 Magnetic field

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. A magnetic field cannot be seen, felt, smelt or heard and therefore is difficult to represent. Michael Faraday suggested that the magnetic field could be represented pictorially, by imagining the field to consist of **lines of magnetic flux**, which enables investigation of the distribution and density of the field to be carried out.

The magnetic fields can be plot by using:

i. Compass
ii. Iron dust method

7.1.3 Characteristics of magnetic field / flux lines:

i. Forming a closing loop
ii. Did not crossed against each other
iii. Has a certain direction
iv. Repel between one another
v. Has a tension along its distance where it will tends to make them as short as possible

![Figure 2: Magnetic field characteristics](image)

7.1.4 a. Magneto motive force, $F_m$

Magneto motive force (mmf) is the cause of the existence of a magnetic flux in a magnetic circuit.

$$mmf, F_m = NI$$ Ampere turns
b. Reluctance, $S$
Reluctance is the ‘magnetic resistance of a magnetic circuit to the presence of magnetic flux.

$$S = \frac{F_m}{\Phi} = \frac{NI}{\Phi} = \frac{HI}{BA} = \frac{l}{\mu_0 \mu_r A}$$

The unit of reluctance is $1/H$ or $A/Wb$

c. Magnetic field strength, $H$
Magnetic field strength (or magnetizing force)

$$H = \frac{NI}{l} \text{ Ampere per metre}$$

Where $l$ is the mean length of the flux path in metres.

d. Magnetic flux and flux density
Magnetic flux is the amount of the magnetic field (or the number of lines of force) produced by a magnetic source. The symbol for magnetic flux is $\Phi$. The unit of magnetic flux is the Weber, Wb.

Magnetic flux density is the amount of flux passing through a defined area that is perpendicular to the direction of the flux:

$$\text{Magnetic flux density}, B = \frac{\text{magnetic flux}, \Phi}{\text{area}, A}$$

The symbol for magnetic flux density is $B$. The unit of magnetic flux density is Tesla, T.

e. Permeability and B-H curve for different magnetic materials
- Permeability is the ability of a magnetic circuit to produce magnetic flux lines in a material or substance that formed with a magnetic force is known as ‘permeability’.
- Symbol of permeability: $\mu$ ($m\mu$) and unit is Weber/ampere turns (Wb/AT)
- where $\mu = \frac{B}{H} = \frac{\text{flux density}}{\text{magnetic force}}$ or $\mu_0 \mu_r = B / H$

  $\mu = \text{absolute permeability}$
  $\mu_0 = \text{free space permeability}, 4\pi \times 10^{-7}$
  $\mu_r = \text{relative permeability}, \mu_r = B / B_0$ (substance) / $B$ (vacuum) for the same $H$, $\mu_r = B / B_0$

- **Notes**: for air, vacuum and non-magnetic material $\mu_r = 1$ ($\mu = \mu_0$)
7.2 Composite series magnetic circuit

For a series magnetic circuit having \( n \) parts, the total reluctance \( S \) is given by:

\[ S = S_1 + S_2 + \ldots + S_n \]

(This similar to resistor connected in series in an electrical circuit.)

**Example 1**

A closed magnetic circuit of cast steel contains a 6cm long path of cross-sectional area 1cm\(^2\) and a 2 cm path of cross-sectional area 0.5 cm\(^2\). A coil of 200 turns is wound around the 6 cm length of the circuit and a current of 0.4 A flows. Determine the flux density in the 2 cm path, if the relative permeability of the cast steel is 750.

**Solution:**

For the 6cm long path:

Reluctance \( S_1 = \frac{l_1}{\mu_0 \mu_r A_1} = \frac{6 \times 10^{-2}}{(4\pi \times 10^{-7})(750)(1 \times 10^{-4})} = 6.366 \times 10^5 / H \)

For the 2cm long path

Reluctance \( S_2 = \frac{l_2}{\mu_0 \mu_r A_2} = \frac{2 \times 10^{-2}}{(4\pi \times 10^{-7})(750)(0.5 \times 10^{-4})} = 4.244 \times 10^5 / H \)

Total circuit reluctance

\[ S = S_1 + S_2 = (6.366 + 4.244) \times 10^5 = 10.61 \times 10^5 / H \]

Flux density, \( B \) in the 2cm path

\[ B = \frac{\Phi}{A} \]
Where flux, $\Phi = \frac{NI}{s} = \frac{200 \times 0.4}{10.61 \times 10^5} = 7.5 \times 10^{-5} \text{ Wb}$

\[ B = \frac{7.5 \times 10^{-5}}{0.5 \times 10^{-4}} = 1.51 T \]

### 7.3 Comparison between electrical and magnetic quantities

<table>
<thead>
<tr>
<th>Electrical circuit</th>
<th>Magnetic circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.m.f, $E$ (V)</td>
<td>mmf, $F_m$ (A)</td>
</tr>
<tr>
<td>Current, $I$ (A)</td>
<td>Flux, $\Phi$ (Wb)</td>
</tr>
<tr>
<td>Resistance, $R$ (Ω)</td>
<td>Reluctance, $S$ (H⁻¹)</td>
</tr>
</tbody>
</table>

\[
I = \frac{E}{R} \\
R = \frac{\rho l}{A} \\
\Phi = \frac{mmf}{S} \\
S = \frac{l}{\mu_0 \mu_r A}
\]

### 7.4 Hysteresis and Hysteresis Loop

**Hysteresis** is the ‘lagging’ effect of flux density $B$ whenever there are changes in the magnetic field strength $H$. When an initially unmagnetized ferromagnetic material is subjected to a varying magnetic field strength $H$, the flux density $B$ produced in the material varies as shown in Figure 4, the arrows indicating the direction of the cycle. Figure 4 is known as a hysteresis loop.

From Figure 4, distance $OX$ indicates the residual flux density or remanence, $OY$ indicates the coercive force, and $PP'$ is the saturation flux density.

Hysteresis results in a dissipation of energy which appears as a heating of the magnetic material. The energy loss associated with hysteresis is proportional to the area of the hysteresis loop.

The area of a hysteresis loop varies with the type of material. The area, and thus the energy loss, is much greater for hard materials than for soft materials.

Figure 4: Hysteresis loop
7.5 Electromagnetism

7.5.1 Magnetic field due to an electric current

Let a piece of wire be arranged to pass vertically through a horizontal sheet of cardboard, on which is placed some iron filings, as shown in Figure 5(a).

If a current is now passed through the wire, then the iron filings will form a definite circular field pattern with the wire at the centre, when the cardboard is gently tapped. By placing a compass in different positions the lines of flux are seen to have a definite direction as shown in Figure 5(b).

![Figure 5(a)](image1)

![Figure 5(b)](image2)

If the current direction is reversed, the direction of the lines of flux is also reversed. The effect on both the iron filings and the compass needle disappears when the current is switched off. The magnetic field is thus produced by the electric current. The magnetic flux produced has the same properties as the flux produced by a permanent magnet. If the current is increased the strength of the field increases and, as for the permanent magnet, the field strength decreases as we move away from the current-carrying conductor.

Magnetic field is surrounding a conductor that carries current, thus the form of magnetic field that surrounds a straight conductor is in concentric cylindrical (Figure 6(a)).

The direction of magnetic field flux depends on the direction of current that flows in the conductor. Figure 6(b) shows the direction of flux, which is according to clock-wise when current enters the conductor (sign as “+” at the center of conductor). Meanwhile, Figure 6(c) shows the opposite case, where the direction of current is exit from the conductor (sign as “•”, where it will produce magnetic field flux according to anti-clockwise).
Example

Draw magnetic field that exist when two conductors carrying current are put near to each other, where:-

i. Current flows in the same direction on both of conductors.
ii. Current flows in the opposite direction between both conductors.

Solution

i. Current in same direction

A magnetic field set up by a long coil, or **solenoid**, is shown in Figure 7(a) and is seen to be similar to that of a bar magnet. If the solenoid is wound on an iron bar, as shown in Figure 7(b), an even stronger magnetic field is produced, the iron becoming magnetized and behaving like a permanent magnet.
The direction of the magnetic field produced by the current \( I \) in the solenoid may be found by either of three methods:

a) **Compass**

\[
\text{Figure 8}
\]

b) **Screw rule**

States that ‘If a normal right-hand thread screw is screwed along the conductor in the direction of the current, the direction of rotation of the screw is in the direction of the magnetic field.’

\[
\text{Figure 9}
\]

c) **The grip rule**

States that ‘If the coil is gripped with the right hand, with the fingers pointing in the direction of the current, then the thumb, outstretched parallel to the axis of the solenoid, points in the direction of the magnetic field inside the solenoid.’

\[
\text{Figure 10}
\]

### 7.6 Electromagnetic Induction

#### 7.6.1 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.’
**Fleming’s Right-hand rule** 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 Figure 11). If the first finger points in the direction of the magnetic field, 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.

![Figure 11](image)

In a generator, conductors forming an electric circuit are made to move through a magnetic field. By Faraday’s law an e.m.f. is induced in the conductors and thus a source of e.m.f. is created. A generator converts mechanical energy into electrical energy. The induced e.m.f. $E$ set up between the ends of the conductor shown in Figure 12 is given by:

$$E = Blv \text{ Volts}$$

where $B$, the flux density, is measured in teslas, $l$, the length of conductor in the magnetic field, is measured in metres, and $v$, the conductor velocity, is measured in metres per second.

![Figure 12](image)

If the conductor moves at an angle $\theta^\circ$ to the magnetic field (instead of at $90^\circ$ as assumed above) then

$$E = Blv \sin \theta \text{ Volt}$$

**Example 1**

A conductor 300 mm long moves at a uniform speed of 4 m/s at right-angles to a uniform magnetic field of flux density 1.25 T. Determine the current flowing in the conductor when

(a) its ends are open-circuited,
(b) its ends are connected to a load of 20 $\Omega$ resistance.

**Solution**

When a conductor moves in a magnetic field it will have an e.m.f. induced in it but this e.m.f. can only produce a current if there is a closed circuit.

Induced e.m.f. $E = Blv = (1.25)(300/1000)(4) = 1.5$ V
(a) If the ends of the conductor are open circuited no current will flow even though 1.5 V has been induced.

(b) From Ohm's law, \( I = \frac{E}{R} = \frac{1.5}{20} = 0.075 \text{ A or } 75 \text{ mA} \)

**Example 2**
At what velocity must a conductor 75 mm long cut a magnetic field of flux density 0.6 T if an e.m.f. of 9 V is to be induced in it? Assume the conductor, the field and the direction of motion are mutually perpendicular.

Solution
Induced e.m.f. \( E = Blv \), hence velocity \( v = \frac{E}{Bl} \)
Hence \( v = \frac{9}{(0.6)(75 \times 10^{-3})} = \frac{9 \times 10^3}{0.6 \times 75} = 200 \text{ m/s} \)

**Example 3**
A conductor moves with a velocity of 15 m/s at an angle of (a) 90°, (b) 60° and (c) 30° to a magnetic field produced between two square-faced poles of side length 2 cm. If the flux leaving a pole face is 5 μWb, find the magnitude of the induced e.m.f. in each case.

Solution
\( v = 15 \text{ m/s}; \) length of conductor in magnetic field, \( l = 2 \text{ cm} = 0.02 \text{ m}; \)
\( A = 2 \times 2 \text{ cm}^2 = 4 \times 10^{-4} \text{ m}^2, \Phi = 5 \times 10^{-6} \text{ Wb} \)

(a) \( E_{90} = Blv \sin 90° = (\Phi/A)lv \sin 90° = (5 \times 10^{-6})(0.02)(15)/(4 \times 10^{-4}) = 3.75 \text{ mV} \)
(b) \( E_{60} = Blv \sin 60° = E_{90} \sin 60° = 3.75 \sin 60° = 3.25 \text{ mV} \)
(c) \( E_{30} = Blv \sin 30° = E_{90} \sin 30° = 3.75 \sin 30° = 1.875 \text{ mV} \)