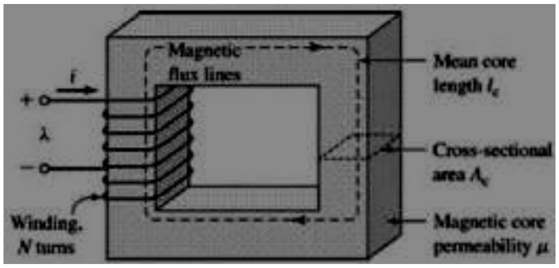
Magnetic Circuit Concepts:

- **Magnetic Circuit**: A closed path followed by magnetic flux is known as magnetic circuit (shown in diagram below), just like a closed path followed by current is known as electric circuit.

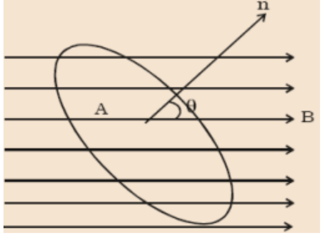


- **Magneto-Motive Force (MMF):** It is the force required for establishing magnetism or magnetic field in any conductor or coil or circuit. It is given by,

$$\boxed{\textbf{MMF= NI ampere-turn (AT)}}$$

where, N = number of turn in the coil.
I = current in the coil.
AT= Ampere-turn, unit of MMF.

- **Magnetic Flux (ϕ):** The magnetic flux (ϕ) linked with a surface held in a magnetic field (B) is defined as the number of magnetic lines crossing a closed area (A). as shown below-



If θ is the angle between the direction of the field and normal to the area then $\phi = \boldsymbol{B.A}$

$$\boxed{\phi = BA\cos\theta}$$

$$\boxed{if\ \theta = 0°, then, \phi = BA \quad weber(Wb)}$$

- **Magnetic Flux Density:**

The flux per unit area, measured in a plane perpendicular to flux is defined as the flux density (**B**).

i.e

$$\boxed{\boldsymbol{B = {}^{\phi}/_{A}}}$$

It has unit in weber per meter- square or Tesla

- **Magnetic Field Strength or Intensity or Magnetizing force:**

MMF per unit length of a coil in magnetic field in defined as Magnetic Field Strength. It is denoted by **'H'** given by,

$$\boxed{\boldsymbol{H = \frac{NI}{l} \quad {}^{AT}/_{m}}}$$

- **Permeability**:

  It is the ability of a material to carry the flux lines.

  - **High permeability material**- They allow the flux-lines to pass through them easily. e.g.-Iron, Steel etc.
  - **Low Permeability material**- They don't allow the flux lines to pass through them easily. e.g. - Wood.

For any magnetic material, we can define-

- **Absolute Permeability (μ):** It is the ratio of magnetic flux density (B) in a particular medium to the magnetic field strength (H), which produces magnetic flux density (B).

$$\boxed{\mu = \frac{B}{H} \qquad Henry\ per\ meter}$$

- **Permeability of the space/air/vacuum (μ_0):** If the medium in which the magnet is kept is air or vacuum, then the ratio of flux density (B) and magnetic field strength (H) is defined as the permeability of free space.

$$\boxed{\mu_0 = \frac{B\ of\ air}{H\ of\ air} \qquad Henry\ per\ meter}$$

$$\boxed{value\ of\ \mu_0 = 4\pi \times 10^{-7} \qquad Henry\ per\ meter}$$

- **Relative Permeability (μ_r):** The term relative permeability is defined as the ratio of the flux density in a particular medium produced by a magnet to the flux density in air or vacuum by the same magnet under the identical operating conditions.

$$\mu_r = \frac{B}{B_0}$$

$$B = \mu H \quad for\ a\ given\ medium$$

$$B_0 = \mu_0 H \quad for\ air\ orfreespace$$

$$\mu_r = \frac{B}{B_0} = \frac{\mu H}{\mu_0 H} = \frac{\mu}{\mu_0}$$

$$\boldsymbol{\mu = \mu_r \mu_0}$$

- **Reluctance:**

  It is defined as the opposition to the flux in material. It is denoted by '**Rl**' and given by,

$$\boxed{\boldsymbol{Rl = \frac{l}{\mu_0 \mu_r a}}}$$

where, $\boldsymbol{l}$ = length of the magnetic material in meters

$\boldsymbol{\mu_0}$ = permeability of free space or air = $4\pi \times 10^{-7} \quad H/M$

$\boldsymbol{\mu_r}$ = relative permeability

$\boldsymbol{a}$ = area of cross section of magnetic material in meter^2

- Since reluctance of magnetic circuit is something similar to resistance of electric circuit, hence it may also be defined as,

$$\boldsymbol{Rl = \frac{MMF}{flux} = \frac{NI}{\phi} \qquad Ampere - turn/weber}$$

- **Permeance:** It is defined as reciprocal of reluctance. $\boldsymbol{Permeance = \frac{1}{Reluctance} \qquad \frac{weber}{Ampere{-}turn}}$

- **Similarities between electrical and magnetic circuits are given below:**

Electric Circuit	Magnetic Circuit
Path traced by the current is known as electric current.	Path traced by the magnetic flux is called as magnetic circuit.
EMF is the driving force in the electric circuit. The unit is Volts.	MMF is the driving force in the magnetic circuit. The unit is ampere turns.
There is a current I in the electric circuit which is measured in amperes.	There is flux ϕ in the magnetic circuit which is measured in the weber.
The flow of electrons decides the current in conductor.	The number of magnetic lines of force decides the flux.
Resistance (R) opposes the flow of the current. The unit is Ohm	Reluctance (Rl) is opposed by magnetic path to the flux. The Unit is ampere turn/weber.
$R = \rho. l/a$. Directly proportional to l. Inversely proportional to a. Depends on nature of material.	$Rl = l/ (\mu_0\mu_r a)$. Directly proportional to l. Inversely proportional to $\mu = \mu_0\mu_r$. Inversely proportional to a
The current I = EMF/ Resistance	The Flux = MMF/ Reluctance
The current density(J)	The flux density(B)
Kirchhoff current law and voltage law is applicable to the electric circuit.	Kirchhoff mmf law and flux law is applicable to the magnetic flux.

- **There are few dissimilarities between the two circuits which are listed below:**

Electric Circuit	Magnetic Circuit
In the electric circuit, the current is actually flows. ie there is movement of electrons.	Due to mmf flux gets established and does not flow in the sense in which current flows.
There are many materials which can be used as insulators (air, PVC, synthetic resins etc) which current can not pass	There is no magnetic insulator as flux can pass through all the materials, even through the air as well.
Energy must be supplied to the electric circuit to maintain the flow of current.	Energy is required to create the magnetic flux, but is not required to maintain it.
The resistance and conductivity are independent of current density under constant temperature. But may change due to the temperature.	The reluctance, permanence and permeability are dependent on the flux density.
Electric lines of flux are not closed. They start from positive charge and end on negative charge.	Magnetic lines of flux are closed lines. They flow from N pole to S pole externally while S pole to N pole internally.
There is continuous consumption of electrical energy.	Energy is required to create the magnetic flux and not to maintain it.

- **Comparison between electrical and magnetic quantities :**

Electric Circuit	Magnetic Circuit
e.m.f. E (V)	M.M.F.
current I (A)	flux Φ (Wb).
resistance R (Ω)	reluctance (*Rl*) (H^{-1})
R= (ρl) / A	$Rl = l / \mu_0\mu_r A$
I = E / R	Φ = MMF / *Rl*

Magnetic Materials:

1. **Diamagnetic Materials-**
   - The materials which are repelled by a magnet such as zinc, mercury, lead, Sulphur, copper, silver, bismuth, wood etc., are known as diamagnetic materials.
   - Their relative permeability is slightly less than unity. For example, the relative permeabilities of bismuth, copper and wood are 0.99983, 0.999995 and 0.9999995, respectively.
   - They are slightly magnetized when placed in a strong magnetic field and act in the direction opposite to that of applied magnetic field.
   - In diamagnetic materials, the two relatively weak magnetic fields (one caused due to orbital revolution and other due to axial rotation) are in opposite directions and cancel each other.
   - Permanent magnetic dipoles are absent in them.

2. **Paramagnetic Materials-**
   - The materials, which are not strongly attracted by a magnet, such as aluminium, tin, platinum, magnesium, manganese etc., are known as paramagnetic materials.
   - Their relative permeability is small but positive. For example, the relative permeability for aluminium, air and platinum are 1.00000065, 1.0000031 and 1.00036, respectively.
   - Such materials are slightly magnetized when placed in a strong magnetic field and act in the direction of the magnetic field.
   - In paramagnetic materials the individual atomic dipoles are oriented in a random fashion. The resultant magnetic field is, therefore, negligible.
   - When an external magnetic field is applied, the permanent magnetic dipoles orient themselves parallel to the applied magnetic field and give rise to positive magnetization.
   - Since the orientation of the dipoles parallel to the applied magnetic field is not complete, the magnetization is small.
3. **Ferromagnetic Materials:**
   - The materials, which are strongly attracted by a magnet such as iron, steel, nickel, cobalt, and some of their alloys are known as ferromagnetic materials.
   - Their relative permeability of ferromagnetic material is very high (varying from several hundreds to many thousands).
   - The opposing magnetic effects of electron orbital motion and electron spin do not eliminate each other in an atom of such a material.
   - There is a relatively large contribution from each atom which aids in the establishment of an internal magnetic field, so that when the material is placed in a magnetic field, its value is increased many times the value that was present in the free space before the material was placed there.

   Ferromagnetic materials are of two types: (a) those easily magnetized, called the soft magnetic materials and (b) those retaining their magnetism with great determination, designated as hard magnetic materials.

   (a) **Soft Ferromagnetic Materials:**
      - They have high permeability, low coercive force, easily magnetized and demagnetized and have extremely small hysteresis.
      - Soft ferromagnetic materials are iron and its alloys with nickel, cobalt, Dagestan and aluminium.
      - Ease of magnetization and demagnetization makes them highly suitable for applications involving changing magnetic flux as in Electromagnets, Electric Motors, Transformers, Inductors, Telephone receivers, Relays etc.

- Large magnetic moment at room temperature makes soft ferromagnetic materials extremely useful for magnetic circuits but ferromagnetic material are very good conductors and suffer energy loss from Eddy currents produced within them.
- There is additional energy loss due to the fact that magnetization does not proceed smoothly but in minute jumps. This loss is called magnetic residual loss and it depends purely on the frequency of the changing flux density and not on its magnitude.

(b) Hard Ferromagnetic Materials:

- They have relatively low permeability, and very high coercive force. These are difficult to magnetize and demagnetize.
- Typical hard ferromagnetic materials include cobalt steel and various ferromagnetic alloys of nickel, aluminum and cobalt.
- They retain high percentage of their magnetization and have relatively high hysteresis loss. They are highly suited for use as permanent magnets in loudspeakers etc. Sometimes they are also called the permanent magnetic materials.
- During manufacturing, a high degree of dislocation is introduced. Hard ferromagnetic materials are frequently heated to high temperature and then quenched in suitable liquid to introduce strains.

4. Ferrites:

- This is a special group of ferromagnetic materials that occupy an intermediate position between ferromagnetic and nonmagnetic materials.
- They consist of extremely fine particles of a ferromagnetic material possessing high permeability and are held together with a binding resin.

The magnetization produced in the ferrites is large enough to be of commercial value, but their magnetic saturations are not as high as those of ferromagnetic materials. As in the case of ferromagnetic materials, ferrites may be soft or hard ferrites

Magnetization Curve or B-H Curve:

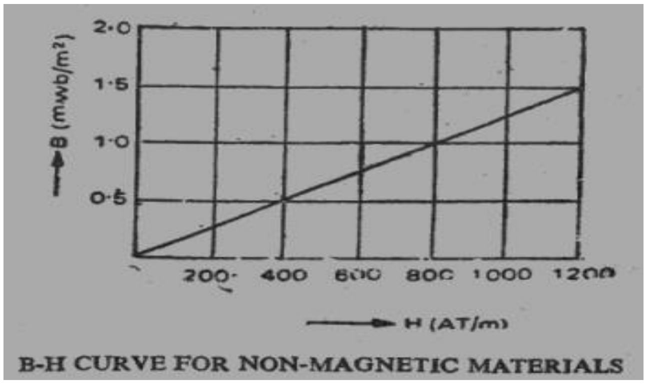
The B-H Curve (or magnetization curve) indicates the manner in which the flux density (B) varies with the magnetizing force or magnetic field intensity (H).

- **For non-magnetic materials**: For nonmagnetic materials (e.g., air, copper, rubber, wood etc.) the relation between B and H is given by,

$$B = \mu_0 H \quad \text{, since } \mu_0 = 4\pi \times 10^{-7}\ \frac{H}{M}\ \textit{is constant}$$

$$\textit{therefore},\ B \propto H$$

Hence B-H curve of a non-magnetic material is a straight line passing through origin as shown in fig below.



B-H CURVE FOR NON-MAGNETIC MATERIALS

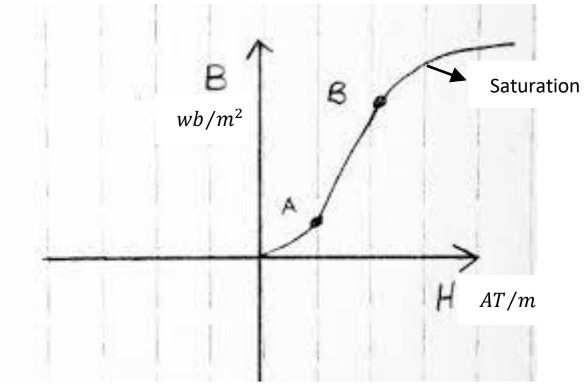
- **For magnetic materials:**

For magnetic materials (e.g., iron, steel etc.), the relation between B and H is given by,

$$B = \mu_0 \mu_r H$$

In above equation, relation between B and H is no more constant but, it varies with μ_r , as μ_r is not constant but varies with the flux density (B).

Consequently, the B-H curve of a magnetic material is not linear as shown below.



B-H curve of magnetic material

Magnetic Hysteresis:

When a ferromagnetic material is subjected to cycle of magnetization (i.e it is magnetized first in one direction and then in the other direction), it is found that magnetic flux density B in the material lag behind the applied magnetizing force or magnetic field intensity H. This phenomenon is known as **magnetic hysteresis**.

A typical B-H curve for magnetic material is shown below.

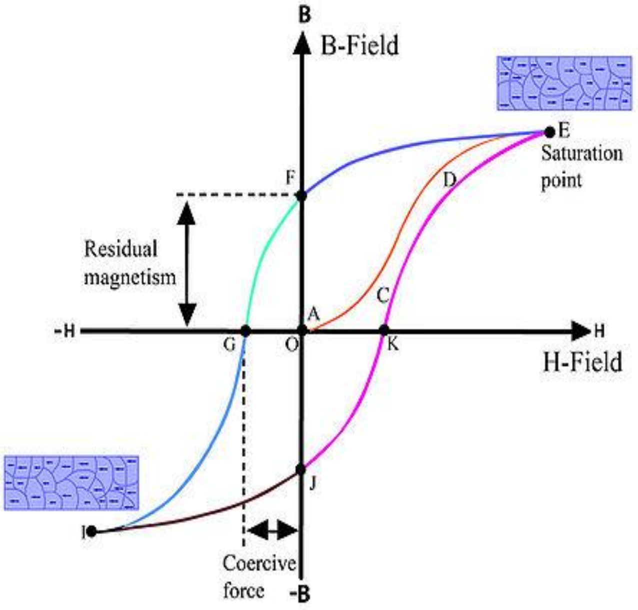


Fig Typical hysteresis loop of a ferromagnetic material

Note: A loop *OEFGIJKE* shown above is known as Hysteresis Loop

- **Important terms related to Hysteresis Loop:**
  - **Residual Magnetism-** The value of B (magnetic flux density) that remains after magnetic field intensity (H) is removed called residual magnetism or residual flux density.
  - **Retentivity:** The maximum possible value of the residual flux density is called retentivity.
  - **Coercive Force:** The amount of magnetic field intensity (H) required to reduce the residual flux density to zero is called coercive force.

Hysteresis Loss:

- When a magnetic material is subjected to a cycle of magnetization (i.e., it is magnetized first in one direction and then in the other direction), any energy loss takes place due to molecular friction in the material.
- That is, the domains* (or molecular magnets) of the material resist being turned first in direction and then in other.
- Energy is thus expended in the material in overcoming this opposition.

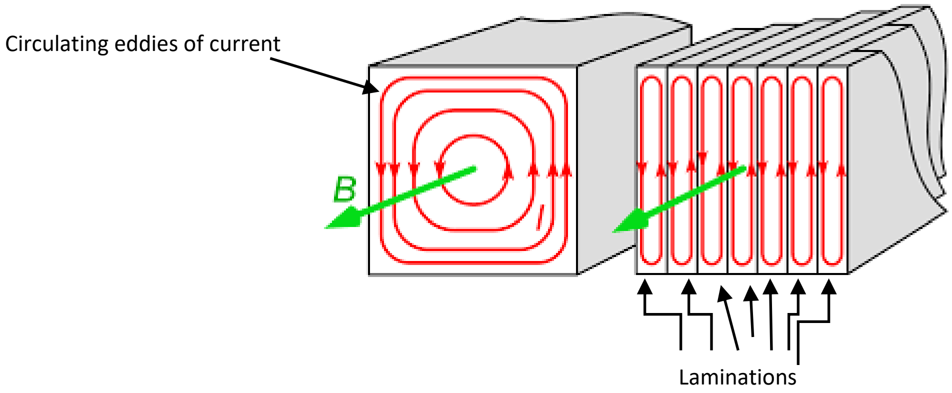
- This loss is in the form of heat and is called ***hysteresis loss***.
- Hysteresis loss is given by: $\boxed{P_H = kB_{max}^{1.6} fV \quad watts}$

Where B_{max} = Maximum flux density in the material
f = Frequency of magnetic reversals
V = volume of material in m^3
k = Steinmetz hysteresis coefficient

Note: *Domains is group of atoms (nearly 10^{11}) which have come together and aligned there magnetic dipole moment in one direction.

Eddy-Current Loss:

- Eddy current is formed due to change in magnetic flux linked with a metal.
- Consider a solid iron core (shown below in figure), with which a time varying flux is linking.
- The core may be considered to be made up of concentric shells. Since iron is conducting material, each shell may be treated as a closed coil.
- Each shell links with some portion of the flux.



- Hence emf induced in each shell, as per faraday's law of electromagnetic induction.
- Each induced emf causes current to flow in its closed shell.
- Hence circulating eddies of current is formed over the surface of iron core.
- As per Lenz's law this induced current will oppose change in magnetic field and also heat is generated due to the flow of eddy currents through the core.
- The power loss due to eddy currents is called ***eddy-current loss***.
- The eddy-current loss per unit volume of a magnetic core subjected to a time varying flux is given by:

$$\boxed{P_e = \frac{1.645}{\rho} t^2 f^2 B_{max} \qquad watt/meter^3}$$

Where B_{max} = Maximum flux density in the material
f = Frequency of magnetic reversals
t = thickness of core
ρ = resistivity of core

- **Methods of reducing eddy-currents:**
  - By making holes or slots on the metallic plate, thus reducing the area available to flow of eddy currents.
  - Eddy currents are minimized by using laminations of metal to make a metal core. The lamination must be separated by an insulating material like lacquer.
- **Application of Eddy-currents:**
  - Eddy current heating is used for heating metals, for example melting, hardening and other heat-treatment processes.
  - Eddy current damping is used in permanent-magnet moving –coil instrument for damping.
  - Eddy current braking is used in induction energy meters.