Chapter Four
Magnetic properties of matter

1. State and explain Faraday's Law of induction.

Statement:

First Law:

Whenever there is a change in the number of magnetic field lines or magnetic flux passing through a closed coil, then an electromotive force or electric current is induced in the coil. The induced electromotive force or electric current exists as long as the magnetic field lines or magnetic flux keeps changing.

Second Law:

The magnitude of induced electromotive force in a closed coil is directly proportional to the negative of the rate of change of magnetic flux, passing through the coil.

Let,

ϕ_1 = magnetic flux passing through a closed coil or circuit at a particular moment

ϕ_2 = magnetic flux through the coil or circuit after time t.

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Therefore, change of magnetic flux during time t is $= \phi_2 - \phi_1$

rate of change of magnetic flux $= \frac{\phi_2 - \phi_1}{t}$

According to the 2nd Law of Faraday

$$\varepsilon \propto -\frac{\phi_2 - \phi_1}{t}$$

$$\varepsilon = -K \frac{\phi_2 - \phi_1}{t}$$

$$\varepsilon = -\frac{\phi_2 - \phi_1}{t}$$

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

when $\varepsilon = 1$, $\phi_2 - \phi_1 = 1$, $t = 1$, then $K = 1$

for N turns of the coil

$$\boxed{\varepsilon = -N \frac{d\phi}{dt}}$$

2. What is Lenz's Law?

Law:

The direction of induced electromotive force or current is such that it always tends to oppose the very cause for which it is produced.

Thus from Lenz's Law we can know the direction of induced electromotive force and current. For this reason, minus sign is given before the quantity, $\varepsilon = -N\frac{d\phi}{dt}$.

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3. What is inductance?

Inductance is the tendency of an electrical conductor to oppose a change in the electric current flowing through it.

4. Define self-inductance and mutual-inductance.

Self inductance:

The magnetic flux linked with a circuit changes if the current in the charges or if the circuit moves in a magnetic field. The electromagnetic induction due to this change is called self induction.

Suppose, the magnetic flux crossing a coil is ϕ due to current I. then

$$\phi \propto I$$

$$\text{or, } \phi = LI$$

Again, we know,

$$\mathcal{E} \propto -\frac{d\phi}{dt}$$

$$\Rightarrow \mathcal{E} = -\frac{d}{dt}(LI)$$

If the number of turns in the coil is N, then

$$\mathcal{E} = -NL\frac{dI}{dt}$$

Unit of self inductance is henry.

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Mutual inductance:

Due to flow of unit current in the primary coil, the total flux linked with the secondary coil is called the mutual inductance.

Here,

$$\mathcal{E} = -\frac{d\phi}{dt} = -\frac{d}{dt}(MI) \quad \left[\because \phi = MI\right]$$

$$\Rightarrow \mathcal{E} = -M\frac{dI}{dt}$$

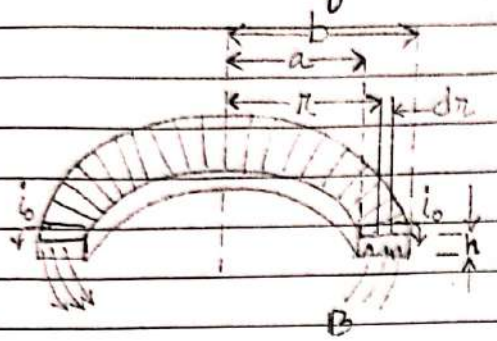
M is called mutual conductance.
unit henry.

5. Distinguish between self-inductance and mutual-inductance.

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2.6 Calculate the value of self inductance for toroid.

Inductance of a toroid of rectangular cross section.



Let us consider a toroid of rectangular cross section as shown in the figure.

The lines of magnetic field $\vec{B}$ for the toroid are concentric. According to Ampere's law we have,

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 i.$$

$$\Rightarrow B(2\pi r) = \mu_0 i_0 N \quad \left[\oint d\vec{l} = 2\pi r\right] \quad \ldots (1)$$

Where N is the number of turns, r is the radius and i_0 is the current in the toroid windings. And it is given that i is the total current that passes through the path of integration.

The magnetic field B is given by from eqn (1).

$$B = \frac{\mu_0 i_0 N}{2\pi r}$$

The flux ϕ_B for the cross section of the toroid is

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$$\Phi_B = \int \vec{B} \cdot d\vec{s}$$

$$= \int_a^b (B)(h\,dr)$$

$$= \int_a^b \frac{\mu_0 i_0 N}{2\pi r} h\,dr$$

$$= \frac{\mu_0 i_0 N h}{2\pi} \int_a^b \frac{dr}{r}$$

$$= \frac{\mu_0 i_0 N h}{2\pi} \left[\ln r\right]_a^b$$

$$= \frac{\mu_0 i_0 N h}{2\pi} \left[\ln b - \ln a\right]$$

$$= \frac{\mu_0 i_0 N h}{2\pi} \ln \frac{b}{a}$$

The inductance L is given by

$$L = \frac{N \Phi_B}{i_0} = \frac{N}{i_0} \frac{\mu_0 i_0 N h}{2\pi} \ln \frac{b}{a}$$

$$\therefore L = \frac{\mu_0 N^2 h}{2\pi} \ln \frac{b}{a}$$

This is the expression for the self inductance of a toroid.

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$$\mathcal{E}_{21} = -M_{21} \frac{di_1}{dt}$$

or, $$\mathcal{E}_{21} = M_{21} \frac{di_1}{dt}$$

Similarly,

$$\mathcal{E}_{12} = M_{12} \frac{di_2}{dt}$$

The negative sign indicates the direction of emf induced.

The process is called mutual induction.

2.7 Self Inductance

Calculation of inductance: for solenoid.

Let us consider a section of length l near the center of a long solenoid. Let the cross sectional area be A, the number of turns per unit length be n; the magnetic induction inside the solenoid be B.

The number of flux linkage in the length l of the solenoid is

$$N\Phi_B = (nl)(BA) \quad \text{..... (1)}$$

and B is given by

$$B = \mu_0 n i \quad \text{..... (2)}$$

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Combining eqn (1) and (2) we get

$$N\Phi_B = (nl)(\mu_0 n i A)$$

$$\therefore N\Phi_B = \mu_0 n^2 l i A$$

For a closed-packed coil the inductance is given by

$$L = \frac{N\Phi_B}{i}$$

$$= \frac{\mu_0 n^2 l i A}{i}$$

$$\therefore L = \mu_0 n^2 l A$$

Thus, the inductance of a length l of a solenoid is proportional to its volume (lA) and to the square of the number of turns per unit length.

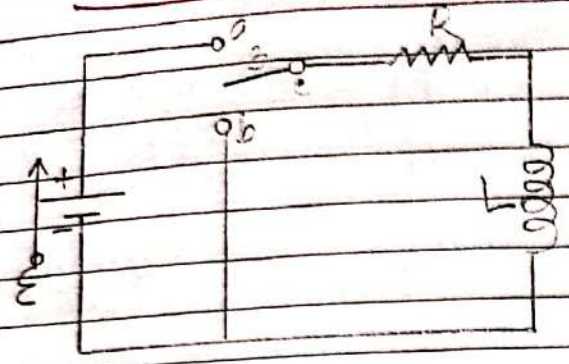
The inductance depends on geometrical factors only.

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An LR Circuit :



Let us consider an LR circuit containing a resistor R and and inductor L. When the switch S in figure (a) is closed on a, the current in the resistor starts to rise. If the inductor was not present, the current would rise rapidly to a steady value ε/R. Because of the inductor a self induced emf ε_L appears in the circuit and from Lenz's law, this emf opposes the rise of current. Thus the resistor responds to the difference between two emfs, they are ε which is constant and $\varepsilon_L = -L\, di/dt$ due to self induction.

As time goes on, the current increases slowly and ε_L becomes smaller.

According to loop theorem,

$$-iR + \varepsilon_L + \varepsilon = 0.$$

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$$\text{or, } -iR - L\frac{di}{dt} + \mathcal{E} = 0$$

$$\text{or, } L\frac{di}{dt} + iR = \mathcal{E}$$

$$\text{or, } L\frac{di}{dt} = \mathcal{E} - iR$$

$$\text{or, } \frac{di}{dt} = \frac{\mathcal{E}}{L} - \frac{iR}{L}$$

$$\text{or, } \frac{di}{dt} = \frac{R}{L}\left(\frac{\mathcal{E}}{R} - i\right)$$

$$\text{or, } \frac{di}{\left(\frac{\mathcal{E}}{R} - i\right)} = \frac{R}{L}dt$$

$$\text{or, } \int \frac{di}{\left(\frac{\mathcal{E}}{R} - i\right)} = \int \frac{R}{L}dt$$

$$\text{or, } -\ln\left(\frac{\mathcal{E}}{R} - i\right) = \frac{R}{L}t + c \quad \ldots\ldots (1)$$

When $t = 0$, $i = 0$

From eqn (1),

$$-\ln\left(\frac{\mathcal{E}}{R}\right) = c$$

Putting the value of c in eqn (1) we get

$$-\ln\left(\frac{\mathcal{E}}{R} - i\right) = \frac{R}{L}t - \ln\left(\frac{\mathcal{E}}{R}\right)$$

$$\text{or, } \ln\left(\frac{\mathcal{E}}{R} - i\right) - \ln\frac{\mathcal{E}}{R} = -\frac{R}{L}t$$

$$\text{or, } \ln\frac{\mathcal{E}/R - i}{\mathcal{E}/R} = -\frac{R}{L}t$$

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$$\text{or, } \ln i - \ln i_0 = -\frac{R}{L}t$$

$$\text{or, } \ln \frac{i}{i_0} = -\frac{R}{L}t$$

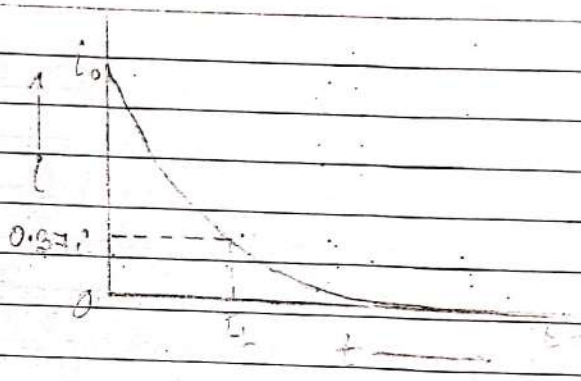
$$\text{or, } \frac{i}{i_0} = e^{-\frac{R}{L}t}$$

$$\text{or, } i = i_0 e^{-\frac{t}{\tau_L}} \quad \text{where } \tau_L = \frac{L}{R}.$$

When time $t = 0$, $i = i_0$

$t = \tau_L$, $i = 0.37 i_0$

$t = \infty$, $i = 0$



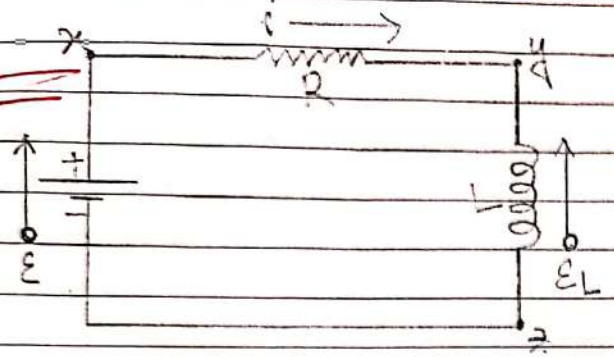
So, at time $t = 0$, when the time starts, the current was on its maximum value. At time τ_L, the current was fallen at 37% of its initial value.

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15 Energy stored in magnetic field :

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Let us consider a circuit which shows a source of emf $\mathcal{E}$ connected to a resistance R and d inductance L. From Kirchhoff's law,

$$\mathcal{E} = iR + L\frac{di}{dt}$$

or, $\mathcal{E}i = i^2R + Li\frac{di}{dt}$

If a charge dq passes through the source of emf in time dt, then the work done by source in time dt is $\mathcal{E}dq$. The rate of doing work is

$$\mathcal{E}\frac{dq}{dt} = \mathcal{E}i$$

That is, $\mathcal{E}i$ is the rate at which the source of emf delivers energy to the circuit.

i^2R is the rate at which energy appears as heat in the resistance R.

The energy that does not appear as heat ~~must~~ is

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stored in the magnetic field according to conservation of energy. Therefore, $Li\frac{di}{dt}$ represents the rate at which the energy is stored in the magnetic field. i.e.,

$$\frac{dU_B}{dt} = Li\frac{di}{dt}$$

or, $dU_B = Li\,di$

The energy stored in increasing the current from 0 to i_0 is

$$U_B = \int_0^{i_0} Li\,di = \frac{1}{2}Li_0^2 \quad \text{.... (1)}$$

This is the total stored magnetic energy in an inductance L carrying current i_0.

This relation is identical to the expression for the energy associated with a capacitor C carrying charge q, i.e.,

$$U_E = \frac{1}{2}\frac{q^2}{C}.$$

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10. What is a magnetic dipole?

Magnetic dipole is an arrangement of two unlike magnetic poles of equal pole strength separated by a very small distance, e.g., a small bar magnet, a magnetic needle, a current carrying loop etc.

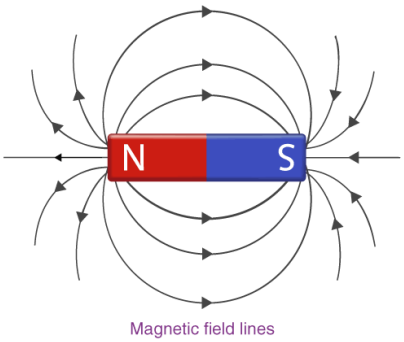
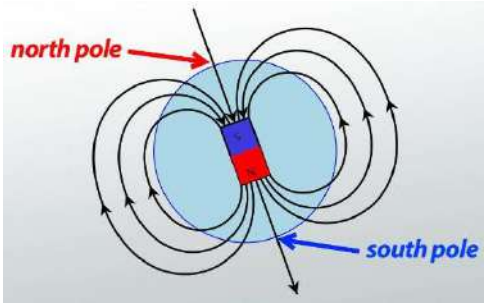


Figure 10: Magnetic dipole

11. What is pole?

Magnetic pole, region at each end of a magnet where the external magnetic field is strongest. A bar magnet suspended in Earth's magnetic field orients itself in a north–south direction. Unlike poles of different magnets attract each other; like poles repel each other.



12. Define magnetization?

Magnetization is the density of magnetic dipole moments that are induced in a magnetic material when it is placed near a magnet. Magnetization is also known as magnet polarization.

13. State and explain Gauss's law for magnetism.

In physics, Gauss's law for magnetism is one of the four Maxwell's equations that underlie classical electrodynamics. It states that the magnetic field B has divergence equal to zero, in other words, that it is a solenoidal vector field. It is equivalent to the statement that magnetic monopoles do not exist.

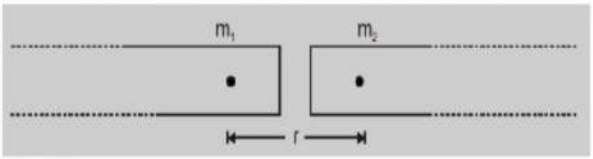
- We can write a similar relation for the magnetic case, however, there are *no* isolated magnetic charges (monopoles) exist. Therefore:

$$\oint \vec{B} \bullet d\vec{A} = 0$$

- This is Gauss's Law for Magnetism

14. State and explain coulomb's law for magnetism / magnetic induction.

Coulomb's Law in Magnetism



If two magnetic poles of strengths m_1 and m_2 are kept at a distance r apart then the force of attraction or repulsion between the two poles is directly proportional to the product of their pole strengths and inversely proportional to the square of the distance between them

$$F \propto \frac{m_1 m_2}{r^2} \quad or \; F = \frac{\mu_0}{4\pi} \frac{m_1 m_2}{r^2}$$

Where $\frac{\mu_0}{4\pi} = 10^{-7} WbA^{-1}m^{-1} = 10^{-7}$ henry/m where μ_0 is permeability of free space.

15. Write down (at least 6) characteristics of Paramagnetic, Diamagnetic and ferromagnetic material.

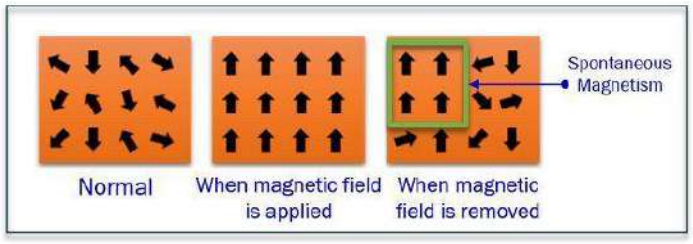
16. Write down the difference between Paramagnetic, Diamagnetic and ferromagnetic material.

PROPERTIES	FERROMAGNETIC MATERIALS	PARAMAGNETIC MATERIALS	DIAMAGNETIC
State	They are solid.	They can be solid, liquid or gas.	They can be solid, liquid or gas.
Effect of Magnet	Strongly attracted by a magnet.	Weakly attracted by a magnet.	Weakly repelled by a magnet.
Behavior under non-uniform field	tend to move from low to high field region.	tend to move from low to high field region.	tend to move from high to low region.
Behavior under external field	They preserve the magnetic properties after the external field is removed.	They do not preserve the magnetic properties once the external field is removed.	They do not preserve the magnetic properties once the external field is removed.
Effect of Temperature	Above curie point, it becomes a paramagnetic.	With the rise of temperature, it becomes a diamagnetic.	No effect.
Permeability	Very high	Little greater than unity	Little less than unity
Susceptibility	Very high and positive	Little greater than unity and positive	Little less than unity and negative
Examples	Iron, Nickel, Cobalt	Lithium, Tantalum,	Copper, Silver, Gold

17. What do you mean by Hysteresis and eddy current losses?

Definition of Hysteresis Loss

The hysteresis loss occurs in the core of the transformer. The core of the transformer is made of the CRGO steel which is a type of ferromagnetic material. The ferromagnetic material is made by the small atomic magnetic moments. When no field is applied to the material, in that case, the molecules are randomly arranged in the substance. When the MMF force applied to the material then the atomic magnetic moment arranged themselves parallel to each other in the axis of the magnetomotive force.When force removes then the atomic magnetic moment again arranges



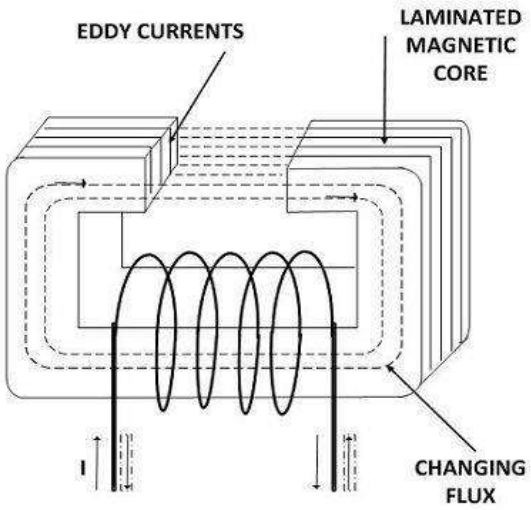
Ferromagnetic Material

Circuit Globe

themselves randomly but few of them still align parallel to each other. Because of these atomic magnetic moments the substance becomes slightly magnetizes. This type of magnetism is known as the spontaneous magnetism. For removing the spontaneous magnetism the reversed MMF applied to the material. The losses which occur because of the reversal of magnetism is known as the hysteresis losses.

Definition of Eddy Current Loss

The eddy current induces in the core of the transformer when the alternating flux links with them. The flux induces the EMF in the core because of which the circulating current develops. The circulating current cause losses in terms of heat which increases the temperature of the coil. The eddy current losses are independent of load and hence known as the constant losses.



18. Describe hysteresis curve of magnetization.

A **magnetic hysteresis**, otherwise known as a **hysteresis loop**, is a representation of the magnetizing force (H) versus the magnetic flux density (B) of a ferromagnetic material. The curvature of the hysteresis is characteristic of the type of material being observed and can vary in size and shape (i.e. narrow or wide). The loop can be generated by using a Hall Effect sensor to measure the amount of magnetic field at various points - when in the presence of a magnetic field, when it is removed from the magnetic field, and when a force is applied to bring the magnetic flux back to zero. These loops are important in the memory capacity of devices for audio recording or magnetic storage of data on computer disks.



Figure 1. The magnetic dipole moments for (a) paramagnetic and (b) ferromagnetic materials.

Figure 1: b). These dipole moments are so highly ordered that when removed from the magnetic field, there is still some remnant magnetization. In order to reduce the magnetic flux back to zero, a coercive force must be applied wherein the dipole moments cancel each other out. This hysteresis loop therefore summarizes the pathway that a ferromagnetic material takes from the addition and removal of a magnetizing force.

Hysteresis Loop Structure

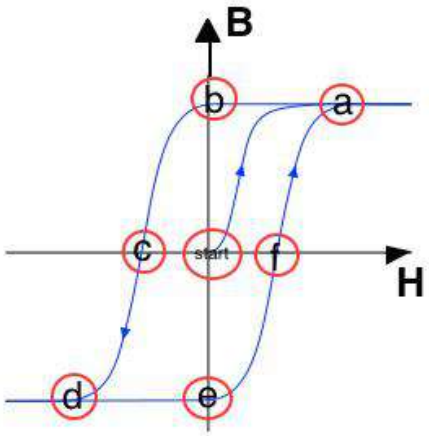


Figure 2. Schematic representation of a hysteresis loop for a ferromagnetic material portraying the saturation points (a and d), retentivity points (b and e), and coercivity points (c and f).

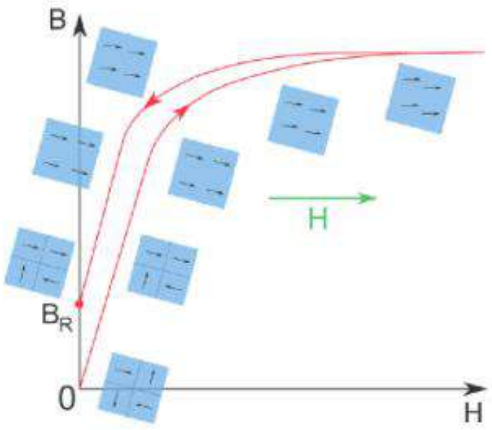
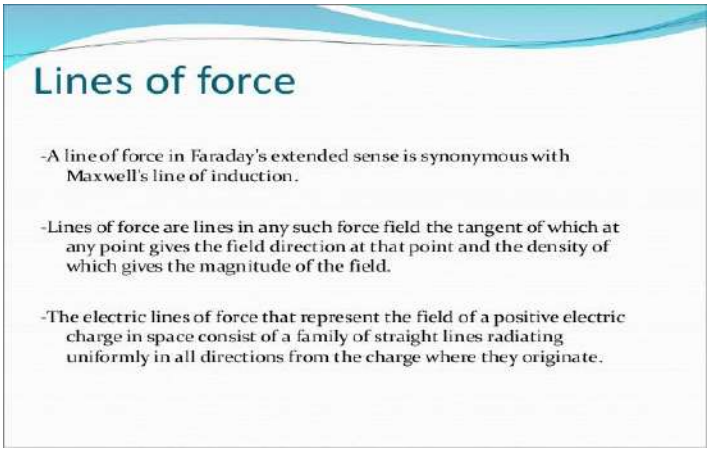


Figure 3. Schematic representation of the magnetic dipole moments with increasing and decreasing magnetizing force.

Hysteresis loops begin at a starting point (H=0) wherein its magnetic dipole moments are disoriented and the material portrays paramagnetism. When a magnetizing force (H) is adding to the material, it follows the pathway up to the saturation point (+Hs). At this point all the magnetic dipole moments are aligned in the direction of the magnetizing force and the magnetic flux no longer increases. When H is reduced to zero, some remnant magnetization remains; this point is known as the retentivity point (+Br). In order to remove this remnant magnetization, a coercive magnetizing force is applied in the reverse direction. The point in which there is no longer a magnetic flux (B=0) due to the cancelation of dipole moments acting in opposite directions is known as the coercivity point (-Hc). As the magnetizing force increases in the negative direction, the same saturation occurs as it did before however in the opposite direction (-Hs). The loop continues with an equal but opposite retentivity point (-Br) and coercivity point (+Hc) until its original saturation point (+Hs). Figure 2 portrays this full cycle hysteresis loop wherein points a and d are the +/- Hs, points b and e are the +/- Br, and points c and f are the +/- Hc. The magnetic dipole spins at these respective points can be seen in Figure 3 wherein the spins begin disoriented, then align with the magnetic field, and finally misalign until the moments cancel each other out to produce no net magnetic moment. Also notice that the curve does not ever go back to the origin (B and H=0). In order to get back to this point, the material will need to be demagnetized (i.e. return to having paramagnetic behavior) by hitting the material against a surface, reversing the direction of the magnetizing field, or heating it passed its Neel temperature. At this temperature, a ferromagnetic material becomes paramagnetic due to thermal fluctuations in the magnetic dipole moments that disorient the spins.

19 .**What is the difference between line of force and line of induction?**



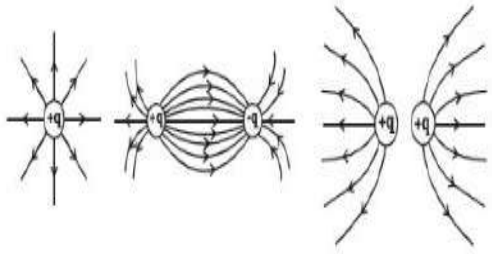


Fig1.5 Lines of Forces

Lines of Induction

Imaginary lines within a body marking the direction taken within it by magnetic induction. These are not necessarily parallel to lines of force, but may, in bodies of uniform agglomeration, or in crystalline bodies, take various directions.