Magnetic circuits

1) Introduction

Any body which possesses the power of attracting pieces of iron is known as magnet. And the property of a body by a virtue of which this attraction takes place is known as magnetism. Magnetism is one of nature's forms of energy. Some other forms are heat, light, sound and electricity. Natural magnetism is found in lodestone a type of iron ore, and the earth's vast magnetic field. Lodestone possesses magnetism when it is taken out from the Earth, so it is known as a natural magnetic. Lodestone was found in Magnesia (Upper part of Greece). Chinese later discovered that a slender piece of lodestone if suspended freely would Orient itself approximately in the direction of the earth's geographical north-south direction

2) Magnetic materials: Magnet materials are classified into three categories

1. Diamagnetic
2. Paramagnetic
3. Ferromagnetic

a. Diamagnetic materials:

A diamagnetic material, when placed in magnetic field, gets a feeble induce magnetic field in a direction opposite to that of the external magnetic field, it has a tendency to move from the region where the field is strong, to the region where the field is week, its permeability is less than unity. Temperature has no effect on the diamagnetic properties of a material.

E.g. Bismuth, Lead, Copper, Zink and Silver.

b. Paramagnetic material:

If a paramagnetic material is placed in a magnetic field, the magnetic field within the material gets enhanced. When placed in a non-uniform external field, it tends to move from the law to the high field region. The behavior of paramagnetic material is opposite to that of diamagnetic material. These materials have a permanent magnetic dipole moment. Paramagnetic decreases with rise in Temperature.

E.g. Aluminum, Sodium, Copper chloride.

c. Ferromagnetic Materials

A Ferromagnetic material gets magnetized even by weak magnetic field. A large magnetization occurs the direction of the external magnetic field. When placed in a non-uniform field; it is attracted towards the stronger magnetic field regions. ferromagnetism depresses with rise in Temperature.

E.g. Iron, Nickel, Cobalt

3) Classification of magnets: Magnets can be broadly classified inti following categories.

Permanent magnets and **electromagnets**

Permanent magnets retain their magnetism after the magnetic field used to magnetize them has been removed. These are of two types natural and artificial.

Natural magnets are comparatively weak, of irregular shape and of arbitrary size. These cannot be effectively to serve useful purposes.

The material such as special steel, hardened steel and alloys can be transformed into permanent magnets. These are termed as artificial magnets.

If the magnetization is done by passing electric current in a coil surrounding the material the magnet is termed as an electromagnet.

4) Magnetic induction

The phenomenon by which a magnetic substance becomes magnet when it is placed near a magnet is called magnetic induction.

A magnet has two distinctive properties attraction and repulsion and the depiction for magnetic substances and other magnetics the two ends of a magnet are called North (N) and South (S) poles.

A magnet will point towards north and south when freely suspended in air.

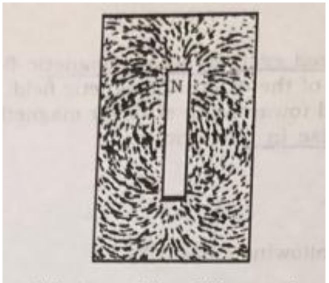
5) Magnetic field

It is space or region around a magnetic with in which the magnet effect can be detected. Suppose that a bar magnet is placed on a plane surface and iron filings are sprinkled on the surface around the magnet. on tapping the plane gently iron filings are found to arrange themselves in a certain pattern.

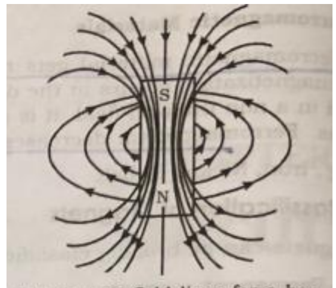
This proves that in the space around the magnet the influence of the magnet exists.

It is further important to observe that the iron filing arrange themselves along certain lines as shown in figure. These lines are called magnetic field lines from closed loops, leaving the magnet at its north pole and entering at its south pole.

A magnet field line is an imaginary line in space. The field lines are closed loops running from the north pole to south pole through the air and from south pole to north poles from the magnet.



(a) Pattern of iron fillings under the influence of a magnet



(b) Magnetic field lines for a bar magnet

6) Magnetic flux

Magnetic flux represents the total number of magnetic lines of force in a magnetic field. Magnetic flux is denoted by Greek letter phi ϕ. The unit of magnetic flux is Weber [Wb].

A north pole of pole strength m wb would radiate a magnetic flux of m wb.

7) Magnetic flux density

The flux passing through a unit area through a plane at right angles to the plane is defined as a magnetic flux density. It is denoted by the letter B. the unit of magnetic flux density is Tesla [T] or Wb/m^2

If ϕ Weber of magnetic flux is passing normally through an area of $metre^2$, the magnetic flux density B is given by:

$$B = \frac{\phi}{A}\ \mathrm{Wb}/m^2$$

8) Permeability

The ability of a material to conduct a magnetic flux through it is called permeability (absolute permeability) of that material. it is denoted by $\mu(mu)$. The permeability of free space or air is denoted by μ_0 and its value in S.I. unit is $4\pi 10^{-7}$Henry /meter.

9) Relative permeability

Relative permeability of a material relative to that of free space or air. It is denoted by μ_r

$$\mu_r = \frac{\mu}{\mu_0} \quad or\ \mu = \mu_0\mu_r$$

For air relative permeability is 1

10) Magnetic field intensity or magnetizing force

Magnetic field intensity at any point in a magnetic field is the force experienced by a unit north pole placed at the point. It is denoted by the letter H. the unit of H is A/m.

Relation between $B, H\ and\ \mu$

Consider a bar of magnetic material placed in uniform magnetic field of strength $H\ N/Wb$ resulting in magnetic flux density B Wb/m^2in the bar. Then the absolute permeability of the material of the bar is

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

11) Magneto motive force (MMF)

The magnetic pressure which sets up magnetic flux in a magnetic circuit is called magneto motive force (MMF).

Consider a coil N turns carrying a current of 1 ampere the mmf is given by:

MMF = Number of turns in the coil x Current = NI Amp. turns.

The unit of mmf is ampere- turns [At].

12) Reluctance

The opposition offered to the magnetic lines of force in a magnetic circuit is called reluctance.

It is denoted by the letter $\mathcal{R}$. Reluctance is analogues to resistance in an electric circuit. The unit of the reluctance is At/Wb.

Reluctance $\mathcal{R} = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A}$ Where :

$\boldsymbol{l}$: length of the magnetic path.

$\boldsymbol{\mu_0}$: permeability of free space

$\boldsymbol{\mu_r}$: relative permeability

$\boldsymbol{A}$: Cross- sectional area

13) Hopkinson's law

Hopkinson's Law describes the relationship between the reluctance of a magnetic circuit, the magnetomotive force and the magnetic flux. It is similar to Ohm's Law

Ohm's Law defines the relationship between voltage, current and resistance

It is described as

Voltage = Current x Resistance

Similarly, Hopkinson's Law can be written as

Magnetomotive Force = Flux x Reluctance

$$\boldsymbol{MMF = \mathcal{R}\phi}$$

Hopkinson's Law is also known as Rowland's Law

14) Permeance

It is the reciprocal of reluctance. It is expressed in $\frac{wb}{AT}$

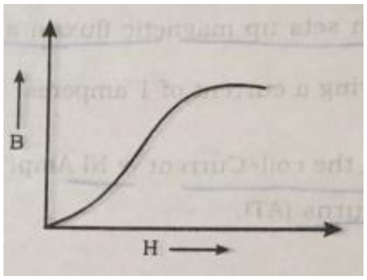
Permeance = $\frac{1}{reluctance} = \frac{Magnetic\ flux}{mmf}$ $\quad Or \quad Reluctance = \frac{mmf}{Magnetic\ flux}$

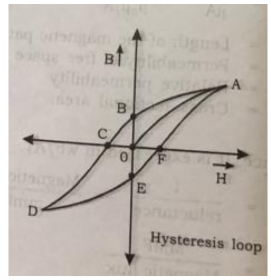
15) Comparison between magnetic and electric circuits

Magnetic circuit	Electric circuit
Magnetic flux $\phi = \frac{MMF}{\mathcal{R}}$ $[wb]$ Reluctance $\mathcal{R} = \frac{l}{\mu A}$ $[At/wb]$ Permeance $P = \frac{1}{\mathcal{R}}$ $[\frac{wb}{At}]$	Current $I = \frac{EMF}{R}$ [A] Resistance $R = \frac{\rho l}{A} = \frac{l}{\sigma A}$ Ω Conductance $G = \frac{1}{R}$ Ω^{-1}

16) Magnetization curve or B. H curve

It is the graph between the flux density (B) and magnetizing force (H) of a magnetic material. The following figure shows the B-H curve for cast iron.





Initially H increase rapidly with B up to a certain point. The rate of increase of B becomes very low and finally reaches steady value. i.e., Saturation of the material takes place.

17) Magnetic hysteresis

it is the lagging of flux density (B) behind the magnetic force (H) in a magnetic material.

Let a magnetizing force H be applied to an unmagnified bar of iron. Let the magnetizing Force H increased from Zero to a certain maximum value and then gradually reduced to zero. The curve OAB is obtained. At the point B, H becomes Zero. But there is still some magnetization left in the material. The flux density B does not fall to zero. The remaining value of B at the point is called residual magnetism. The power of retaining the magnetism is called “retentivity” of the material.

The value of H is reversed, B reduces and becomes zero at the point C. The value of H required to wipe of residual magnetism is known as a “Coercive Force”. OC is the coercive Force as shown in the figure. Further increase of H in the negative direction curve CD is obtained. Now the gradual decrease of H to Zero and then a build up in the original direction is described by the curve DEFA.

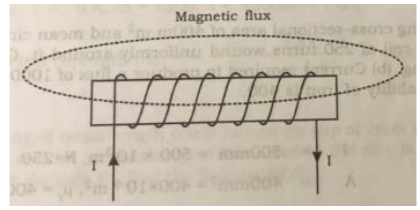
As H is increased and then decreased to its original values, the flux density B does not return to its original value. The fact is called “hysteresis”. The curve ABCDEFA is called hysteresis loop.

18) Magnetic circuit

A magnetic circuit is a closed path followed by magnetic lines of force. In electromagnetic there are two circuits or path, one for the current through the coil and one for the flux through the core.

Simple magnetic circuit.

The figure shown a solenoid having iron core and N turns of winding. The current through the winding is I. The mmf in the circuit is NI and this mmf sets up a magnetic field in the solenoid.

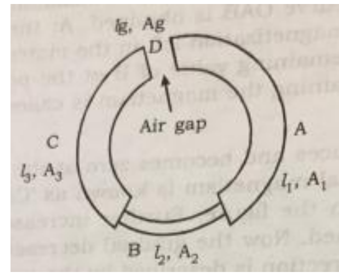


The length of the iron is l meter rand cross-sectional area $A\ m^2$.

Reluctance $\mathcal{R} = \frac{l}{\mu A}$.

Field intensity inside the solenoid: $H = \frac{NI}{l}$

19) Composite magnetic circuit



In several cases, the magnetic circuit consists of several regions of different materials and different dimensions. The figure shows four regions A, B, C, and D lengths $l_1, l_2, l_3, and\ l_g$ respectively. The area of cross-sectional are $A_1, A_2, A_3, and\ A_g$ respectively. Each of these regions has different reluctance. Then the total reluctance of the circuit is the sum of the individual reluctances.

Total reluctance $= \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3} + \frac{l_g}{\mu_0 A_g}$

Where: μ_1, μ_2, μ_3 and μ_0 are the permeability of A, B, C, and air respectively.

And: Flux $\phi = \frac{MMF}{\text{Total reluctance}}$

Example

An iron ring having cross- sectional area of 400 mm^2 and mean circumference of 500 mm carries a coil of 250 turns wound uniformly around it. Calculate:

1. Reluctance of the ring
2. Current required to produce a flux of 1000 $\mu\ wb$ in the ring.

Relative permeability of the iron is 400.

$l = 500mm = 500\ .\ 10^{-3}m, N = 25O$

$A = 400\ \ mm^2 = 400\ .\ 10^{-6}\ ;\ \mu_r = 400$

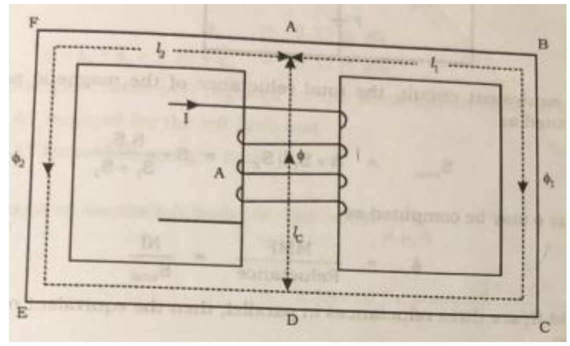
Reluctance $\mathcal{R} = \frac{l}{\mu_0 \mu_r A} = \frac{500\ .10^{-3}}{4\pi 10^{-7} \text{ x } 400 \text{ x } 400\ .10^{-6}} = 2487 \text{ x}10^3\ \frac{At}{wb}$

MMF = $\mathcal{R}\ \phi$, Hence: $I = \frac{\mathcal{R}\phi}{N} = \frac{1000 \text{ x } 10^{-6} \text{x } 2487 \text{ x}10^3}{250}$ = 9.948 A.

20) Parallel Magnetic Circuits

A magnetic circuit which has two or more than two paths for the magnetic flux is called parallel magnetic circuit.

The figure shows a magnetic circuit exited by a current of 1 ampere passing through N turns of a coil placed in the central limb. The $MMF = NI$ creates a flux of ϕ weber in the central limb of length l_c meter. The flux gets divided into two fluxes ϕ_1 and ϕ_2 in the outer limbs of lengths l_1 and l_2 meter respectively.



Thus: $\phi = \phi_1 + \phi_2$

The two magnetic paths $ABCD$ and $AFED$ are in parallel, the ampere turns required for this parallel circuit is equal to the ampere turns required foe any one of the paths.

Total MMF required = MMF required for path $AD + MMF$ required for path $ABCD$ or $AFED$

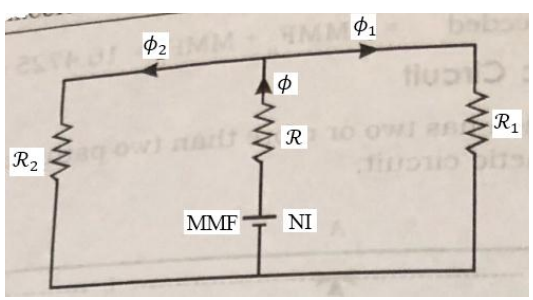
$$= \mathcal{R}\phi + \mathcal{R}_1\phi_1 \text{ or } = \mathcal{R}\phi + \mathcal{R}_2\phi_2$$

Where: $\boldsymbol{\mathcal{R}}$ is the reluctance of the central limb, $\boldsymbol{\mathcal{R}_1}$: is the reluctance of the path $ABCD$

$\boldsymbol{\mathcal{R}_2}$: is the reluctance of the path $ABCD$

$\mathcal{R} = \frac{l_c}{\mu_0 \mu_{rc} A_c}$, $\mathcal{R}_1 = \frac{l_1}{\mu_0 \mu_{r1} A_1}$ & $\mathcal{R}_2 = \frac{l_1}{\mu_0 \mu_{r2} A_2}$

The equivalent circuit of the magnetic shown in figure is as follows:



From the equivalent circuit, the total reluctance of the magnetic path $\mathcal{R}_T$ may be computed as:

$$\mathcal{R}_T = \mathcal{R} + \mathcal{R}_1 \parallel \mathcal{R}_2 = \mathcal{R} + \frac{\mathcal{R}_1 \mathcal{R}_2}{\mathcal{R}_1 + \mathcal{R}_2}$$

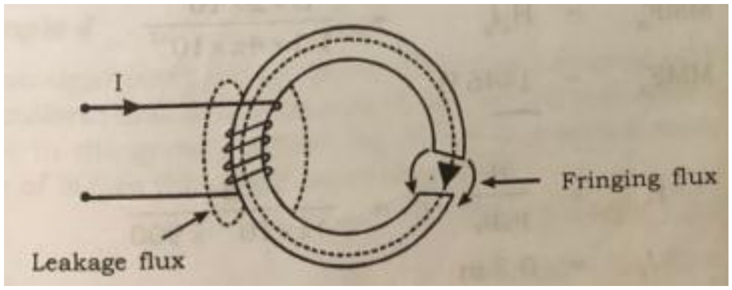
And the flux ϕ may be computed as: $\phi = \frac{NI}{\mathcal{R}_T}$

If $\mathcal{R}_1, \mathcal{R}_2\ and \mathcal{R}_3$ are three reluctances in parallel, then the equivalent reluctance

$$\frac{\mathbf{1}}{\boldsymbol{\mathcal{R}_{eq}}} = \frac{\mathbf{1}}{\mathcal{R}_1} + \frac{\mathbf{1}}{\mathcal{R}_2} + \frac{\mathbf{1}}{\mathcal{R}_3}$$

21) Leakage and Fringing in magnetic circuits

The flux which does not follow the desired path in a magnetic circuit is called Leakage flux.



Total flux set up = Useful flux + Leakage flux

Leakage factor $\boldsymbol{\lambda}$

It is defined as the ratio of total flux to the useful flux.

$$\lambda = \frac{Total\ flux}{Useful\ flux}$$

Fringing flux

Out of the total flux in air gap, a part of the flux diverges outside the main gap. As a result, effective cross-sectional area of the air gap increases and the flux density in the air gap decreases. The diverging flux is called the Fringing flux.