UNIT – I

MAGNETIC CIRCUIT AND MAGNETIC MATERIALS

1. **Write Lorentz force equation?(May-2011)**

   If a particle carrying charge +Q and moving with velocity $\overline{V}$ is present in a region where both electric and magnetic fields are present,then the particle in a motion experience forces $\overline{\mathrm{F_e}}\,and\,\overline{\mathrm{F_m}}$ due to the electric and magnetic fields are present respectively and resultant force

   $$\overline{\mathrm{F}} = \overline{\mathrm{F_e}} + \overline{\mathrm{F_m}} = \mathrm{Q}\,(\mathrm{E} + \overline{\mathrm{V}} \times \overline{\mathrm{B}})\ \text{Newton}$$

2. **Give Analogy between electric circuit and Magnetic circuit (Dec-2010)(May 2013)**

S.No	Electric Circuit	Magnetic circuit
1	Current=$\frac{\mathrm{Emf}}{\mathrm{Resistance}}$	Flux=$\frac{\mathrm{MMF}}{\mathrm{Reluctance}}$
2.	Resistance =$\frac{\rho\ell}{\mathrm{A}}$	Reluctance =$\frac{\ell}{\mu_o\mu_r\mathrm{A}}$
3.	Conductance =$\frac{1}{\mathrm{Resistance}}$	Permeance =$\frac{1}{\mathrm{Reluctance}}$
4.	E=$\frac{\mathrm{V}}{\mathrm{d}}$	H=$\frac{\mathrm{NI}}{\mathrm{l}}$

3. **Define torque? (May-2010)**

   A turning or a twisting force about an axis defined as torque.

4. **Distinguish between statically induced emf and dynamically induced emf.(Dec 2014)(May-Jun 2015)**

S.No	Statically Induced emf	Dynamically Induced emf
1	Magnetic field or flux changes its position but conductor remains constant	Conductor changes its position but magnetic field remains constant
2.	Eg:Transformer	Eg: Generator

5. **A conductor 80cm long moves at right angle to its length at a constant speed of 30 m/s in a uniform magnetic field of flux density 1.2T. Find the emf induced when the conductor motion is normal to the field flux?(May-2011)**

   $$\mathrm{E} = \mathrm{B}\,\ell\,\mathrm{v}\,\sin\theta$$
   $$= 1.2 \times 80 \times 10^{-2} \times 30 \times \sin 90°$$
   $$\mathrm{E} = 28.8\ \mathrm{V}$$

6. **What are the core losses and how can this loss be minimized? (May-2012)**

   When a magnetic material undergoes cyclic magnetization, two kinds of power losses occur on it. Hysteresis and eddy current losses are called as core loss

   Hysteresis loss– This loss can be reduced by selecting good quality magnetic material.

   Eddy current loss – This loss can be reduced by using thin laminations for the core.

7. **Clearly define MMF and EMF. (May-2012& Dec 2014)**

MMF: Itis the cause for producing flux in a magnetic circuit. The amount of flux setup in the core depends upon the current (I) and number of turns (N).

MMF=NI

EMF: It is the driving force in the electric circuit

$$\mathrm{EMF} = \mathrm{Current} \times \mathrm{Resistance}, \mathrm{EMF} = \ \mathrm{I} \times \mathrm{R}\ (\mathrm{Volts})$$

8. What is hysteresis loss and how can this loss be minimized? (Dec-2011, 2013, 2016)

When the magnetic material is subjected to **repeated cycles of magnetizationand demagnetization**, it results into disturbance in the alignment of the various domain. **All the energy is never returned** through field completely collapses. **This loss of energy appears as heat** in the magnetic material. This can be minimized by selecting good quality magnetic material like Silicon.

9. Define the term MMF and Reluctance(Dec 2009, 2003,2007)

MMF= NI (Ampere Turns)

Reluctance=MMF/flux=NI/ ϕ (AT/Wb)

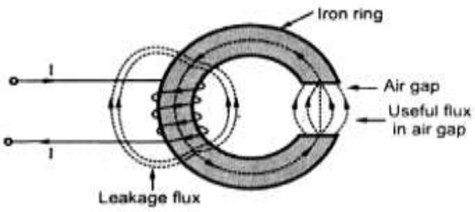
10. A coil of 1000 turns in linking a flux of 0.01 Wb, The flux is reversed in an interval of 0.1 S.Calculate the average value of emf induced in the coil?(May-2007)

$e=-N\frac{d\phi}{dt}$ [Flux changing from 0.01 to - 0.01]

$=-1000\times\frac{-0.01-0.01}{0.1}=-1000\times\frac{-0.02}{0.1}=200\mathrm{V}$

11. What is meant by leakage flux? (May-2004) (May 2016)

The flux which is passing through unwanted path is called leakage flux.



12. State ohms law of magnetic circuit?(Apr-2009)

MMF $=\phi\times s$

13. Classify magnetic material?(Dec 2008)

Magnetic material classified according to the nature of its relative permeability

$\mu_r > 1\ paramgnetic\ meterial$

$\mu_r < 1\ diamagnetic\ material$

$\mu_r > 1$

Ferromagnetic Ferrimagnetic

Hard Soft Hard Soft

For hard Ferro magnetic material- Alnico

Self Ferro magnetic material-Iron with its alloy with Ni, CO

Super magnetic material-Nichol, Zinc, Ferrites

14. Mention the factors on which hysteresis loss depends?

- The hysteresis loss is directly $\propto$ to the area under the hysteresis curve.
- It is directly $\propto$ to f (ie) number of cycle of magnetization
- It is directly $\propto$ to volume of the material.

15. **Name the main magnetic quantities with their symbols having the following Units. Webers, Telsa, AT/wb, H/m. (Dec 2013)**

Weber-flux

Telsa-Magnetic flux density

AT/wb-Reluctance

H/m –permeability

16. What is Permanent magnets?

The PM is an important excitation source commonly employed for imparting energy to magnetic circuits used in rotating machines and other types of electromechanical devices. There are three classes of PM materials (or hard magnetic material) used for PMDC Motors. Alnicos, ceramics (ferrites) and rare earth material. Alnico material are used in motors up to 200kwwhile ceramic materials most economic in fractional KW motors. For very high temperature applications Alnico or rare earth cobalt magnets must be used.

17. Define coactivity.

It is the measure of MMF which, when applied to the magnetic circuit would reduce its flux density to zero, i.e., it demagnetizes the magnetic circuit.

18. Mention some magnetic materials (May-Jun 2015)

Alnicos, chromium steels, copper–nickel alloy, nickel, cobalt, tungsten and aluminum.

19. What is magnetostriction?

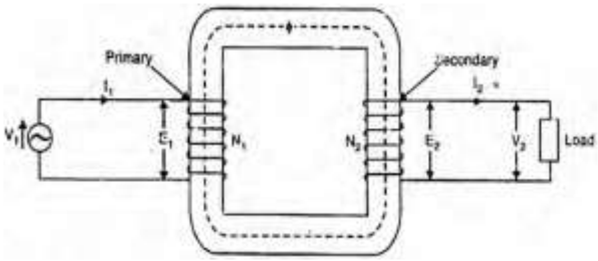
When ferromagnetic materials are subjected to magnetizing MMF, these may undergo small changes in dimension; this phenomenon is known as magnetostriction.

20. Define magnetic reluctance (May -2014)

The opposition offered by the magnetic circuit for the magnetic flux path is known as magnetic reluctance. It is analogous to electric resistance.

21. What is magnetically circuit Transformer?

A transformer is a static piece of equipment used either for raising or loweringthe voltage of an A.C. supply with a corresponding decrease or increase incurrent.



It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig. When the two circuits are placed very close to each other such that a magnetic flux produced by one circuit links with both the circuits, then the two circuits are said to be magnetically circuit.

22. What are quasi-static fields? (May 2014)(Nov-Dec 2015)

The field pattern in space is fixed but the field intensity at every point varies as a replica of the time variation of current.

23. What is Stacking factor? (Nov-Dec 2015)

The laminated construction helps to keep eddy current losses to low value. Due to stacks of lamination, the net cross sectional area occupied by the magnetic material less than its gross cross sectional area.

$$\text{Stacking factor } = \frac{\text{Net cross sectional area occupied by magnetic material}}{\text{gross cross} - \text{sectional area}}$$

Value always <1

24. State Ampere's Law. (May 2016)

Theintegralaroundaclosedpathofthecomponentofthemagneticfield Tangenttothedirectionofthepathequalsμ0timesthecurrentinterceptedbytheareawithin the path

$$\oint \overrightarrow{B}.\overrightarrow{ds} = \mu_0 I$$

25. Define flux linkage. Dec - 2016

It is known that a current carrying conductor is surrounded by concentric circles of magnetic. Flux linkage = Turns × Flux = NØ

26. What is eddy current loss?

When a magnetic core carries a time varying flux, voltages are induced in all possible path enclosing flux. Resulting is the production of circulating flux in core. These circulating current do no useful work are known as eddy current and have power loss known as eddy current loss.

27. Define relative permeability. May 2017

The ratio of flux density produced in that material to the flux density produced in air by the same magnetizing force.

$\mu_r = \frac{\mu}{\mu_o}$where, μ – Absolute permeability of the material

μ_o- Absolute permeability of air/vacuum

μ_r -Rlative permeability of the material

28. Give the expression for hysteresis losses and eddy current losses. May 2017

Hysteresis loss=$K_h (B_m)^{1.6} f \times$ Volume

K_h-Characteristic constant of the material, B_m-Maximum flux density

F-frequency in cycles per second

Eddy current loss=$K_e[B_{max}]^2 f^2 t^2 v$ watt

K_e - eddy current coefficient it depends on type of the material used
f-numbers of complete magnetization cycle per second
B_{max} – maximum flux density, t- thickness of the lamination
v- volume of the material.

29. Define Magnetic flux density (Nov 2017)

Magnetic flux density is defined as the amount of magnetic flux in an area taken perpendicular to the magnetic flux's direction.

30. Define Self-inductance (Nov 2017)

Self-inductance is defined as the induction of a voltage in a current-carrying wire when the current in the wire itself is changing.

31. what are the types of magnetic losses?(May2018)

1. Iron loss- hysteresis and eddy current losses

2. Cupper loss- I^2R Losses

32. How are hysteresis and eddy current losses minimized? (May 2018)

Core losses majorly include Hysteresis loss and eddy current loss. Eddy Current loss can be reduced by increasing the number of laminations. The laminations provide small gaps between the plates. As it is easier for magnetic flux to flow through iron than air or oil, stray flux that can cause core losses is minimized.

PART-B

1. Explain clearly the statically induced emf and dynamically induced emf?(May-2012) (Dec-2013, 2014, 2015, 2016)

Or

Derive the expression for self-inductance and mutual inductance and also define coefficient of coupling. (May 2017)

EMF gets induced in a conductor, whenever their exits change in flux with that conductor, according to Faraday's Law. Such change in flux can be brought about by different methods. Namely,

1. Dynamically Induced emf
2. Statically Induced emf

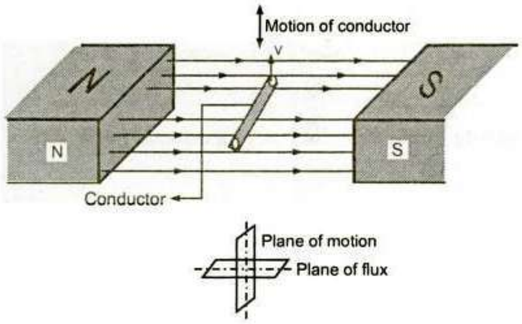
1. Dynamically induced emf:

The change in the flux linking with a conductor (or) circuit can be brought about by its motion relative to magnetic field. This is possible by moving flux with respect to coil conductor or circuit or it is possible by moving conductor, coil, and thecircuit with respect to stationary magnetic flux.

Magnitude of dynamically induced emf:

Consider a conductor moves in the air gap between poles of magnet. If plane of the motion of the conductor is parallel to the plane of the magnetic field then there is no cutting of flux lines, no induced emf.

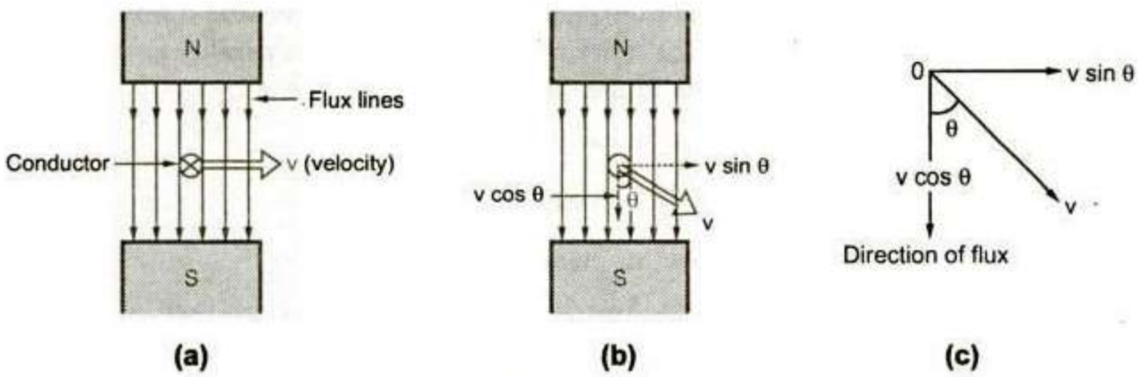
In second case, the motion of the conductor is perpendicular to the flux. Hence whole length of conductor is cutting the flux line hence there is maximum possible induced emf in the conductor. Under such condition plane of flux and plane of motion arte perpendicular to each other.



Maximum cutting of flux

Consider a conductor moving with velocity v m/s such that its plane of motion or direction of velocity is perpendicular to the direction of flux lines as shown below.

B-Flux density wb/m^2
ℓ-Active length of conductor in meters
V-Velocity in m/s



Let the conductor is moved through distance dx in a small time intervaldt, then

Area swept by conductor=$l \times \mathrm{dx}\ \ \mathrm{m}^2$

Flux cut by conductor=Flux density× Area swept

$\mathrm{d}\phi\ = B \times \ell \times \mathrm{dx} \qquad \omega\mathrm{b}$

According to Faraday's law the magnitude of induced emf is perpendicular to rate of change of flux

$$\mathrm{e}\ = \frac{\textbf{Flux cut}}{\textbf{Time}}$$

$$= \frac{\mathrm{d}\phi}{\mathrm{dt}} = \frac{\mathrm{B}\ \ell\ \mathrm{dx}}{\mathrm{dt}}$$

$$e = Blv\ volts$$

This is (maximum) induced emf when plane of motion is exactly perpendicular to the plane of flux. But if the conductor is moving with a velocity v at a certain angle θ measured with respect to direction of field.

Under this condition,

Magnitude of Induced emf

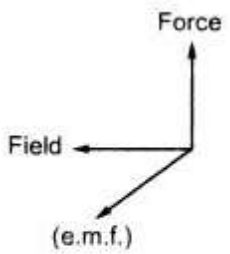
$$e = Blv\ \ sin\theta \text{volts}$$

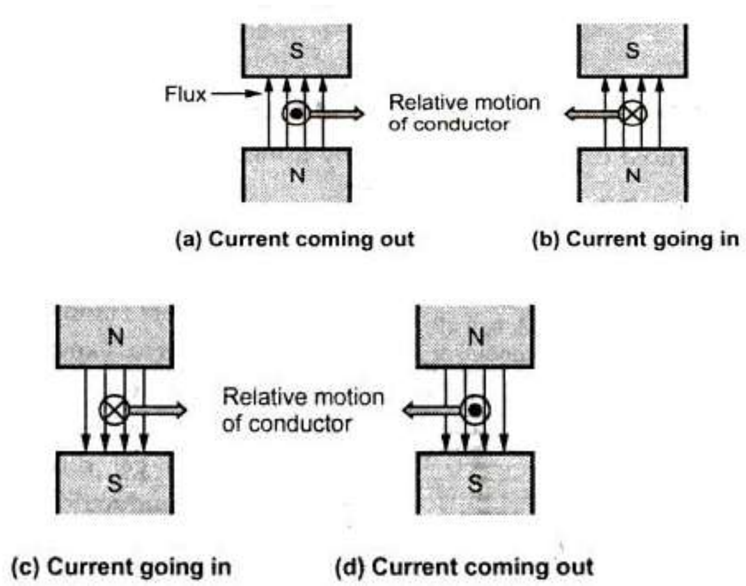
θ – is measured with respect to plane of the flux.

<u>Direction of Induced emf</u>

1. Fleming's Right hand rule:

   The thumb, fore finger, middle finger of right hand at right angle to one another. If fore finger points in the direction of magnetic field, thumb in the direction of motion of the conductor, then the middle finger will point in the direction of induced emf.





2. Fleming's Left hand Rule;

The fore finger, middle finger and thumb of the left hand at right angle to one another. If the fore finger points in the direction of magnetic field, the middle finger points towards the direction of current, then the thumb will points in the direction of motion of the conductor.

3. Lenz's law:

The direction of an Induced emf produced by the electromagnetic induction is such that it sets up a current which always opposes the cause that is responsible for inducing the emf.

$$e = -N\frac{d\phi}{dt}$$

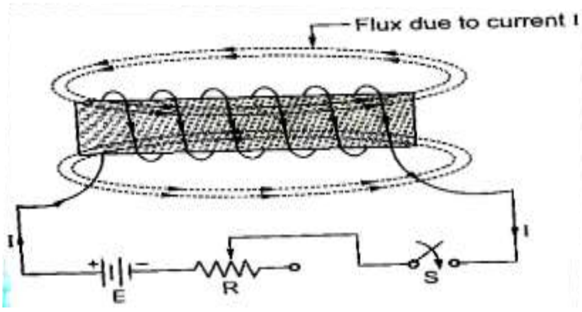
2. Statically Induced EMF:

The change in flux lines with respect to coil can be achieved without physically moving the coil or magnet is known as statically induced emf..

It is classified into

- ✓ Self inducede.m.f.
- ✓ Mutually induced e.m.f.

Self inducede.m.f.



Consider a coil having 'N' turns and carrying current 'I' when switch 'S' is in closed position. The current magnitude can be varied with the help of variable resistance connected in series with battery.

The flux produced by the coil links with the coil itself. The total flux linkages of coilwill be Nϕ wb turns.

If 'I' changed flux also changed. Flux linkage also be changed.According to Faraday's law, due to rater of change of flux linkages there will be induced e.m.f in the coil. So without physically moving coil or flux there is induced e.m.f. in the coil. The phenomenon is called self induced.

<u>Expression or Magnitude of self inducede.m.f.</u>

According to Faraday's Law of electromagnetic induction, self inducede.m.f. can be expressed as,

$$e = -N\frac{d\phi}{dt}$$

Negative sign indicates that direction of the e.m.f. is opposing change in current due to which it exists.$\Phi = \frac{\phi}{I} \times I$

$$\text{Rate of change of flux} = \frac{\phi}{I} \times \text{Rate of change of current}$$

$$\frac{d\phi}{dt} = \frac{\phi}{I}.\frac{dI}{dt}$$

$$e = -N\frac{\phi}{I}.\frac{dI}{dt}$$

$$= -\left(\frac{N\phi}{I}\right)\frac{dI}{dt}$$

$\frac{N\phi}{I}$is called as coefficient of self inductance it is denoted by L

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

$$e = -L\frac{dI}{dt}\ Volts$$

<u>Expression for Coefficient of self-Inductance</u>:

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

$$\Phi = \frac{\text{mmf}}{\text{Reluctance}} = \frac{\text{NI}}{\text{S}}$$

$$L = \frac{N}{I}\frac{NI}{S} = N^2/S = \frac{N^2}{\ell/\mu a}$$

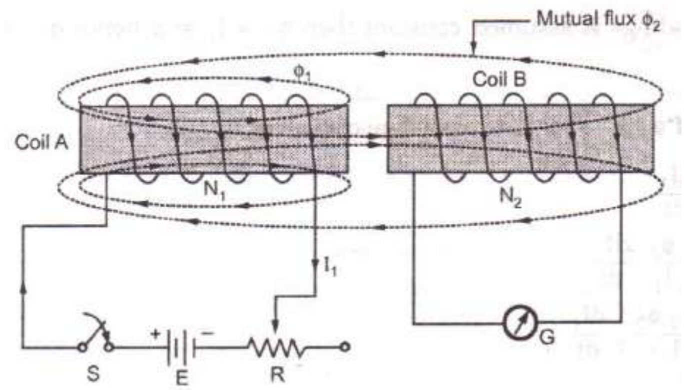
$$\mathbf{L} = \frac{\boldsymbol{N^2}\,\boldsymbol{\mu o\ \mu r\ a}}{\boldsymbol{\ell}}$$

ℓ - length of magnetic circuit

a- Area of cross section of magnetic circuit through which flux is passing.

Expression for mutual Inductance or Mutually induced emf

Iftheflux produced byone coil is getting linked with another coil and due to change in this flux produced by first coil, there is induced e.m.f. in the second coil, then such an e.m.f. is called mutually induced e.m.f.



Consider two coils which are placed adjacent to each other as shown in figure. The coil A hasN_1 turns while coil B has N_2 number of turns. The coil A has switch S, variable resistance R and battery of 'E' in series with it. A galvanometer is connected across coil B to sense induced e.m.f. and current because of it.

Current through coil A is I_1 producing flux $\emptyset_1$. Part of this flux will link with coil B, will complete its path through coil B as shown in figure (mutual flux $\emptyset_2$).

Now if current through coil A is changed by means of variable resistance R, then flux $\emptyset_1$ changes. Due to this, flux associated with coil B, which is mutual flux $\emptyset_2$also changes. Due to Faraday's law there will be induced e.m.f. in coil B which will set up a current through coil B, which will be detected by galvanometer G.

Magnitude of Mutually induced emf

N_1-Number of turns of coil A
N_2- Number of turns of coil B
I_1-Current flowing through coil A
Φ_1-Flux produced due to current I_1 in Weber's
Φ_2- Flux linking with coil B

According to Faraday's law, the induced e.m.f in coil B is

$$e2 = -N2\frac{d\phi_2}{dt}$$

-ve sign indicates that this emf will setup a current which will oppose the change of flux linking with it.

$$\Phi 2 = \frac{\phi_2}{I_1} \times I_1$$

$$\text{Rate of change of } \Phi 2 = \frac{\phi_2}{I_1} \times \text{Rate of change of current } I_1$$

$$\frac{d\phi_2}{dt} = \frac{\phi_2}{I_1} \cdot \frac{dI_1}{dt}$$

$$e2 = -N2 \frac{\phi_2}{I_1} \cdot \frac{dI_1}{dt}$$

$$e2 = -\left(\frac{N_2\phi_2}{I_1}\right) \frac{dI_1}{dt}$$

Here $\frac{N_2\phi_2}{I_1}$ is called coefficient of mutual Inductance

$$\mathbf{e2 = -M \frac{dI_1}{dt}}$$

<u>Expression for Coefficient of mutual Inductance</u>

$$M = \frac{N_2 k_1 \phi_1}{I_1} \& M = \frac{N_1 k_2 \phi_2}{I_2}$$

Multiply both M

$$M \times M = \frac{N_2 k_1 \phi_1 N_1 k_2 \phi_2}{I_1 I_2}$$

$$M2 = K1\, K2 \frac{N_1\phi_1}{I_1} \frac{N_2\phi_2}{I_2}$$

$$M^2 = K_1 K_2 L_1 L_2$$

$$M = \sqrt{K_1 K_2 L_1 L_2} = \sqrt{K_1 K_2}\sqrt{L_1 L_2}$$

$$M = K\sqrt{L_1 L_2}$$

Where, $K = \sqrt{K_1 K_2}$ is called coefficient of coupling.

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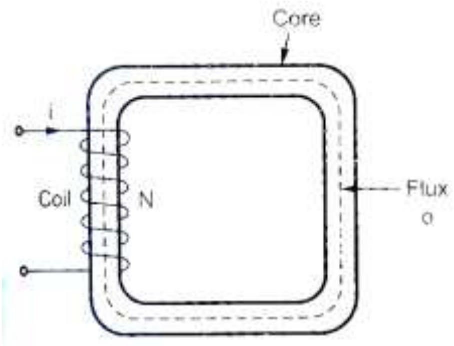
2. **Discuss the AC operation of Magnetic circuit (May-2012& Dec 2014, 2016)**

In many applications and machines such as transformers and A.C machines, the magnetic circuits are excited by A.C. supply. In such an operation, inductance plays vital role even in steady state operation through in D.C., it acts as a short circuit. In such cases the flux is determined by the A.C. voltage applied and the frequency. Thus the exciting current has to adjust itself according to the flux so that every time B-H relationship is satisfied.

Consider a coil having N turns wound on iron core. The coil carries an alternating current I varying sinusoidally, thus the flux Ø produced by the exciting current 'I' is also sinusoidally varying with time.



$$\Phi = \emptyset_m sin\omega t$$

Where, $\emptyset_m$= maximum value of flux in core

$\omega = 2\pi f$ where, f is frequency in Hz

According to Faraday's law, the flux changes with respect to coil, the emf gets induced in the coil given by,

$$e = N\frac{d\phi}{dt} = N\frac{d}{dt}[\phi_m \sin \omega t]$$

$$\mathbf{e = N\phi_m \omega cos\, \omega t volts}$$

E_m=maximum value= $N\phi_m \omega$

E=r.m.s value =$\frac{Em}{\sqrt{2}} = \frac{N\phi_m \omega}{\sqrt{2}}$

$$\mathbf{E = \frac{N\phi_m 2\, \pi f}{\sqrt{2}} = 4.44\ fN\phi_m}$$

$$\phi_m = AcBm$$

$$\mathbf{E=4.44\ f\ N\ A_cB_m}$$

Energy stored under A.C operation.

Electric power input into the magnetic circuit through the coil terminals is given by

P=e.i but $e = \frac{d\lambda}{dt}$

$$P = \frac{d\lambda}{dt}.i$$

Power is the rate of change of energy hence energy input which gets stored in the magnetic field during interval t_1 to t_2 is,

$$\omega f = \int_{t_1}^{t_2} p\ dt = \int_{t_1}^{t_2} i\ \frac{d\lambda}{dt}\ dt$$

$$\mathbf{\omega f = \int_{\lambda 1}^{\lambda 2} i\ \ d\lambda}$$

Thus ω_f is the increase in the field energy as the flux linkages of the coil changes from λ_1 and λ_2 during the interval t_1 and t_2

$H_c\ell c$ =m.m.f= NI

$$I = \frac{Hc\,\ell c}{N}$$

Where λ=N$\emptyset$ and $\emptyset$=B_c a_c

i.eλ =N a_c B_c

$d\lambda$ = N a_c dBc

The flux density of the core is changing from B_1 to B_2 as the flux linkages change from λ_1 to λ_2

$$\omega f = \int_{\lambda 1}^{\lambda 2} \frac{Hc\,\ell c}{N}\, d\lambda$$

$$\omega f = \int_{B_1}^{B_2} \left(\frac{Hc\, lc}{N}\right) N\ a_c\, dB_c$$

$$\omega f = \int_{B_1}^{B_2} Hc\, lc\ a_c\ dB_c$$

This is the field energy interms of field quantities.

$$\boldsymbol{\omega f = a_c l_c \int_{B_1}^{B_2} Hc\ dB_c}$$

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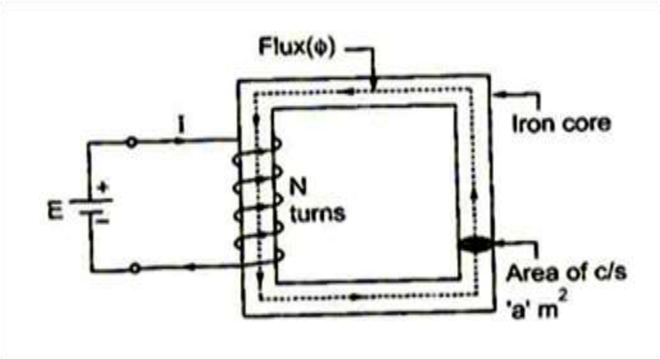
3. Discuss in detail the magnetic circuits and electrical analogy of magnetic circuit (May-2011)

Magnetic circuit is defined as the closed path traced or followed by the magnetic lines of force, ie flux. Such a magnetic circuit is associated with different magnetic quantities as m.m.f, flux, reluctance, permeability etc,

Consider simple magnetic circuit which consists of an iron core with cross sectional area of ‘a’ m^2 with a mean length of ‘l’ m. A coil of N turns is wound on one of the sides of the square core which is excited by a supply. This supply drives a current I through the coil. This current carrying coil produces the fluxwhich completes its path through the core fig (a).

This is analogous to simple electric circuit in which a supply iee.m.f. of E volts drives a current I which completes its path through a cored conductor having resistance R. This analogous electrical circuit shown in fig (b).

I=current flowing through coil
N=Number of turns
Φ=Flux in Weber’s; B =Flux density in the core
μ=Absolute permeability of the magnetic material
μ_r=Relative permeability of the magnetic material



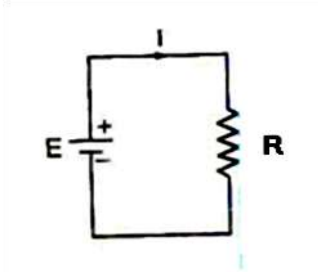


fig.a fig.b

$$H = \frac{NI}{\ell} \text{AT/m}$$

Now flux density is, B =μ H

$$B = \frac{\mu_o \mu_r N I}{\ell} \omega b/$$

$$\Phi = \beta a = \frac{\mu_o \mu_r N I a}{\ell} \omega b/m^2$$

$$\Phi = \frac{\frac{NI}{\ell}}{\mu_o \mu_r a}$$

$$\Phi = \frac{m.m.f}{\text{Reuctance}} = \frac{F}{S}$$

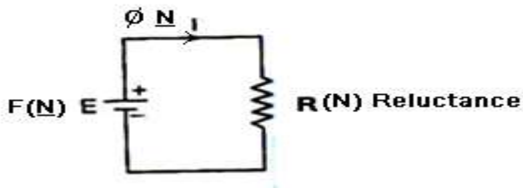
NI=magneto motive force m.m.f in AT

$$S = \frac{l}{\mu_o \mu_r a} \text{ (Reluctance)}$$

Flux is similar to in electric circuit

$$I = \frac{e.m.f}{\text{Resistance}}$$

Electrical Analogy of simple magnetic circuit diagram



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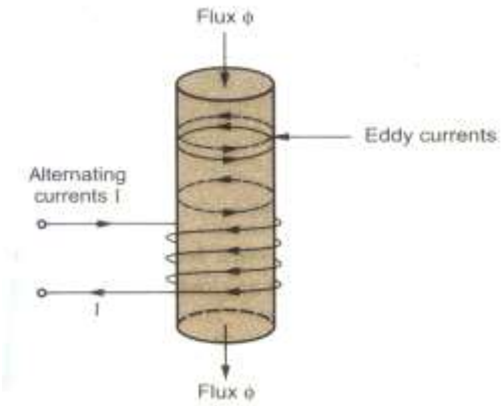
4. What is eddy current? Explain in detail eddy current loss (May-2011,2015, 2016) (DEC 2015)

Consider a coil wound on the core and carries an alternating current, i.e current magnitude varies with respect to time, and then flux produced by current is also of alternating nature. So core is under the influence of the changing flux and under such condition, according to Faraday's law of electromagnetic induction emf gets induced in the core Now if the core is solid, then the induced emf circulates currents through the core. Such currents in the core which are due to induced emf in the core are called as eddy currents. Due to such currents there is power loss in the core. Such loss is called eddy current loss.



Eddy current loss depend on the various factors

i) Nature of the material
ii) Maximum flux density
iii) Frequency
iv)Thickness of laminations used to constant to core soul
v)Volume of magnetic material

Eddy current loss=$K_e[B_{max}]^2f^2t^2v$ watt

K_e - eddy current coefficient it depends on type of the material used
f-numbers of complete magnetization cycle per second
$B_{max} -$ maximum flux density
t-thickness of the lamination
v-volume of the material.

Reduce the eddy current loss;

1) Higher resistivity of the magnetic material and longer length

2) Insurance the effective resistance resulting in reduction of eddy current loss

3) Dividing of the material into thin lamination with highly insulated material such as varnish is used for reduce eddy current loss.

Lamination thickness usually varies from 0.3 to 5mm for electromagnetic devices used for power station and 0.01 to 0.5 mm for devices used in electronic application.

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5. Explain power loss that occurs in magnetic material when it undergoes a cyclic magnetization?(May-2011,2015, 2016)

Two type of power loss appears in magnetic material when it undergoes a cyclic magnetization.

1. Hysteresis loss
2. Eddy current loss.

1. **Hysteresis loss**

When a magnetic material is subjected to repeated cycle of magnetization and demagnetization, it results into disturbance in the alignment of the various domains. Energy gets stored when magnetic field established and energy is returned when the fields collapses. Due to hysteresis, all the energy is never returned through field completely collapses. The loss of energy as heat in the magnetic material. This is called hysteresis loss. Due to hysteresis loss heat is produced.

Hysteresis loss depend up the following factors

1) It is directly ∝ to the area under the hysteresis curve

2) It is directly ∝ to f

3) It is directly ∝ to volume of material

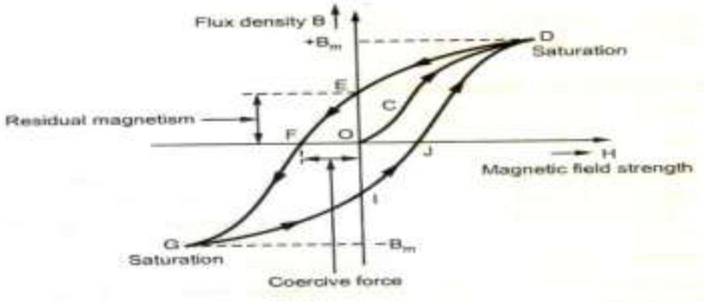
Hysteresis loss=K_h $(B_m)^{1.6}$ f × Volume

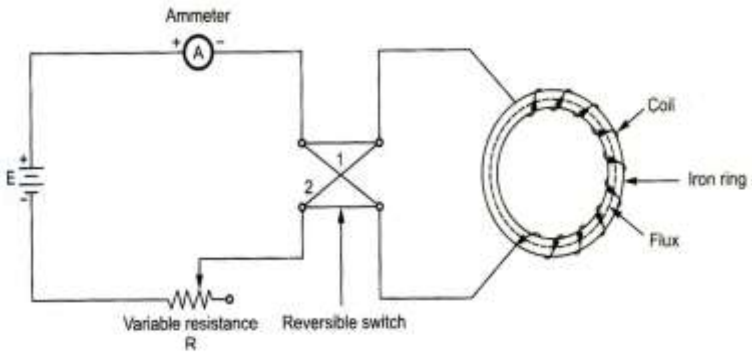
K_h-Characteristic constant of the material

B_m-Maximum flux density

F-frequency in cycles per second

Obtaining Hysteresis loop:





i) Initially variable resistance is kept maximum current through circuit low. H also low I is increased for low value of H, B do not increase rapidly. But after knee point B increases rapidly upto certain point. This point is called **point of saturation**.

ii) After saturation point now current is again reduced to zero. Due to this field strength also reduces to zero. But B do not trace the same curve back but fall back as compared to previous magnetization curve. This phenomenon of falling back of flux density while demagnetization cycle is called **hysteresis**.

iii) The value of flux density when exciting current through the coil and magnetic field strength is reduced to zero is called residual flux density. The magnitude of this residual flux or magnetism depends on the nature of the material of the core. And this property of material is called **retentivity.**

iv) But now if it is required to demagnetize the core entirely then it is necessary to reverse the direction of current through the coil.This is possible with the help of the intermediate switch.

v) If now this reversed current increased,core get saturated in opposite direction.

vi) If I decreased to zero, core shows hysteresis properly, Hysteresis loss reduced by selecting good quality of magnetic material.

Eddy current loss:

Ref. Question No :4

Ref. Question No :4

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6. Define Inductance of coil? (May-2010)

According to Lenz law the direction of this induced e.m.f will be so as to oppose the cause producing it. The cause is the current I hence the self inducede.m.f. try to set up a current which is opposite direction to that of current I. When I increased self inducede.m.f. decreased the current tries to keep it to its original value. If current decreased self inducede.m.f. increased increase current to attain original value.

The property of the coil which opposes any change in the current passing through it is called self Inductance or Inductance

$L=\frac{N\phi}{I}$ or $L=\frac{N^2}{S}$ or $L=\frac{N^2\mu_o\mu_r a}{l}$

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7. Define permeability of a magnetic material and the factors on which it depends (May-2010)

It is related to the medium which magnet is placed. The force excited by one magnetic pole to other depends on the medium in which magnets are placed.

It is defined as the ability with which the magnetic material forces the magnetic flux through a given medium

Types

i) Absolute permeability
ii) Relative permeability

i) **Absolute permeability**:
It is the ratio of B in a particular medium to H producing that flux density.

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

Permeability of free space

$$\mu_o = \frac{B}{H} \text{in vacuum} = 4\pi \times 10^{-7}\ H/M$$

If magnet placed in a free space or vacuum or in air then theratio of B and H is called permeability of free space.

ii) Relative permeability

It is defined as the ratio of flux density produced in a medium to flux density produced in free space, under the influence of same H and under identical conditions

$\mu_r = \frac{\mu}{\mu_o}$ where, H is same

For free space μ_r=1 $\mu=\mu_o\mu_r$ H/m

μ_r- varies from 100 to 100,000 (metal like iron, steel)

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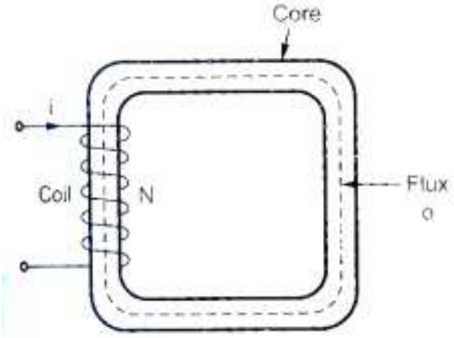
8. Explain operation of magnetic circuit when A.C. current is applied to the coil wound on iron core. Draw the B-H curve and obtain an expression for hysteresis loss.

Ref: Question No- 2 and 5 [Notes]



$\Phi = \phi_m \sin\omega t$

Where, ϕ_m= maximum value of flux in core

$\omega = 2\pi f$ where, f is frequency in Hz

According to Faraday's law, the flux changes with respect to coil; the emf gets induced in the coil given by,

$$e = N\frac{d\phi}{dt} = N\frac{d}{dt}[\phi_m \sin\omega t]$$

$e = N\phi_m \cos\omega t$ volts

Em=maximum value= $N\phi_m\ \omega$

E=r.m.s value $=\frac{Em}{\sqrt{2}} = \frac{N\phi_m\ \omega}{\sqrt{2}}$

$$E = \frac{N\phi_m\ 2\ \pi f}{\sqrt{2}} = 4.44\ fN\phi_m$$

$E=4.44\ f\ N\ A_cB_m$

Energy stored under A.C operation.

Electric power i/p into the magnetic circuit through the coil terminals is given by

P= e × i but $e = \frac{d\lambda}{dt}$

$$P = \frac{d\lambda}{dt}.i$$

Power is the rate of change of energy hence energy input which gets stored in the magnetic field during interval t_1 to t_2 is,

$$\omega f = \int_{t_1}^{t_2} p\,dt = \int_{t_1}^{t_2} i\,\frac{d\lambda}{dt}\,dt$$

$$\omega f = \int_{t_1}^{t_2} i\ d\lambda$$

Thus ω_f is the increase in the field energy as the flux linkages of the coil changes from $\lambda 1$ and $\lambda 2$ during the interval t_1 and t_2

$H_c \ell c$ =m.m.f=Ni

$$I = \frac{Hc\,\ell c}{N}$$

$$\omega f = \int_{\lambda 1}^{\lambda 2} \frac{Hc\,\ell c}{N}\,d\lambda$$

Where λ=N$\emptyset$ and $\emptyset$=B_c a_c.

i.eλ =N a_c B_c

The flux density of the core is changing from B_1 to B_2 as the flux linkages change from $\lambda 1$ to $\lambda 2$

$\omega_f = \int_{B_1}^{B_2} \left(\frac{Hc\ lc}{\cancel{N}}\right) \cancel{N}\ a_c\ dB_c$

$\omega_f = \int_{B_1}^{B_2} Hc\,\ell c\ a_c\ dB_c$

$\omega_f = a_c \ell_c \int_{B_1}^{B_2} Hc\ dB_c$

---

9. Compare the electric and magnetic circuit by their similarities and dissimilarities Similarities(Dec 2011& Dec 2014).

S.No	Electric circuit	Magnetic circuit
1	Path traced by current is called electric circuit	Path traced by magnetic flux is called magnetic circuit
2.	EMF is the driving force in electric circuit	MMF is the driving force in magnetic circuit
3.	There is current I in the electric circuit measured in amperes	There is fluxϕ in the magnetic circuit measured in Weber's
4	The flow of electrons decides the current in conductor	The number of magnetic lines of force decides flux
5.	Resistance oppose the flow of current	Reluctance opposed by magnetic path to the flux
6.	R=$\frac{\rho\ell}{A}$	S=$\frac{\ell}{\mu_o \mu_r A}$

	$R \propto \ell$ $\frac{1}{\alpha}$ a → depend on nature of material	$\frac{1}{\alpha}\mu$ $\frac{1}{\alpha}$ to area 'a'
7.	$I=\frac{\text{Emf}}{\text{Resistance}}$	$\phi=\frac{\text{MMF}}{\text{reluctance}}$
8.	$\delta = \frac{I}{a} A/m^2$	$B=\frac{\phi}{a}\ \omega b/m^2$
9.	Conductivity is Reciprocal of resistivity=1/R	Permeance is reciprocal of the reluctance=1/S
10.	Kirchhoff's current and voltage law is applicable to the electric circuit	Kirchhoff's m.m.f. law and flux law is applicable to the magnetic circuit

Dissimilarities

Sl.No	Electric circuit	Magnetic circuit
1.	In the electric circuit the current actually flows i.e there is movement of electron	Due to m.m.f. flux gets established and does not flow in the sense in which current flows.
2.	There are many material which can be used as Insulator ie air, p.v.c., Synthetic resin etc, from which current cannot pass	There is no magnetic insulator as flux can pass through all the materials, even through the air as well.
3.	Energy must be supplied to the electric circuit to maintain the flow of current	Energy is required to create the magnetic flux, but it is not required to maintain it.
4.	The resistance and the conductivity are independent of current density (δ) under constant temp. But may change due to the temp	The reluctance, permeance and permeability are dependent on the flux density
5.	Electric lines of flux are not losed 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
6.	There is continuous consumption of electrical energy	Energy is required to create the magnetic flux and not to maintain it

10. Derive an expression for energy density in the magnetic field?(Dec-2010, 2015)

Induced emf in a coil

$$e = -L\frac{dI}{dt}$$

This opposes the supply voltage.

$$V = -e = -\left[-L\frac{dI}{dt}\right] = L\frac{dI}{dt}$$

$$POwer = V \times I = L\frac{dI}{dt} \times I$$

$$E = \text{power} \times \text{time} = L\frac{dI}{dt} \times I \times dt$$

E=LIdI joules.

The above expression is energy in current dI.

$$E = \int_0^I L\, dI\ \ I$$

$$E = L\int_0^I I\, dI = \frac{LI^2}{2}$$

Energy density=$\frac{\text{Energy}}{\text{Unit volume}}$

We know that $L=N\,\emptyset/I$

$E=1/2\ L\ I^2$

$=1/2\times \frac{N\phi}{I}\times I^2$

$E=\frac{1}{2}\ N\ \emptyset\ I$

We know that $NI=H\ell$

$\Phi=Ba$

$E = \frac{1}{2}\times H\ell\ \times Ba$

Where $a\times \ell$ =volume of magnetic material per unit volume E=1/2 B H

Where $B=\mu\ H$

$$\therefore \frac{E}{\text{Unit volume}} = \frac{1}{2}\ \mu\ H^2 \text{Jolules/m}^3$$

$$\frac{E}{\text{Unit volume}} = \frac{1}{2}\frac{B^2}{\mu}\ \text{Jolules/m}^3$$

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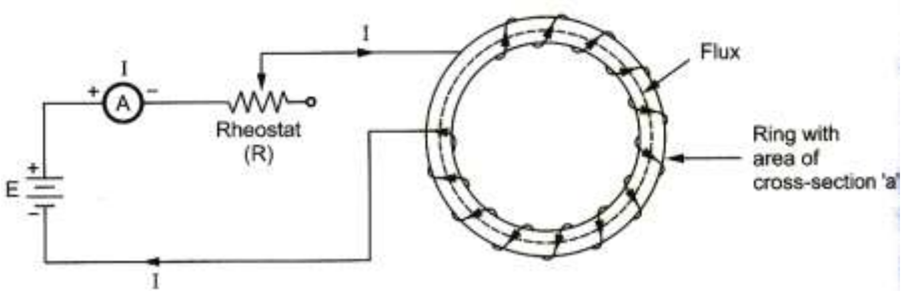
11. Explain in detail?(May-2010)

1) B-H relationship
2) Leakage flux
3) Fringing
4) Stacking factor

1) B-H relationship:-

$H=\frac{NI}{l}$, As current in coil changes magnetic field strength alo changes. Due to this flux produced and hence the flux density also changes.

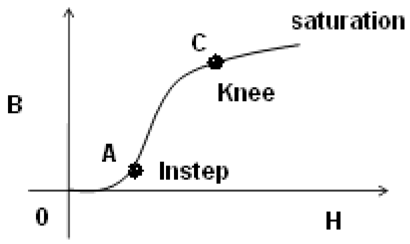
A graph b/w flux density (B) and the magnetic field strength (H) for magnetic material is called as its magnetization curve or B-H curve



The experiment need to find relationship b/w B& H.

A ring specimen has 'l' meter length, 'a' cross sectional area. Coil is wound for 'N' turns carrying a current I which can be varied by changing the variable resistance R connected in series, Ammeter connected series to measure current flux meter is introduced to measure flux.

'H' can be calculated as $\frac{NI}{l}$and b can be calculated by $\emptyset$/A, with help of R. I is varied H also varied



<u>Initial portion</u>: - Low value H 'B" is not increase rapidly. It is denoted by OA

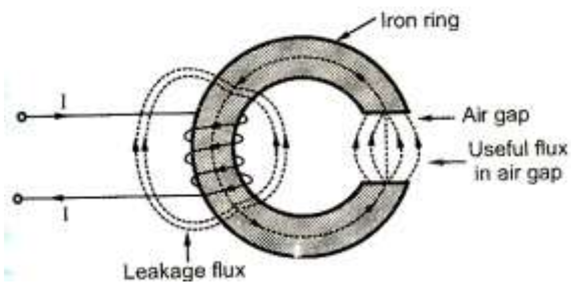
<u>Middle portion</u>: -H increases B also increases. The point at which portion of the curve bends is called knee point.

<u>Saturation portion</u>: - After knee point, rate of increase in B reduce drastically finally the curve parallel to 'X' axis. It is called saturation portion.

$$B=\mu H=\mu_o \mu_r H; \qquad \mu_r = \frac{B}{\mu_o H}$$

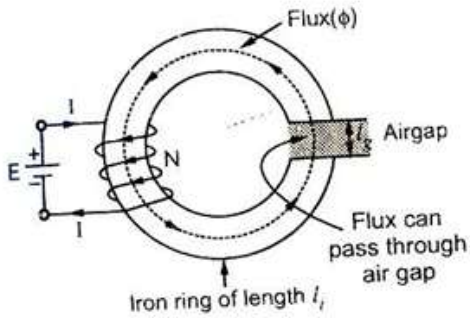
2) Leakage flux

Flux which does not follow the desired path is called leakage flux. The flux which is available in the air gap and utilized to produce the desired effect is called metal flux denoted by ϕ_u



3) Fringing

When flux enters into the air gap, it passing through the air gap in terms of parallel flux lines. There exists a force of repulsion between the magnetic lines of force which are parallel and having same direction. Due to this repulsive force there is tendency of the edge of the air gap. The tendency of **the flux to bulge out at the edges of the air gap** is called magnetic fringing.



Effects:

1)It increases the effective cross sectional area of air gape
2) It reduces the flux density in the air gap

4) Stacking factor:-

The laminated construction helps to keep eddy current losses to low value. Due to stacks of lamination, the net cross sectional area occupied by the magnetic material less than its gross cross sectional area.

$$\text{Stacking factor} = \frac{\text{Net cross sectional area occupied by magnetic material}}{\text{gross cross} - \text{sectional area}}$$

Value always <1

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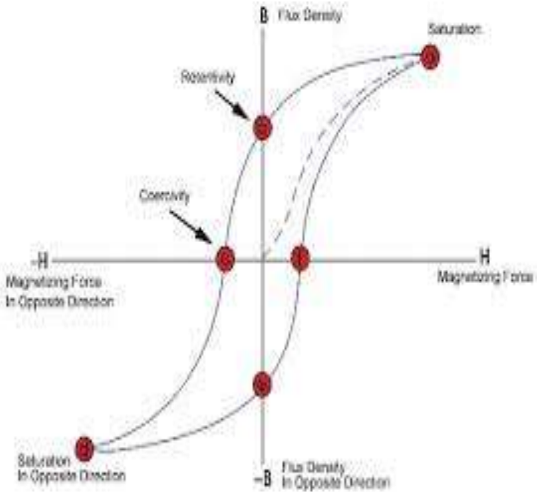
12. Explain the basic Properties of magnetic materials. Or State properties of magnetic material suitable for fabrication permanent magnet and electromagnet?(May 2015, 2016)

i)Non Liner B-H relationship:

Magnetic materials are characterized by high permeability and nonlinear B-H relationship which exhibits both saturation and hysteresis. The B-H relationship H is the hysteresis loop shown in fig. for two values of maximum flux density. It is easily observed from this figure that B is a symmetrical two -valued function of H. at any given H, B is higher if H is reducing compared to when H is increasing.



This is the basic hysteresis property in which B lags behind. It can also be recognized as a memory typenonlinearity in which the materials remember its previous history. Further it is observed that the hysteresis loop becomes wider for increasing maximum flux densities. The dotted curve drawn through the positive and negative tips of the hysteresis loop with increasing maximum flux densities is the normal magnetization and is obtainable in virgin (Unmagnetized) material by increasing the DC magnetization in either direction. It is easily seen that because of hysteresis and saturation, the magnetic characteristic of a given material cannot be described by a few overall parameters but must be expressed in the form of a set curves. It will be shown that the area of the hysteresis loop is the energy loss (it appears in the form of heat energy) per unit volume in one cycle of magnetization. This loss depends upon the quality of material and maximum flux density at which the material is operated.

ii) Saturaion:

Saturation is the state reached when an increase in applied external magnetic field *H* cannot increase the magnetization of the material further, so the total magnetic flux density *B* more or less levels off. (It continues to increase very slowly due to the vacuum permeability.) Saturation is a characteristic of ferromagnetic and ferromagnetic materials, such as iron, nickel, cobaltand their alloys.

iii) Hysteresis:

Hysteresis the lag in a variable property of a system with respect to the effect producing i t as this effect varies, espthe phenomenon in which the magnetic flux density of a ferromagnet ic material lags behind the changing external magnetic field strength

iv) Permeability:

Permeability is the measure of the ability of a material to support the formation of a magnetic field within itself. Hence, it is the degree of magnetization that a material obtains in response to an applied magnetic field.

Or

- The importance of magnetic materials is twofold:
- Magnetic materials are used to obtain large magnetic flux densities with relatively low levels of magnetizing force.
- Magnetic materials can be used to constrain and direct magnetic fields in well-defined paths.

Ferromagnetic materials, typically composed of iron and alloys of iron with cobalt, tungsten, nickel, aluminum, and other metals, are by far the most common magnetic materials.

- They are found to be composed of a large number of domains.
- When unmagnetized, the domain magnetic moments are randomly oriented.
- When an external magnetizing force is applied, the domain magnetic moments tend to align with the applied magnetic field until all the magnetic moments are aligned with the applied field, and the material is said to be fully saturated.
- When the applied field is reduced to zero, the magnetic dipole moments will no longer be totally random in their orientation and will retain a net magnetization component along the applied field direction.

The relationship between *B* and *H* for a ferromagnetic material is both nonlinear and multivalued.

- In general, the characteristics of the material cannot be described analytically but are commonly presented in graphical form.

- The most common used curve is the *HB*−curve.
- DC or normal magnetization curve
- *Hysteresis loop*

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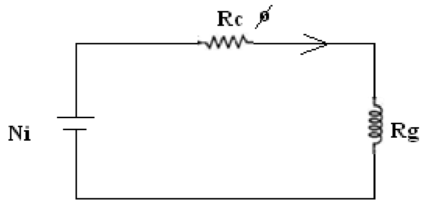
13. Draw and explain the typical magnetic circuit with air gap and its equivalent electric circuit. Hence derive the expression for air gap flux.(May 2013,Nov 2017)

The series magnetic circuit can also have a short air gap.Such air gap is not possible in case of electric circuit.



Consider a ring having mean length of iron path as 'l_i'

Total m.m.f =NI AT

Total reluctance $S_T = S_i + S_g$

Where S_i = reluctance of iorn path

S_g = Reluctance of air gap

$S_i = \frac{l_i}{\mu a_i}$ For μ = $\mu_o \mu_r$

$S_g = \frac{l_g}{\mu_0 \mu r \, a_i}$ for air $\mu_{r = 1}$

The cross sectional area of air gap is assumed to be equal to area of the iorn ring

$$S_T = \frac{\ell_i}{\mu a_i} + \frac{\ell_g}{\mu_0 a_i}$$

$\Phi = \frac{m.m.f}{reluctance} = \frac{NI}{S_T}$

NI=$S_i\Phi + S_g \Phi$ AT

$\Phi = \frac{NI}{S_i + S_g}$

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PROBLEMS

1. The total core loss of a specimen of silicon steel is found to be 1500 w at 50 Hz. Keeping the flux density constant the loss becomes 3000w when the frequency is raised to 75Hz. Calculate separately the hysteresis and eddy current loss at each of their frequencies?(May-2011, Dec- 2013, 2015)

Given:

Core Loss=1500w,F=50,B=3000w, Frequency Is Raised=75hz

Formula used:

$\omega_h = \eta B_{m^{1.6}} f$

$\omega_h = Af$

$\omega_e = K_e B_{m^2} f^2 t^2 V$

$= Bf^2$

Solution:

$P = Af + Bf^2$ ------------------ 1

Divequ 1 by f

$$\frac{p}{f} = A + Bf$$

At 50Hz, the losses in 1500 watts

$$\frac{1500}{50} = A + 50B$$

30=A+50B ------------------ 2

At 75 Hz

$$\frac{3000}{75} = A + 75B$$

40=A+ 75B -------------------- 3

Solve 2, 3

A+50B=30

A+ 75B=40

B=0.4

A=10

Result:

<u>At 50Hz</u>

Hysteresis loss

$Af = 10 \times 50$

$= 500$ w

Eddy current loss

$Bf^2 = 0.4 \times 50^2$

$= 1000$ watts

<u>At 75 Hz</u>

Hysteresis loss=10 ×75=750w

Eddy current loss=$0.4 \times 75^2 = 2250$w

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2. **A ring composed of three sections. The cross section area is 0.001 m^2 for each section. The mean arc length area l_a=0.3m, l_b=0.2m,l_c=0.1m, an air gap length of 0.1mm is cut in the ring, μ_r for sections a, b,c, are 5000,1000, 10000 respectively. Flux in the air gap is 7.5×10^{-4}wb. Find i)mmf ii) exciting current if the coil has 100 turns,iii) reluctance of the section(Dec-2011)**

Given:

a=0.001 m^2, l_a=0.3m, l_b=0.2m,l_c=0.1m, ℓ_g = of 0.1mm, μ_r=5000,1000, 10000,$\emptyset = 7.5 \times 10 - 4$wb.

Formula used:

Total reluctance=R_g+ R_a+ R_b+ R_c, $Rg = \frac{\ell_g}{\mu_o \mu_{rg}\, a}$

Solution:

$$\text{i) Rg} = \frac{\ell_g}{\mu_o \mu_{rg}\, a} = \frac{0.1\times10^{-3}}{4\pi\times10^{-7}\times1\times0.001} = 79554$$

$$\text{Ra} = \frac{\ell_a}{\mu_o \mu_{ra} a} = \frac{0.3}{4\pi\times10^{-7}\times5000\ \times0.001} = 47748$$

$$\text{Rb} = \frac{\ell_b}{\mu_o \mu_{rb}\, a} = \frac{0.2}{4\pi\times10^{-7}\times1000\ \times\ 0.001} = 159109$$

$$\text{Rc} = \frac{\ell_c}{\mu_o \mu_{rc}\, a} = \frac{0.1}{4\pi\times10^{-7}\times10000\ \times0.001} = 7957$$

Total reluctance **= 294368**

ii)Mmf=flux × reluctance=7.5 $\times10^{-4}\times294585$

=221AT

$$\text{iii)Current required} = \frac{\text{MMF}}{\text{N}} = \frac{221}{100}$$

=2.21 Amps.

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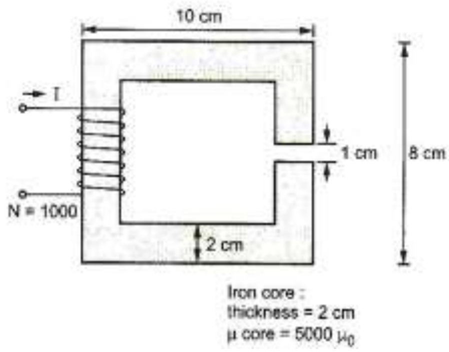
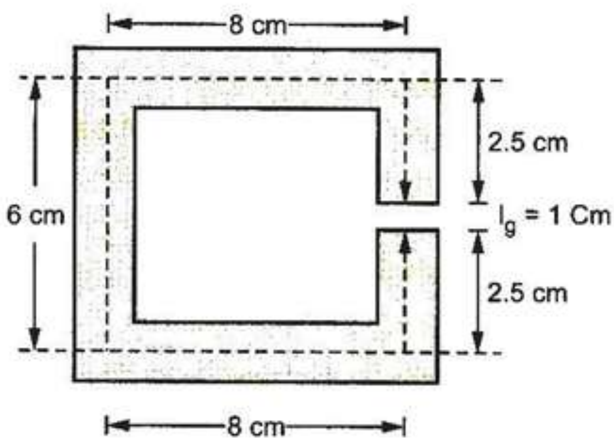
3. For the magnetic circuit shown in fig determine the current required to establish a flux density of 0.5T in the air gap.





Given:

N=1000, B=0.5T, a=2×2=4 $cm^2 l_g$=1cm

l_i=length of iron path=8+8+6+5=27cm

$$\mu_{core} = 5000\mu_o$$

$$\mu_r = 5000$$

Formula used: $Si = \frac{l_i}{\mu_o\mu_r a}, Sg = \frac{l_g}{\mu_o a}, \Phi = \frac{mmf}{s_T}$

Solution:

$$\Phi = B \times a$$

$$= 0.5 \times 4 \times 10^{-4} = 0.2\ m\omega b$$

$$Si = \frac{l_i}{\mu_o\mu_r a} = \frac{27 \times 10^{-2}}{5000 \times 4\pi \times 10^{-7} \times 4 \times 10^{-4}}$$

$$= 107.4295 \times 10^3\ AT/wb$$

$$Sg = \frac{l_g}{\mu_o a} = \frac{1 \times 10^{-2}}{4\pi \times 10^{-7} \times 4 \times 10^{-4}}$$

$$= 19.8943 \times 10^6 AT/wb$$

$$S_T = S_i + S_g = 20 \times 10^6\ AT/wb$$

$$\Phi = \frac{mmf}{s_T} = 0.2 \times 10^{-3} = \frac{NI}{20 \times 10^6}$$

I=4A

---&&&&---

4. The magnetic circuit has dimension: A_c= 4×4 cm^2, bl_g= 0.06 cm ,l_c = 40 cm and N= 600 turns. Assume the value of $\mu_r = 6000$ for iorn.Find the exciting current for B_c =1.2 T and corresponding flux and flux linkages.(May 2013)

Given: A_c= 4×4 cm^2, bl_g= 0.06 cm ,l_c = 40 cm and N= 600, $\mu_r = 6000$, B_c =1.2 T

Formula used:

Ni=$\frac{B_c}{\mu_0\mu_r} l_c + \frac{B_g}{\mu_0} l_g$, $\Phi = B_c A_c$ λ=NΦ

Soluation:

Assume fringing neglected

A_c=A_g therefore B_c=B_g

$$i = \frac{B_c}{\mu_{0N}} \left(\frac{l_c}{\mu_r} + l_g\right)$$

$$= \frac{1.2}{4\pi \times 10^{-7} \times 600} \left(\frac{0.4}{6000} + 0.0006\right)$$

$$= 1.06\ A$$

$$\Phi = B_c A_c = 1.2 \times 16 \times 10^{-4} = 19.2 \times 10^{-4}\ wb$$

$$\lambda = N\Phi = 600 \times 19.2 \times 10^{-4} = 1.152\ wb\text{-turns}$$

Assuming fringing effect {If fringing is to be taken into account, one gap length is added to each dimension of the airgap constituting the area. then

A_g=(4+0.06)×(4 + 0.06) =16.484 cm^2=16.484×$10^{-4}m^2$

$B_g = \frac{\Phi}{A_g} = \frac{19.2*10^{-4}}{16.484*10^{-4}}$ = 1.165 T

Ni $= \frac{B_c}{\mu_0\mu_r} l_c + \frac{B_g}{\mu_0} l_g$

Ni $= \frac{1.2\times0.4}{4\pi\times10^{-7}\times6000} + \frac{1.165\times0.0006}{4\pi\times10^{-7}}$=619.90

I $= \frac{619.90}{600}$ =**1.0345 A**

5.The core loss (Hysteresis loss +eddy current loss) for a given specimen of magnetic material is found to be 2000w at 50 hz .keeping the flux density constant, the frequency of the supply is raised to 75 hz resulting in a core loss of 3200W.Compute separately hysteresis and eddy current losses at both the frequencies.(Dec 2013).

Given: Hysteresis loss +eddy current loss=2000w,f=50,

Hysteresis loss +eddy current loss=3200,f=75

Formula used:

$\omega_h = \eta B_{m^{1.6}} f$

$\omega_h = Af$

$\omega_e = K_e B_{m^2} f^2 t^2 V$

$= Bf^2$

<u>Solution</u>

$\omega_h = \eta B_{m^{1.6}} f$; $\omega_h = Af$;

$\omega_e = K_e B_{m^2} f^2 t^2 V$;

$= Bf^2$

P=Af + Bf^2 ------------------ 1

Divide equation 1 by f

$$\frac{p}{f} = A + Bf$$

At 50Hz, the losses in 2000 watts

$$\frac{2000}{50} = A + 50B$$

40=A+50B ------------------ 2

At 75 Hz the losses in 3200 watts

$$\frac{3200}{75} = A + 75B$$

42.67 =A+ 75B -------------------- 3

Solve equation 2 &3

$$A+50B = 40$$
$$A+75B = 42.67$$

$$B=0.10668$$

$$A=34.66$$

At 50Hz, the hysteresis and eddy current losses is calculated by

Hysteresis loss

$$Af=34.66\times 50=1733.3\ w$$

Eddy current loss

$$Bf^2=0.1068\times 50^2=267\ w$$

At 75 Hz the hysteresis and eddy current losses is calculated by

Hysteresis loss = $Af= 34.66\times 75=2599.95\ w$

Eddy current loss= $Bf^2 = 0.1068\times 75^2= 600.75w$

-------------------------------------&&&&--

6.A steel ring has a mean diameter of 20 cm, a cross section of 25 cm² and a radial air gap of 0.8 mm cut across it.When excited by a current of 1 A through a coil of 1000 turns wound on the ring core it produces an air gap flux 1 m wb.Neglecting leakage and fringing. Calculate

i) relative permeability of steel and

ii) total reluctance of the magnetic circuit.(Dec 2013)

Given: d= 20 cm=20x 10^{-2} m N=1000,a=25 cm^2=25 X 10^{-4},Φ_g =1 mwb,l_g=0.8x10^{-3}m,I=1 A

Formula used: $s_g=\frac{\ell_g}{\mu_o a}$, $s_s=\frac{\ell_s}{\mu_o \mu_r a}$

Solution:

d= 20 cm=20x 10^{-2} m

N=1000,a=25 cm^2=25 X 10^{-4},Φ_g =1 mwb,l_g=0.8x10^{-3}m,I=1 A

Mean length=ℓ_t= dπ=0.6283 m (or) $2\pi r$

Length of steel ring=$\ell_s= \ell_t- \ell_g$=0.6283-0.8x10^{-3}=0.6275 m.

i) $\mu=B/H$

B=flux/area= $1\times 10^{-3}/ 25\times 10^{-4} = 0.4\ wb/m^2$

MMF=NI=1000 AT,

H=MMF/ ℓ_t = 1000/0.6283=1591.59 AT/m

$\mu=B/H=0.4/1591.59 =2.505 \times 10^{-4}$ H/m

$\mu = \mu_o \mu_r = 4\pi \times 10^{-7} \times \mu_r = 2.505 \times 10^{-4}$, $\mu_r = 199.34$.

Reluctance of the air gap=$s_g = \ell_g/\mu_o a = 0.8 \times 10^{-3}/(4\pi \times 10^{-7} \times 25 \times 10^{-4})$

$= 254647.9$ AT/wb.

Reluctance of the steel=$s_s = \frac{\ell_s}{\mu_o \mu_r a} = 0.6275/(4\pi \times 10^{-7} \times 199.34 \times 25 \times 10^{-4})$

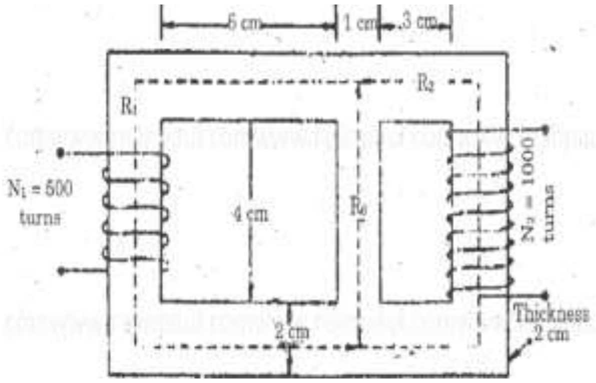
$= 2294379.03$ AT/wb.

Total reluctance of the magnetic circuit= $s_g + s_s = 254647.9 + 2294379.03$

$= 2549026.93$ AT/m.

---

8. **For the magnetic circuit as shown below, find the self and mutual inductance between the two coils. Assume core permeability = 1600. (May 2014,Dec-2017)**



Solution:

$\ell_1 = (6+0.5+1) \times 2 + (4+2) = 21$ cm

$\ell_2 = (3+0.5+1) \times 2 + (4+2) = 15$ cm

$\ell_0 = 4+2 = 6$ cm

$$R_1 = \frac{\ell_1}{\mu_o \mu_r A1} = \frac{21 \times 10^{-2}}{4\pi \times 10^{-7} \times 1600 \times 2 \times 2 \times 10^{-4}} = 0.261 \times 10^6$$

$$R_2 = \frac{\ell_2}{\mu_o \mu_r A2} = \frac{15 \times 10^{-2}}{4\pi \times 10^{-7} \times 1600 \times 2 \times 2 \times 10^{-4}} = 0.187 \times 10^6$$

$$R_0 = \frac{\ell_o}{\mu_o \mu_r A0} = \frac{6 \times 10^{-2}}{4\pi \times 10^{-7} \times 1600 \times 1 \times 2 \times 10^{-4}} = 0.149 \times 10^6$$

1. **Coil 1 excited with 1A**

$R = R_1 + R_0 ll^{el} R_2 = 0.261 \times 10^6 + 0.149\ II^{el}$ with $0.187 = 0.344 \times 10^6$

$\emptyset_1 = \frac{NI}{R} = \frac{500 \times 1}{0.344 \times 10^6} = 1.453$ mwb

$\emptyset_{21} = \frac{(1.453 \times 10^{-3}) \times (0.149 \times 10^6)}{(0.149 \times 10^6) + (0.187 \times 10^6)} = 0.649$ mwb

$M_{21} = N_2\, \emptyset_{21} = 1000 \times 0.649 \times 10^{-3} = 0.64$ H

2. **Coil 2 excited with 1A**

$R = R_2 + R_0 ll^{el} R_1 = 0.284 \times 10^6$

$\emptyset_2 = \frac{N2I}{R} = \frac{1000 \times 1}{0.284 \times 10^6} = 3.52$ mwb

$L_{22} = N_2 \ \emptyset_2 = 1000 \times 3.52 \times 10^{-3} = 3.52$ H

$M_{12} = M_{21} = 0.64$ H

---

9. A single phase 50Hz 50KVA transformer for 6000/240V ratio has a maximum flux density of 1.4 Wb/m² and an effective core section of 150 cm², the magnetizing current (RMS) is 0.1A. Estimate the inductance of each wire an open circuit. (Dec - 2014)

Given: $E_1 = 6000$ V, $E_2 = 240$V f = 50Hz, $B_m = 1.4$ wb/m² A = 150 cm² I = 0.1 A (rms)

Formula used: $E_1 = 4.44 \ f \ \emptyset_m \ N_1$, $L_1 = \frac{N1 \ \phi m}{I}$, $L2 = \frac{N2 \ \phi m}{I}$

Solution:

$E_1 = 6000$ V, $E_2 = 240$V f = 50Hz, $B_m = 1.4$ wb/m² A = 150 cm² I = 0.1 A (rms)

$B_m = \frac{\phi m}{A}$

$1.4 = \frac{\phi m}{150 \times 10^{-4}}$

$\emptyset_m = 0.021$wb

$E_1 = 4.44 \ f \ \emptyset_m \ N_1$

$6000 = 4.44 \times 50 \times 0.021 \times N_1$

$N_1 = 1287$

$E_2 = 4.44 \ f \ \emptyset_m \ N_2$

$240 = 4.44 \times 50 \times 0.021 \times N_2$

$N_2 = 51.48 = 52$

$L_1 = \frac{N1 \ \phi m}{I} = \frac{27.027}{0.1} = 270.3$ H

$L2 = \frac{N2 \ \phi m}{I} = \frac{1.092}{0.1} = 10.92 = 11$ H

---

10. The core of an electromagnet is made of an iron rod of 1 cm diameter, bent in to a circle of mean diameter 10 cm, a radial air gap of 1 mm being left between the ends of the rod. Calculate the direct current needed in coil of 2000 turns uniformly spaced around the core to produce a magnetic flux of 0.2 mwb in the air gap. Assume that the relative permeability of the iron is 150, that the relative permeability of the iron is 150, that the magnetic leakage factor is 1.2 and that the air gap is parallel. (May 2017)
Given:

Mean diameter $D = 10\text{cm} = 10 \times 10^{-2}$ m

$Aa = \frac{\pi}{4} \times (1)^2 = \frac{\pi}{4} cm^2$

$\ell_g = 1mm = 1 \times 10^{-3}$ m

N = 2000, $\emptyset_g = 0.2$ mwb

$\mu_r = 150$, $\lambda = 1.2$

$\ell_i = \pi D = \pi \times 10 \times 10^{-2} = 0.3141$ m

Solution:

AT for airgap:

$$B_g = \frac{\phi g}{a} = \frac{0.2 \times 10^{-3}}{0.785 \times 10^{-4}} = 2.547 \text{ wb/m}^2$$

$$H_g = \frac{Bg}{\mu o} = \frac{2.547}{4\pi \times 10^{-7}} = 2026838 \text{ AT/m}$$

$$AT_g = H_g \times \ell_g = 2026838 \times 1 \times 10^{-3} = 2026.83 \text{ AT}$$

AT for iron path:

$$\emptyset_i = \emptyset_g \times \lambda = 0.2 \times 10^{-3} \times 1.2 = 2.4 \times 10^{-4} \text{ wb}$$

$$B_i = \frac{\phi i}{a} = \frac{2.4 \times 10^{-4}}{0.785 \times 10^{-4}} = 3.057 \text{wb/m}^2$$

$$H_i = \frac{Bi}{\mu r \times \mu o} = \frac{3.057}{150 \times 4\pi \times 10^{-7}} = 16217.8 \text{ AT/m}$$

$$AT_i = H_i \times \ell_i = 16217.8 \times 0.3141 = 5094 \text{ AT}$$

Total AT $= AT_g + AT_i = 2026.83 + 5094 = 7120.83$ AT

Direct Current (I) = $\frac{\text{Total AT}}{N} = \frac{7120.83}{2000}$ **= 3.56 A**

11.An iron rod 1.8 cm diameter is bent to form a ring of mean diameter 25cm and wound with 250 turns of wire. A gap of 1mm exists in between the end faces. Calculate the current required to produce a flux of 0.6mWb. Take relative permeability of iron as 1200.(May-18)

Given Data:

$$\text{Mean Diameter} = 25 \times 10^{-2} m$$
$$N = 250$$
$$lg = 1mm = 1 \times 10^{-3} m$$
$$\varphi = 0.6mwb = 0.6 \times 10^{-3} wb$$
$$\mu_r = 1200 \quad \mu_0 = 4\pi \times 10^{-7}$$
$$d = 1.8cm$$

Solution:

$$a = \frac{\pi d^2}{4} = \frac{\pi}{4}(1.8)^2 = 2.544cm^2$$
$$a = 2.544 \times 10^{-4} m^2$$
$$\text{Flux density} = \frac{\varphi}{a} = \frac{0.6 \times 10^{-3}}{2.544 \times 10^{-4}} = 2.358 wb/m^2$$
$$H_g = \frac{B}{\mu_0} = 1876436.8 AT/m$$

$$\text{AT required for air gap} = H_g \times lg$$
$$= 1876436.8 \times 1 \times 10^{-3}$$
$$AT_g = 1876.43AT$$
$$H_i = \frac{B}{\mu_0 \mu_r} = \frac{2.358}{4\pi \times 10^{-7} \times 1200} = 1563.7AT/m$$
$$l_i = \pi D = \pi \times 25 \times 10^{-2} = 0.7854m$$
$$\text{AT required for iron path} = H_i \times l_i = 1563.7 \times 00.7854$$
$$AT_i = 1228.12AT$$
$$\text{Total AT} = AT_g + AT_i = 1876.43 + 1228.12 = 3104.55$$
$$\text{Current I} = \frac{AT}{T} = \frac{3104.55}{250} = 12.42A$$

12.An electromagnetic relay has an exciting coil of 800 turns. The coil has a cross section of 5cm×5cm.find (a) coil inductance if the air gap length is 0.5cm .(b) field energy stored for a coil current of 1.25A(c) Permeance at air gap. (May-18)

Given:N=800,l=0.5cm I=1.25A

$$L = \frac{N^2 a \mu_0 \mu_r}{l} = \frac{(800)^2 \times 25 \times 10^{-4} \times 4\pi \times 10^{-7} \times 1}{0.5 \times 10^{-2}}$$
$$= 0.401H$$
$$Field\ energy\ stored = \frac{1}{2} LI^2$$
$$= \frac{1}{2}(0.401) \times (1.25)^2$$
$$Field\ energy\ stored = 0.313J$$
$$\text{Permeance} = \frac{1}{S} = \frac{1}{\frac{l}{\mu_0 \mu_r}}$$
$$\text{Permeance} = 6.28 \times 10^{-7}$$

----

13. A toroidal core made of mild steel has a mean diameter of 16cmand a cross-sectional area of 3cm^2.Calculate a)The MMF to produce a flux of $4 \times 10^{-4} Wb$)the corresponding values of the reluctance of the core and relative permeability.

Given: d=16cm, a=3cm^2$\emptyset = 4 \times 10^{-4} Wb$

Formula used: $\mathbf{B = \frac{\emptyset}{A}, S = \frac{mmf}{\emptyset}}$

Solution:

$$\text{The flux density} = \mathrm{B} = \frac{\emptyset}{\mathrm{A}} = \frac{4 \times 10^{-4}}{3 \times 10^{-4}} = 1.33\mathrm{Wb/m2}$$

Magnatic field strength:

$$H = 900AT/m$$
$$mmf = 950 \times \pi \times 16 \times 10^{-2} = 478AT$$

Reluctance$\boldsymbol{S} = \frac{\boldsymbol{mmf}}{\emptyset} = \frac{\mathbf{478}}{4 \times 10^{-4}} = 119.5 \times 10^{-4} AT/Wb$

$$\boldsymbol{S = l/\mu A}$$
$$119.5 \times 10^{-4} = \frac{\pi \times 16 \times 10^{-2}}{\boldsymbol{\mu} \times 3 \times 10^{-4}}$$

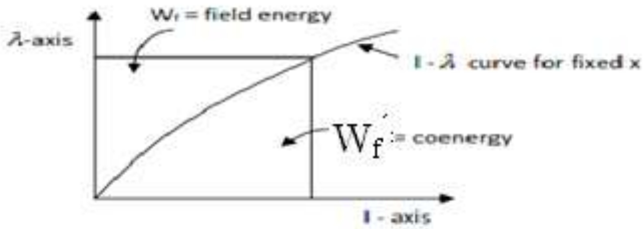
$$\boldsymbol{\mu} = \frac{\pi \times 16 \times 10^{-2}}{119.5 \times 10^{-4}} = \mathbf{0.1043} \times 10^{-2}$$

$$\boldsymbol{\mu}_r = \frac{\mathbf{0.1043} \times 10^{-2}}{4\pi \times 10^{-7}} = 1116$$

UNIT -3

PART-A

1. **In a linear system prove that field energy and co-energy are equal.[May/June-2010]**



In the above figure, if the response is linear then the co-energy becomes equal to that of the field energy.

Therefore $W = W_f = ½\, i(\lambda) = ½\, i\,(Li)$

$W_f' = W_f = ½\, Li^2$

For a linear relation $W_f' = W_f = ½\, L(X)\, i^2$

2. **Draw the power flow diagram for motor and generator operation.[Nov/Dec-2010, 2012 & 2013]**

Motor:

A | **B** | **C**

Ele.I/PMech.O/P → Motor Input → (Cu loss) → Driving Power in Armature → (Iron and friction loss) → Motor Output →

VI watts | **E_bI_a watts** | **in watts**

A – B = Copper losses&B – C = Iron and Friction losses

Generator: **A** | **B** | **C**

MechI/PEle → Mech.Power Input = output of driving engine → (Iron and friction loss) → Electric Power developed in armature → Electric Power output= VI →

E_bI_a watts

3. **Write the expression for the stored energy in the magnetic field.[May/June-2010 &Nov-Dec 2012]**

$$\Delta W_f = \int_{\lambda_1}^{\lambda_2} i(\lambda)\, d\lambda \quad \text{(or)} \quad \Delta W_f = \int_{\Phi_1}^{\Phi_2} \mathcal{F}(\lambda)\, d\phi$$

4. **In a magnetic circuit with a small air gap, in which part the maximum energy is stored and why?[Nov/Dec 2010]**

Energy is stored in air gap. This occur due to the following.

- In a magnetic material in case of iron core (or) steel core the saturation and ageing effects from hindrance to storage.
- In airgap reluctance, as well as permeability are constant, the energy storage takes place linearly without any complexity.

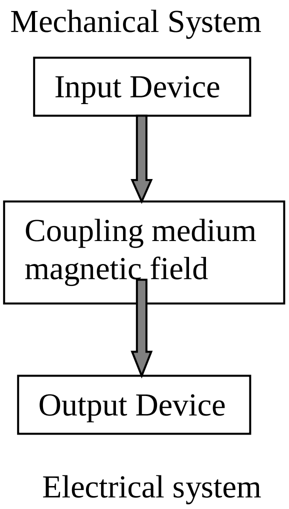
5. **What are the advantages of analyzing the energy conversion devices by field energy concept? Or Write the Advantages of field energy method.[Nov/Dec-2011]**

- It is applicable to all the types of devices such as translator, rotational, vibratory, linear etc.
- Both the steady state as well as transient behaviour of the devices can be analyzed.
- The approach forms the basis of generalized theory of electrical machines.

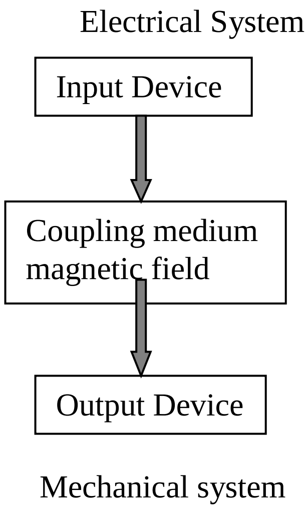
- ➢ The operation of all the electromechanical devices can be studied with great detail giving more physical insight.
- ➢ The various effect such as saturation, communication can be easily studied by introducing conventional approach at any stage.

6. Draw the general block diagram of electromechanical energy conversion device.[Dec-2011& 2013]

(a) Generating device



(b) Motoring device



7. What is an electromechanical energy conversion system?

- ➢ The electrical energy is converted into mechanical energy for motor and mechanical energy is converted to electrical energy for generator.
- ➢ The electromechanical energy conversion takes palace via the medium of a magnetic or electric field is called electromechanical energy conversion system.

8. What is multiply& double excited magnetic field system?[Nov/Dec-2005 &2001]

- ➢ In special devices more than one excitation coils are necessary such systems are called multiple excited systems.
- ➢ Very commonly used multiple excited systems use two excitation coils and are called doubly excited systems

  Ex: Synchronous motor, Alternator or Generator. Loud speakers, Tachometers, DC machines

9. Write the reason for magnetic field as a coupling medium rather than electric field?[May/June-2007,2015](Nov/Dec-2013)

- ➢ When compared to electric field, energy can easily stored and retrieved from a magnetic system with reduced losses comparatively.
- ➢ The energy storing capacity of the magnetic field is much higher than (about 25,600 times) than that of the electric field.

10. Write the application of singly and doubly fed magnetic systems.[Nov/Dec-2006& May- 2013]

- ➢ Single: Electromagnetic relay, Reluctance motor,Toroid coil, &Solenoid coil.
- ➢ Multiple: Alternator, Electro mechanical transducer

11. How energy is stored?[April/May-2004]

- Energy can be stored or retrieved from the magnetic system by means of an exciting coil connected to an electric source.

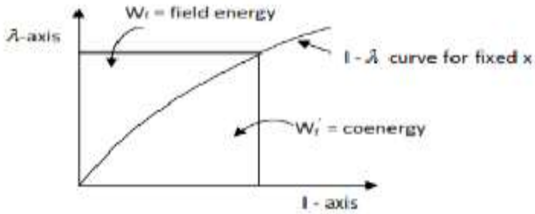
12. Write the equation for mechanical force.

$$F_f = -\frac{\partial W_f(\lambda, x)}{\partial x}$$

13. Define Co-energy and field energy. **[Nov/Dec-2009, April/May - 2012& 2013, 2016]**

- Co energy is an energy used for a linear system computation keeping current as constant. It will not be applied to the non -linear systems **Or** When armature is held open then almost entire mmf is required to drive the flux through air gap and hence magnetic saturation may not occur. – **The energy required for energy conversion (Elect - Mech and Mech – Elect).**
- The energy drawn by virtue of change in the distance moved by the rotor in electrical machines in field configurations are known as field energy.**- The conversion of energy(Elect - Mech and Mech – Elect) is called field energy.**

14. Draw the graphical relation between field energy and coenergy. [Nov/Dec-2009, 2003]



15. Write the expression for the principle of energy conversion.[May/June-2011]

Mechanical energy output= Electrical energy input– Increased or change in field energy.

$$F_f dx = i d\lambda - dw_f$$

16. What is the significance of coenergy? [May/June-2006]

The coenergy has no physical significance but it is important in obtaining magneticforces.

17. How the energy stored in magnetic field? [April/May-2004]

When the moving part of any physical system is held fixed, and then the entire electricalenergy input gets stored in the magnetic field.

18. What are the requirements of the excitation systems?[April/May 2012],[NOV-DEC 2015]

a. Input device (Mechanical or Electrical) 2.Output device 3. Coupling field

19. Enumerate the advantages of using short pitched winding in a synchronous machine. [Dec - 2013]

a) Harmonics are reduced in induced voltage.
b) Saving of copper
c) End connections are shorter.

20. Write the equation which relates rotor speeds in electrical and mechanical radians per second.(MAY/JUNE 2015)

$$\omega_e = \omega_m (P/2)$$

Where, ω_e – Speed is electrical radians per sec.

ω_m- Speed in mechanical radians per sec.

P – No. of poles.

21. State the principle of electromechanical energy conversion.[May/June-2011,Dec 2017]

a) As electric energy is not readily available in nature.
b) It has to be generated to meet the demands of electricity.
c) The mechanical energy is converted to electrical energy vice versa of which is also is possible is called electro-mechanical conversion which takes place through either electric field or magnetic field.

22. State three types of electromechanical energy conversion. AU-NOV/DEC 2008

1. The various transducers such as microphones, loudspeakers and thermocouples. – **Limited Motion**
2. The device which produce the mechanical force or torque based on translatory motion such as electromagnet and relays. – **Small Motion**
3. The devices used for continuous energy conversion using rotational motion such as generators and motors. – **Continuous Motion**

23. Write energy balance equation.

$$dW_e = dW_m + dW_f + dW_{loss}$$

$$dW_m = dW_e + dW_f + dW_{loss}$$

24. What is current excited system? Nov/Dec 2010

This is the expression for system in which i is independent variable. This means input current constant such a system is current excited system

25. How the direction of mechanical force or torque developed in any physical system? April/May 2009

a) decrease the magnetic stored energy at constant λ
b) increase the stored energy and co-energy at constant i
c) decrease the reluctance
d) increase the inductance.

26. What are the three basic type of rotating electrical Machine? (May-2011, Dec 2013)

i)DC Machines
ii)Poly phase synchronous machines
iii) Poly phase Induction machines

27. What is meant by winding inductance?(May 2016)

It is the property of an electric conductor or circuit that causes an electromotive force to be generated by a change in the current flowing.

28. What is magnetic saturation? Dec – 2016

Any further increase in flux density (B) will have no effect on the value of magnetic field strength (H), and the point on the graph where the flux density reaches its limit is called **Magnetic Saturation** also known as **Saturation of the Core.**

29. What is meant by distributed winding? Dec - 2016

If 'x' conductor per phase are distributed amongst the 3 slots per phase available under pole, the winding is called distributed winding.

30. Define winding factor. [Nov – 2011]

The winding factor Kw is defined as the ratio of phasor addition of emf induced in all the coils belonging to each phase winding of their arithmetic addition

31. Define the synchronous speed. Write the expression also. May 2017

In synchronous machine, the rotor and flux at stator rotate in Ns speed whereas in induction machine the stator flux alone moves at this speed.

$$Ns = 120f/p$$

32. Define the term pole pitch and coil pitch. May 2017

Pole Pitch – is the centre to centre distance between any two consecutive poles in a rotating machine, measured in terms of slots per pole.

33. **Predominant energy storage occurs in the air gap of an electromechanical energy conversion device.is this statement correct–true (Dec-2017)**

In airgap reluctance, as well as permeability are constant, the energy storage takes place linearly without any complexity.

34. Why the relation between current and coil flux linkages of electromechanical energy conversion devices are linear (May 2018)

When alternator is held open then almost entire MMF is required to device the flux through air gap and hence magnetic saturation may not occur. so the relationship between current and coil flux linkages of electromechanical energy conversion devices are linear.

35. What are the causes for irrecoverable energy loss when the flux in the magnatic circuit undergoes a cycle (May 2018)

When a magnetic circuit undergoes a cycle $\varphi_1 \rightarrow \varphi_2 \rightarrow \varphi_1$,it undergoes a cycle of magnetization and demagnetization. The hysteresis and eddy current effects are dominant under such condition.

Part – B

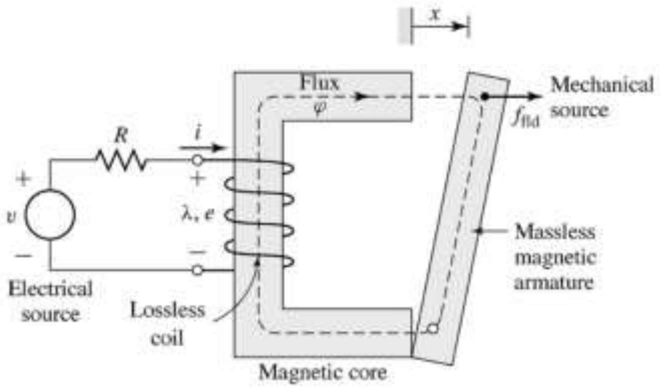
1. **Explain the concept of singly-excited machines and Derive an expression for the magnetic Energy stored in a singly excited electromagnetic relay.[Nov/Dec-2010] [May 2016]**
Discuss in detail the production of mechanical force for an attracted armature relay excited by an electric source (Dec 2017)

Or

Consider an attracted armature relay is excited by an electric source. Explain about the mechanical force developed and the mechanical energy output with necessary equations for linear and nonlinear cases.(May 2018)

Self-excited machines are used to produce magnetic field. E.g: electromagnetic relay, Reluctance Motor, Toroid coil etc.,

The attractive type armature relay is shown below,



It includes electrical input energy, mechanical stored field energy and mechanical force.

- The following assumptions are made while performing the analysis of single excited magnetic system.
- The resistance of the exciting coil is assumed to be present in lumped form, outside the coil. This coil is lossless and ideal.
- The leakage flux does not take part in energy conversion process (80H) is neglected as practically it is small.

Hence all the flux is confined to the ironcore and links all the Nturns of coil.

$$\lambda = N\Phi$$

Where,

N - No: of turns of the coil

Φ - Total flux

Leakage inductance is negligible

There is energy loss in the magnetic core

The reluctance of the iron path is neglected.

Electrical Energy Input:

Due to the flux linkages λ, the reaction emf exists, whose direction is so as to oppose the cause producing it.

Induced emf $e=\frac{d\lambda}{dt}$

Applying KVL to the coil circuit

$$V=ir+e$$

$$V=ir+\frac{d\lambda}{dt}$$

Multiplying on both sides by ‘i’, we get

$$Vi = i^2r + i\frac{d\lambda}{dt}$$

$$Vidt = i^2rdt + id\lambda$$

$$Vidt - i^2rdt = id\lambda$$

$$(V - ir)idt = id\lambda$$

$$eidt = id\lambda \qquad [\text{since } e=V-ir]$$

Now the input electrical energy to the lossless coil is given by,

$$dWe = eidt = id\lambda$$

$$dWe = id\,(N\Phi)$$

$$dWe = Ni\,d\Phi$$

Where,

Ni = mmf of the coil

Thus the magnetic system extracts the electrical energy from the supply.

Magnetic Field Energy stored:

Consider that the armature isheld fixed at position ‘x’.
As armature is not moving, the mechanical work done is zero.
According to energy balance equation,

Input from supply = Mechanical output + Stored energy + loss

The entire electric energy input gets stored in the magnetic field

$$\text{i.e., } dW_e = dW_f \qquad [\text{since } dW_m = 0]$$

$$dW_f = eidt = id\lambda = Nid\Phi \text{---------------------- (1)}$$

The relationship i-λ is basically non-linear for a magnetic circuit, similar to the B-H relationship.
From the Eqn-(1), the energy absorbed for a finite change in flux linkages can be obtained.

$$\Delta Wf = \int_{\lambda_1}^{\lambda_2} i(\lambda)d\lambda = \int_{\Phi_1}^{\Phi_2} Nid\Phi$$

If the initial flux and flux linkages are zero,

i.e. $\phi_1 = \lambda_1 = 0$, then the energy stored in the magnetic field is,

$$Wf = \int_0^{\lambda} i(\lambda)\, d\lambda = \int_0^{\Phi} Nid\Phi$$

I – λ relationship is similar to the magnetization curve for a magnetic material for various values of x.