1.7 AC EXCITATION, INTRODUCTION TO PERMANENT MAGNETS

Permanent magnets are commonly used to generate magnetic fields for electromechanical energy conversion in a number of electromagnetic devices, such as actuators, permanent magnet generators and motors. From fig 1.11 the characteristics of permanent magnets are described by demagnetization curves (the part of hysteresis loop in the second quadrant). The diagram below depicts the demagnetization curve of five permanent magnets. It can be seen that the demagnetization curves of some most commonly used permanent magnets: Neodymium Iron Boron (NdFeB), Samarium Cobalt, and Ceramic 7 are linear. For the convenience of analysis, we consider the magnets with linear demagnetization curves first. Consider a piece of permanent magnet of a uniform cross sectional area of Am and a length lm. The demagnetization curve of the magnet is a straight line with a coercive force of Hc and a remnant flux density of Br as shown below. The demagnetization curve can be expressed analytically as

$$B_m = \frac{B_r}{H_c}(H_m + H_c) = \mu_m(H_m + H_c)$$

The magnetic "voltage drop" across the magnet can be expressed as

$$H_m l_m = \left(\frac{B_m}{\mu_m} - H_c\right) l_m = \frac{l_m}{\mu_m A_m}\phi_m - H_c l_m = R_m\phi_m - F_m$$

which is a function of the magnetic field in the magnet. Notice that Hm is a negative value since it is in the opposite direction of **B**m. The derivation for the magnetic circuit model of a nonlinear magnet is illustrated graphically by the Figure

1.7.2 below.

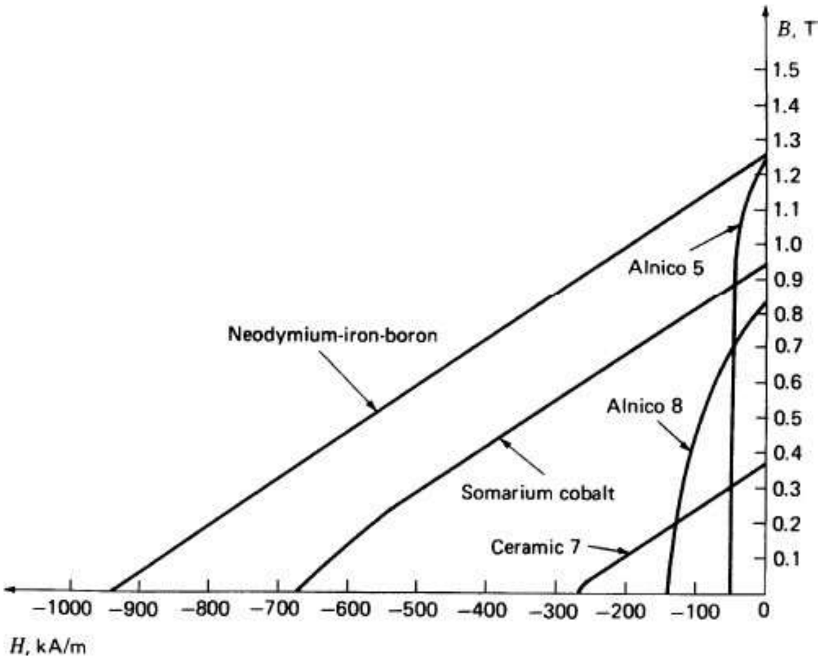


Figure 1.7.1 Demagnetization curves of permanent magnets

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 86]*

It should also be understood that the operating point (Hm,Bm) will not move along the nonlinear demagnetization curve if a small (such that the magnet will not be demagnetized) periodic external magnetic field is applied to the magnet. Instead, the operating point will move along a minor loop or simply a straight line (center line of the minor loop) as illustrated in the diagram on the right hand side.

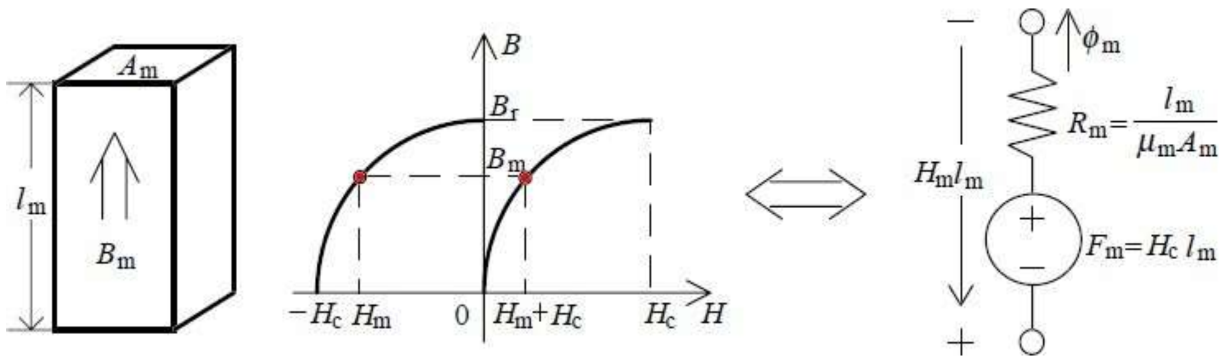


Figure 1.7.2 Magnetic circuit model of a magnet with nonlinear demagnetization curve

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 87]*

1.3 FLUX LINKAGE, INDUCTANCE AND ENERGY

Inductance

Consider a two coil magnetic system as shown below. The magnetic flux linkage of the two coils can be express as

$$\lambda_1 = \lambda_{11} + \lambda_{12} \qquad \text{and} \qquad \lambda_2 = \lambda_{21} + \lambda_{22}$$

where the first subscript indicates the coil of flux linkage and the second the coil carrying current. By defining the self and mutual inductances of the two coils as

$$L_{jk} = \frac{\lambda_{jk}}{i_k} \quad (j=1,2 \text{ and } k=1,2)$$

where L_{jk} is the self inductance of the jth coil when $j=k$, the mutual inductance between the j^{th} coil and the k^{th} coil when $j \neq k$, and $L_{jk}=L_{kj}$, the flux linkages can be expressed as

$$\lambda_1 = L_{11}i_1 + L_{12}i_2 \qquad \text{and} \qquad \lambda_2 = L_{21}i_1 + L_{22}i_2$$

The above definition is also valid for a n coil system. For a linear magnetic system, the above calculation can be performed by switching on one coil while all other coils are switched off such that the magnetic circuit analysis can be simplified.

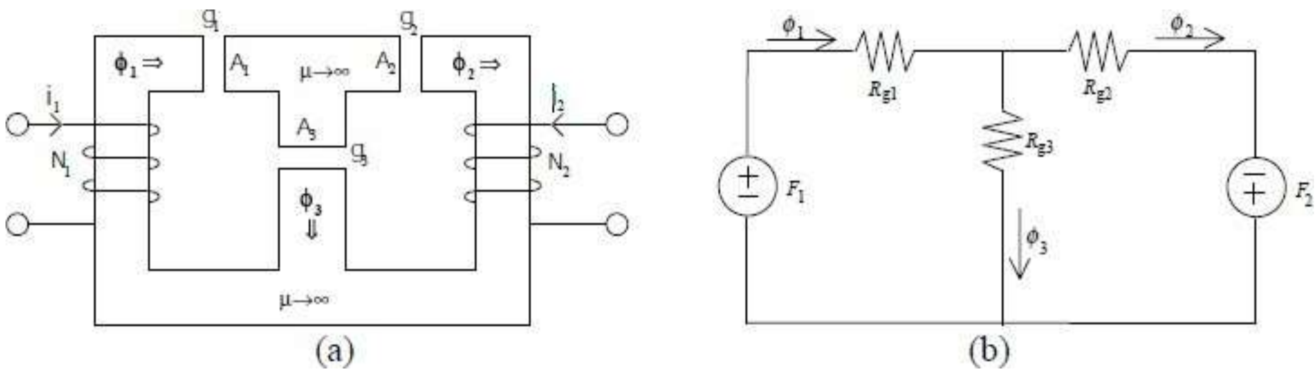


Figure 1.3.1 Magnetic circuit of a two coil system

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 59]*

This is especially significant for a complex magnetic circuit. For a nonlinear magnetic system, however, the inductances can only be calculated by the above definition with all coils switched on.

Electromotive Force

When a conductor of length l moves in a magnetic field of flux density $\mathbf{B}$ at a speed $\mathbf{v}$,

$$\mathbf{e} = l\mathbf{v} \times \mathbf{B}$$

the induced electromotive force (*emf*) can be calculated by
For a coil linking a time varying magnetic field, the induced *emf* can be calculated from the flux linkage of the coil by

$$e_k = \frac{d\lambda_k}{dt} = \sum_{j=1}^{n} \frac{d\lambda_{kj}}{dt} = \sum_{j=1}^{n} L_{kj} \frac{di_j}{dt} \qquad (k=1,2,\ldots n)$$

Magnetic Energy

In terms of inductance, the magnetic energy stored in an n coil system can be expressed as

$$W_f = \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \lambda_{jk} i_j = \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \frac{\lambda_{jk}\lambda_{kj}}{L_{jk}} = \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} L_{jk} i_j i_k$$

1.6 HYSTERESIS AND EDDY CURRENT LOSSES

The area enclosed by the loop is a power loss known as the hysteresis loss, and can be calculated by

$$P_{hyst} = \oint \mathbf{H} \bullet d\mathbf{B} \quad (\text{W/m}^3/\text{cycle}) \text{ or } (\text{J/m}^3)$$

For magnetic materials commonly used in the construction of electric machines an approximate relation is

$$P_{hyst} = C_h f B_p^n \quad (1.5 < n < 2.5) \quad (\text{W/kg})$$

Where

C_h = constant determined by the nature of the ferromagnetic material,

f = frequency of excitation, and B_p is the peak value of the flux density.

When the excitation field varies quickly, by the Faraday's law, an electromotive fore (*emf*) and hence a current will be induced in the conductor linking the field as shown in figure 1.9 . Since most ferromagnetic materials are also conductors, eddy currents will be induced as the excitation field varies, and hence a power loss known as eddy current loss will be caused by the induced eddy currents. The resultant B-H or ?-i loop will be fatter due to the effect of eddy currents, as illustrated in the diagram below. Under a sinusoidal magnetic excitation, the average eddy current loss in a magnetic core can be expressed by

$$P_{eddy} = C_e \left(f B_p \right)^2 \qquad (\text{W/kg})$$

where C_e is a constant determined by the nature of the ferromagnetic material and the dimensions of the core.

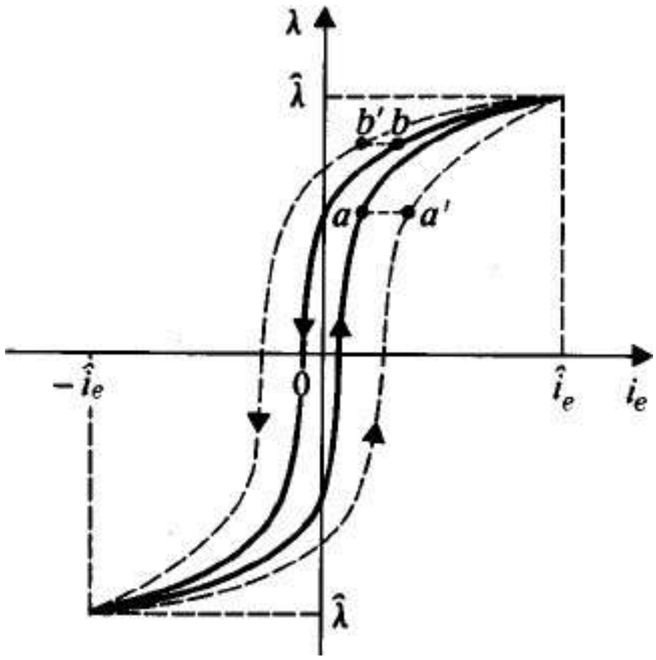


Figure 1.6.1 Hysteresis Loop

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 81]*

Fig 1.6.1 Relationship between flux linkage and excitation current when eddy current is included (dashed line loop), where the solid line loop is the pure hysteresis obtained by dc excitation.

Since the eddy current loss is caused by the induced eddy currents in a magnetic core., an effective way to reduce the eddy current loss is to increase the resistivity of the material. This can be achieved by adding Si in steel. However, too much silicon would make the steel brittle. Commonly used electrical steels contain 3% silicon.Another effective way to reduce the eddy current loss is to use laminations of electrical steels. These electrical steel sheets are coated with electric insulation, which breaks the eddy current path, as illustrated in figure 1.6.2 .

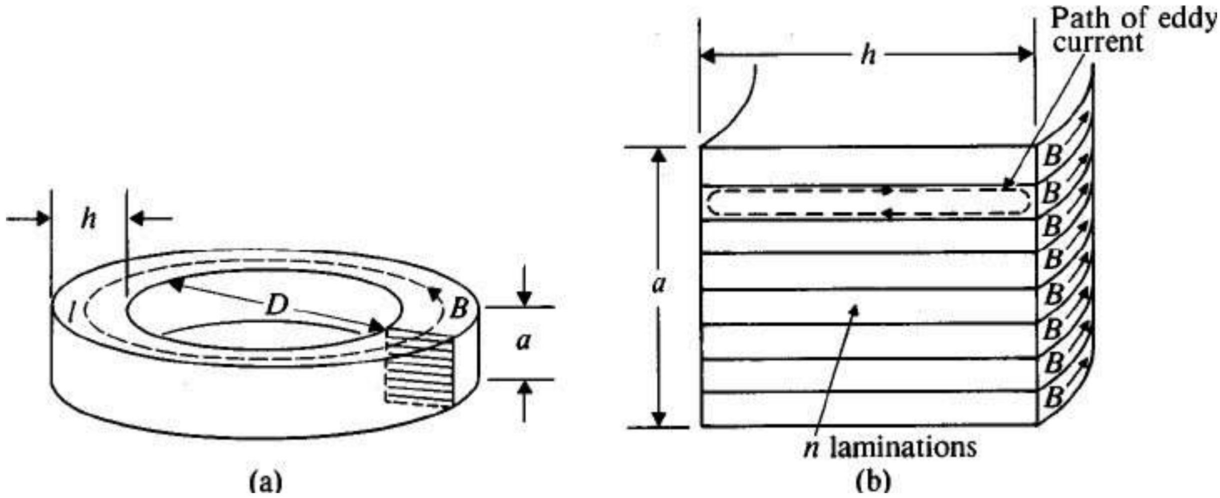


Figure 1.6.2 Eddy currents in a laminated toroidal core

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 86]*

The above formulation for eddy current loss is obtained under the assumption of global eddy current as illustrated schematically in figure1.6.2 (a) of the following diagram. This is incorrect for materials with magnetic domains. When the excitation field varies, the domain walls move accordingly and local eddy currents are induced by the fluctuation of the local flux density caused by the domain wall motion as illustrated in figure1.6.2 (b) of the diagram below. The total eddy current caused by the local eddy currents is in general higher than that predicted by the formulation under the global eddy current assumption.

The difference is known as the excess loss. Since it is very difficult to calculate the total average eddy current loss analytically, by statistical analysis, it was postulated that for most soft magnetic materials under a sinusoidal magnetic field excitation, the excess loss can be predicted by

$$P_{ex} = C_{ex}\left(fB_p\right)^{3/2} \quad (\mathrm{W/kg})$$

where Cex is a constant determined by the nature of the ferromagnetic material. Therefore, the total core loss can be calculated by

$$P_{core} = P_{hyst} + P_{eddy} + P_{ex}$$

1.2 LAWS GOVERNING MAGNETIC CIRCUITS

Consider the magnetic circuit in the last section with an air gap of length lg cut in the middle of a leg as shown in figure (a) in the diagram below. As they cross the air gap, the magnetic flux lines bulge outward somewhat as illustrate in figure (b). The effect of the fringing field is to increase the effective cross sectional area A_g of the air gap. By Ampere's law, we can write

$$F = Ni = H_c l_c + H_g l_g$$

where

$$H_c l_c = \frac{B_c}{\mu_c} l_c = \frac{\phi_c}{\mu_c A_c} l_c = \phi_c R_c$$

and

$$H_g l_g = \frac{B_g}{\mu_o} l_g = \frac{\phi_g}{\mu_o A_g} l_g = \phi_g R_g$$

According to Gauss' law in magnetics,

$$\oint_S \mathbf{B} \bullet d\mathbf{a} = 0$$

we know

$$\phi_c = \phi_g = \phi$$

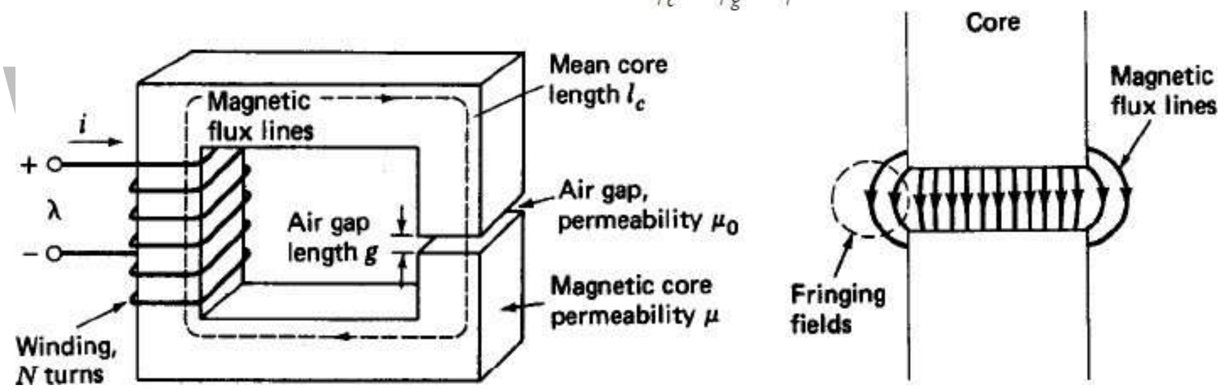


Figure 1.2.1 A Simple Magnetic Circuit with an air gap

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 54]*

Therefore,

$$F = (R_c + R_g)\phi$$

Thatis,theabovemagneticcircuitwithanairgapisanalogoustoaserieselectric circuit. Further, if we regard $H_c l_c$ and $H_g l_g$ as the "voltage drops" across the reluctance of the core and airgap respectively, the above equation from Ampere's law can be interpreted as an analog to the Kirchhoff's voltage law (KVL) in electric circuit theory, or

$$\sum R_k \phi_k = \sum F_k$$

The Kirchhoff's current law (KCL) can be derived from the Gauss' law in magnetics. Consider a magnetic circuit as shown below. When the Gauss' law is applied to the T joint in the circuit, we have

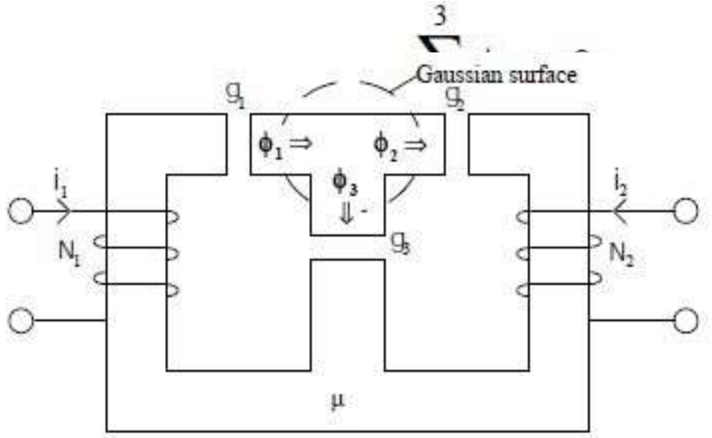


Figure 1.2.1 Magnetic circuit of T joints

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 56]*

Having derived the Ohm's law, KVL and KCL in magnetic circuits, we can solve very complex magnetic circuits by applying these basic laws. All electrical dc circuit analysis techniques, such as mesh analysis and nodal analysis, can also be applied in magnetic circuit analysis. For nonlinear magnetic circuits where the nonlinear magnetization curves need to be considered, the magnetic reluctance is a function of magnetic flux since the permeability is a function of the magnetic field strength or flux density. Numerical or graphical methods are required to solve nonlinear problems.

1.1 Magnetic circuits

Introduction

Ingeneral,magneticmaterialscanbeclassifiedasmagnetically"soft"and"hard" materials. Soft materials are normally used as the magnetic core materials for inductors, transformers, actuators and rotating machines, in which the magnetic fields vary frequently, whereas hard materials, or permanent magnets, are used to replace magnetization coils for generating static magnetic fields in devices such as electric motors and actuators. The B-H relationships and hysteresis loops have been discussed earlier. In this chapter, we are going to examine the power losses in a soft magnetic core under an alternating magnetization, and further develop an electrical circuit model of a magnetic core with a coil. For performance prediction of electromagnetic devices, magnetic field analysis is required.

Analytical magnetic field analysis by the Maxwell's equations, however, has been shown very difficult for engineering problems owing to the fact that most practical devices are of complicated structures. Powerful numerical methods, such as the finite difference and finite element methods, are out of the scope of this subject. In this chapter, we introduce a simple method of magnetic circuit analysis based on an analogy to dc electricalcircuits.

Soft Magnetic Materials under Alternating Excitations

Core Losses

Corelossesoccurinmagneticcoresofferromagneticmaterialsunderalternating magnetic field excitations. The Figure 1.1 on the right hand side plots the alternating core losses of M-36, 0.356 mm steel sheet against the excitation frequency. In this section, we willdiscussthemechanismsandpredictionofalternatingcorelosses.

As the external magnetic field varies at a very low rate periodically, as mentioned earlier, due to the effects of magnetic domain wall motion the B- H. relationship is a hysteresis loop. The area enclosed by the loop is a power loss known as the hysteresis loss, and can be calculated by,

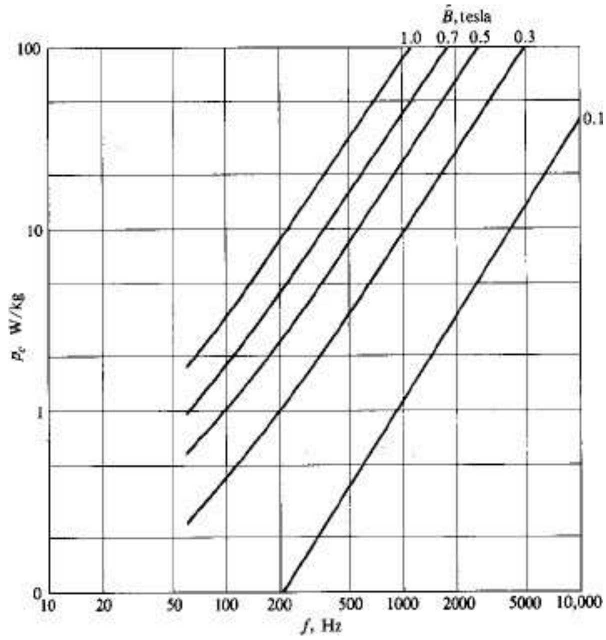


Figure 1.1.1 Alternating core loss of steel sheet at different excitation frequencies

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 45]*

For magnetic materials commonly used in the construction of electric machines an

approximate relation is $P_{hyst} = \oint \mathbf{H} \bullet d\mathbf{B}$ (W/m^3/cycle) or (J/m^3)

where

$$P_{hyst} = C_h f B_p^n \quad (1.5 < n < 2.5) \quad (\text{W/kg})$$

Ch is a constant determined by the nature of the ferromagnetic material,

f is the frequency of excitation, and B_p is the peak value of the flux density.

Example:

A B-H loop for a type of electric steel sheet is shown in the diagram below. Determine approximately the hysteresis loss per cycle in a torus of 300 mm mean diameter and a square cross section of 50*50 mm.

Solution:

The area of each square in the diagram represents

$$(0.1\ \text{T}) \times (25\ \text{A/m}) = 2.5\ (\text{Wb/m}^2) \times (\text{A/m}) = 2.5\ \text{VsA/m}^3 = 2.5\ \text{J/m}^3$$

If a square that is more than half within the loop is regarded as totally enclosed, and one that is more than half outside is disregarded, then the area of the loop is

$$2 \times 43 \times 2.5 = 215 \ \text{J/m}^3$$

The volume of the torus is

$$0.05^2 \times 0.3\pi = 2.36 \times 10^{-3} \ \text{m}^3$$

Energy loss in the torus per cycle is thus

$$2.36 \times 10^{-3} \times 215 = 0.507 \ \text{J}$$

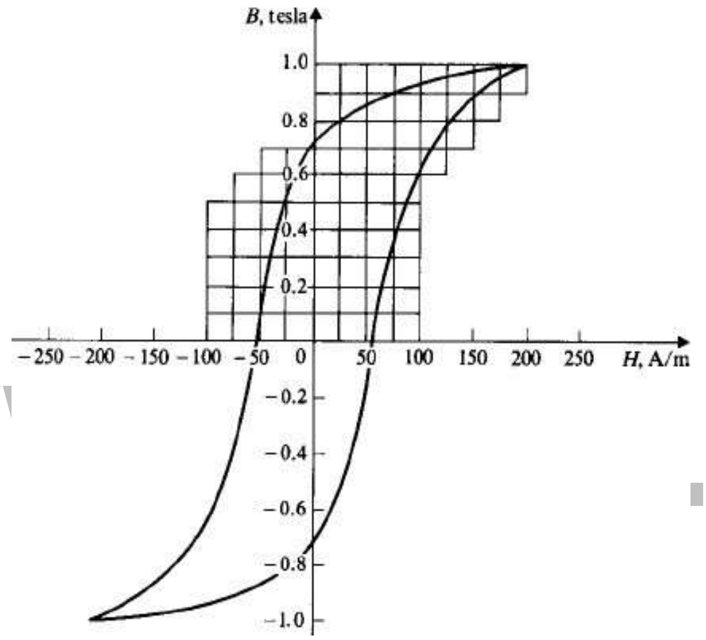


Figure 1.1.2 Hysteresis loop of M-36 steel sheet

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 46]*

A Simple Magnetic Circuit

Consider a simple structure consisting of a current carrying coil of N turns and a magnetic core of mean length l and a cross sectional area A as shown in the diagram below. The permeability of the core material is μ_c. Assume that the size of the device and the operation frequency are such that the displacement current in Maxwell's equations are negligible, and that the permeability of the core material is very high so that all magnetic flux will be confined within the core. By Ampere's law,

$$\oint_C \mathbf{H} \bullet d\mathbf{l} = \oint_S \mathbf{J} \bullet d\mathbf{a}$$

we can write

$$H_c l_c = Ni$$

where Hc is the magnetic field strength in the core, and Ni the magneto motive force. The magnetic flux through the cross section of the core can expressed as

$$\phi_c = B_c A_c$$

where φ_c is the flux in the core and Bc the flux density in the core. The constitutive equation of the core material is

$$B_c = \mu H_c$$

Therefore, we obtain

$$\phi_c = \frac{Ni}{l_c/(\mu_c A_c)} = \frac{F}{R_c}$$

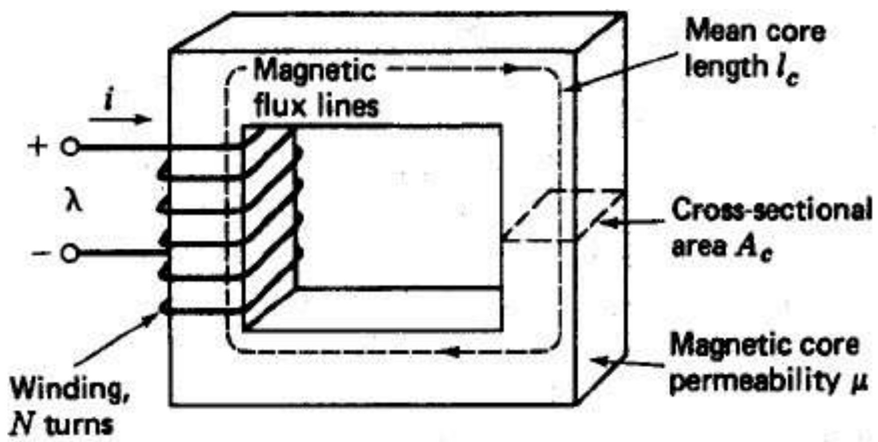
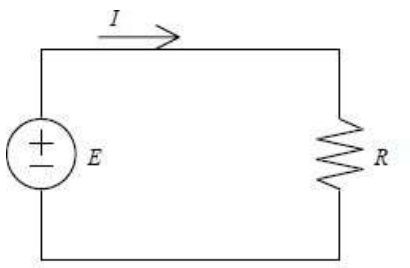


Figure 1.1.3 A Simple Magnetic Circuit

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 49]*

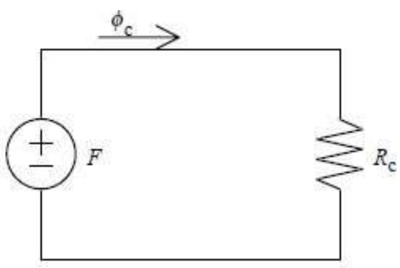
If we take the magnetic flux φ_c as the "current", the magneto motive force F=Ni as the "emf of a voltage source", and $R_c = l_c/(\varphi_c\ A_c)$ (known as the magnetic reluctance) as the "resistance" in the magnetic circuit, we have an analog of Ohm's law in electrical circuit theory.

Electric Circuit



$$I = \frac{E}{R}$$

Magnetic Circuit



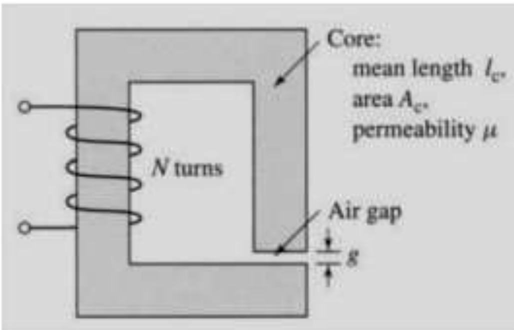
$$\phi_c = \frac{F}{R_c}$$

1.9 Solved Problems Eg
.No.1

A magnetic circuit with a single air gap is shown in Fig. 1.24. The core dimensions are:

Cross-sectional area $A_c = 1.8 \times 10^{-3}$ m^2, Mean core length $l_c = 0.6$ m

Gap length $g = 2.3 \times 10^{-3}$ m , $N = 83$ turns



Assume that the core is of infinite permeability and neglect the effects of fringing fields at the air gap and leakage flux. (a) Calculate the reluctance of the core R_e and that of the gap R_g. For a current of i = 1.5 A, calculate (b) the total flux ϕ, (c) the flux linkages λ of the coil, and (d) the coil inductance L.

Solution:

$$R_c = 0 \quad \text{since } \mu \to \infty \qquad R_g = \frac{g}{\mu_0 A_c} = \frac{2.3\times10^{-3}}{4\pi\times10^{-7}\times1.8\times10^{-3}} = 1.017\times10^{6} \text{ A/Wb}$$

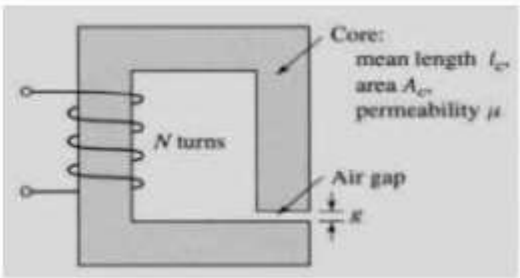
$$\phi = \frac{Ni}{R_c + R_g} = \frac{83\times1.5}{1.017\times10^{6}} = 1.224\times10^{-4} \text{ Wb}$$

$$\lambda = N\phi = 1.016\times10^{-2} \text{ Wb}$$

$$L = \frac{\lambda}{i} = \frac{1.016\times10^{-2}}{1.5} = 6.773 \text{ mH}$$

Eg .No.2

Consider the magnetic circuit of with the dimensions of Problem 1.1. Assuming infinite core permeability, calculate (a) the number of turns required to achieve an inductance of 12 mH and (b) the inductor current which will result in a core flux density of 1.0 T.



Solution:

$$L = \frac{N^2}{R_g} = 12\times10^{-3}\text{ mH} \Rightarrow N = \sqrt{12\times10^{-3}\times1.017\times10^{6}} = 110.47 \Rightarrow N = 110\text{ turns}$$

$$B_c = B_g = 1.0\text{ T} \Rightarrow \phi = B_g A_c = 1.8\times10^{-3}\text{ Wb}$$

$$i = \frac{\lambda}{L} = \frac{N\phi}{L} = \frac{110\times1.8\times10^{-3}}{12\times10^{-3}} = 16.5\text{ A}$$

Eg.No.3

In the magnetic circuit of" Fig. E1.2a, the relative permeability of the ferromagnetic material is 1 200 . Neglect magnetic leakage an‹1 fingering. All dimensions are in centimeters, and the magnetic material has a square cross-sectionsI a rea. Determine the air gap flux, the air gap flux density, arid the magnetic field intensity ty in flue air gap.

Solution

The mean magnetic paths of the fluxes arc shown by dashed lines in Fig. E l .3a. The equivalrnt magnetic circuit is shown in Fig. El.36.

$$F_1 = N_1 I_1 = 500 \times 10 = 500\ At$$

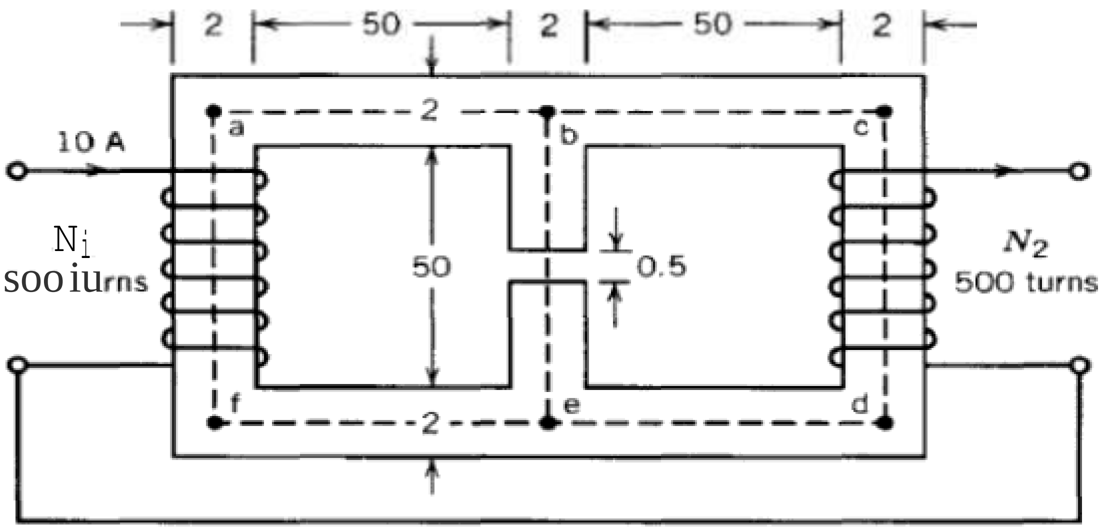
$$F_2 = N_2 I_2 = 500 \times 10 = 500\ At$$

$$\mu_c = 1200\mu_0 = 1200 \times 4\pi 10^{-7}$$

$$R_{bafe} = \frac{I_{bafe}}{\mu_c A_c}$$

$$\frac{3 \times 52 \times 10^{-2}}{1200 \times 4\pi 10^{-7} \times 4 \times 10^{-4}}$$

= 2.58 x 10' At/Wb



From symmetry

$$R_{bcde} = R_{bafe}$$

$$R_g = \frac{l_g}{\mu_0 A_g}$$

$$= \frac{5\times10^{-3}}{4\pi10^{-7}\times2\times2\times10^{-4}}$$

$= 9.94 \times 10^6$ At/Wb

$$R_{be(core)} = \frac{l_{be(core)}}{\mu_c A_c}$$

$$\frac{51.5 \times 10^{-2}}{1200 \times 4\pi10^{-7} \times 4 \times 10^{-4}}$$

$=0.82 \times 10^6$ At/Wb

The loop equations are

$$\emptyset_1(R_{bafe} + R_{be} + R_g) + \emptyset_g(R_{be} + R_g)$$

$$\Phi_1(\mathcal{R}_{be} + \mathcal{R}_g) + \Phi_2(\mathcal{R}_{bcde} + \mathcal{R}_{be} + \mathcal{R}_g) = F_2$$

$$\emptyset_1(13.34 \times 10^6) + \emptyset_2(10.76 \times 10^6) = 500$$

$$\emptyset_1(10.76 \times 10^6) + \emptyset_2(13.34 \times 10^6) = 5000$$

The air gap flux density is

$$B_g = \frac{\Phi_g}{A_g} = \frac{4.134 \times 10^{-4}}{4 \times 10^{-4}} = 1.034\ \text{T}$$

The magnetic intensity in the air gap is

$$H_g = \frac{B_g}{\mu_0} = \frac{1.034}{4\pi10^{-7}} = 0.822 \times 10^6\ \text{At/m}$$

Eg.no.5

Eg.No.4

For the rriagnetic circuit of Fig. l .9, /V = 400 turns.
Mean ccire length I, = SO cm,
Air gap length = 1.0 mm
Cross-sectional area *A*, — *At* — 15 cm'
Relativc permeability c›f core y, 3000
i 1.O A

(a) Flex and flux density in the air gap.
(b) Inductance of the coil.

Solution

(a)

$$\mathcal{R}_c = \frac{l_c}{\mu_r\mu_0 A_c} = \frac{50 \times 10^{-2}}{3000 \times 4\pi\, 10^{-7} \times 15 \times 10^{-4}}$$

$$= 88.42 \times 10^3 \text{ AT/Wb}$$

$$\mathcal{R}_g = \frac{l_g}{\mu_0 A_g} = \frac{1 \times 10^{-3}}{4\pi 10^{-7} \times 15 \times 10^{-4}}$$

$$= 530.515 \times 10^3 \text{ At/Wb}$$

$$\Phi = \frac{Ni}{R_c + R_g}$$

$$= \frac{400 \times 1.0}{(88.42 + 530.515)10^3}$$

$$B = \frac{\Phi}{A_g} = \frac{0.6463 \times 10^{-3}}{15 \times 10^{-4}} = 0.4309 \text{ T}$$

b)

$$L = \frac{N^2}{\mathcal{R}_c + \mathcal{R}_g} = \frac{400^2}{(88.42 + 530.515)^{10^3}}$$

$$= 258.52 \times 10^{-3} \text{ H}$$

$$\text{or} \quad L = \frac{\lambda}{i} = \frac{N\Phi}{i} = \frac{400 \times 0.6463 \times 10^{-3}}{1.0}$$

$$= 258.52 \times 10^{-3} \text{ H} \quad \blacksquare$$

1.4 STATICALLY AND DYNAMICALLY INDUCED EMF

Dynamically induced EMF

Figure 1.7 shows three conductors a, b, c moving in a magnetic field of flux density B in the directions indicated by arrow. Conductor a is moving in a direction perpendicular to its length and perpendicular to the flux lines. Therefore it cuts the lines of force and a motional emf is induced in it. Let the conductor move by a distance dx in a time dt. If the length of conductor is l, the area swept by the conductor is $l\,dx$. Then change in flux linking the coil

Since there is only one conductor = dφ = Bldx

$$e = \frac{d\phi}{dt} = \frac{Bl\,ds}{dt}$$

Since dx/dt is v, i.e velocity of conductor,

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

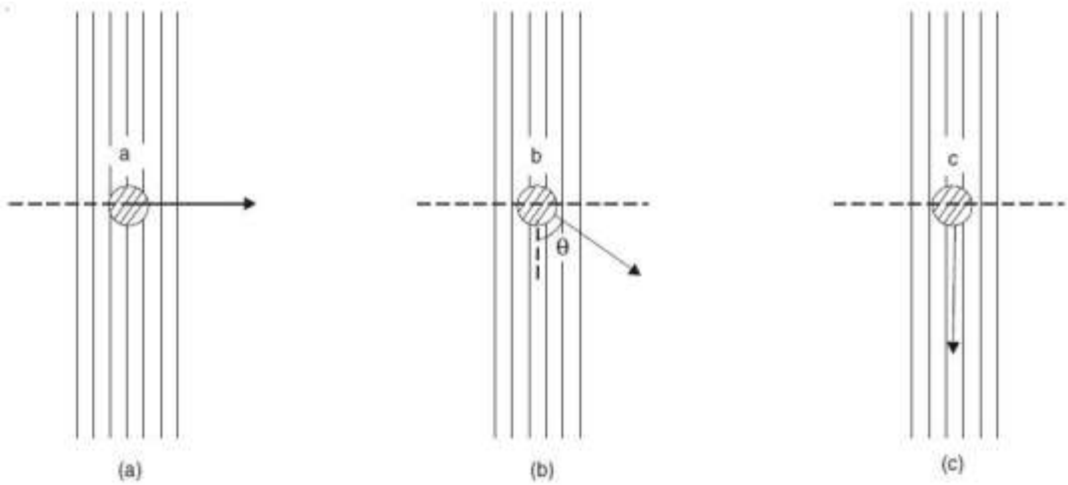


Figure 1.4.1 Motion of a conductor in a magnetic field

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 59]*

where

e = emf induced, volts

B = flux density, tesla

v = velocity of conductor, metres/second

l = length of conductor, metres

The motion of conductor b (Fig. 1.7b) is at an angle θ to the direction of the field. If the conductor moves by a distance dx, the component of distance travelled at right angles to the field is (dx sin θ) and, proceeding as above, the induced emf is

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

The force F on a particle of charge Q moving with a velocity v in a magnetic field B is Dividing F

$$F = Q(v \times B) \quad N$$

by Q we get the force per unit charge, *i.e.* electric field E, as

$$E = \frac{F}{Q} = v \times B \quad \text{volts/m}$$

The electric field E is in a direction normal to the plane containing v and B. If the charged particle is one of the many electrons in a conductor moving across the magnetic field, the emf e between the end points of conductor is line integral of electric field E, or

where

$$e = \oint E \cdot dl = \oint (v \times B) \cdot dl$$

e = emf induced, volts
E = electric field, volts/m
dl = elemental length of conductor, m
v = velocity of conductor, metres/second
B = flux density, tesla.

Statically induced emf (or Transformer emf)

Statically induced emf (also known as transformer emf) is induced by variation of flux. It may be (a) mutually induced or (b) self induced. A mutually induced emf is set up in a coil whenever the flux produced by a neighbouring coil changes. However, if a single coil carries alternating current, its flux will follow the changes in the current. This change in flux will induce an emf known as self-induced emf in the coil, the word 'self' signifying that it is induced due to a change in its own current. The magnitude of statically induced emf. It is also known as transformer emf, since it is induced in the

windings of a transformer. The total flux linkages λ of a coil is equalto the integral of the normal component of flux density B over the surface bounded by the coil, or
The surface over which the integration is carried out is the surface bounded by the periphery of the coil. Thus, induced emf

$$\lambda = \iint B \cdot ds$$

$$e = \frac{d\lambda}{dt} = \frac{d}{dt}\iint B \cdot ds$$

When the coil is stationary or fixed

$$e = \frac{d}{dt}\int_s B \cdot ds$$

$$e = \int_s \frac{\partial B}{\partial t} \cdot ds$$

where
e = emf induced, volts B
= flux density, tesla ds =
elementofarea, m^2 t =
time, seconds.

1.5 TORQUE

Figure 1.5.1 shows a coil carrying I and lying in a magnetic field of flux density B.itisseenthatanupwardforceisexertedontherighthandconductorandadownward force on the left hand conductor.

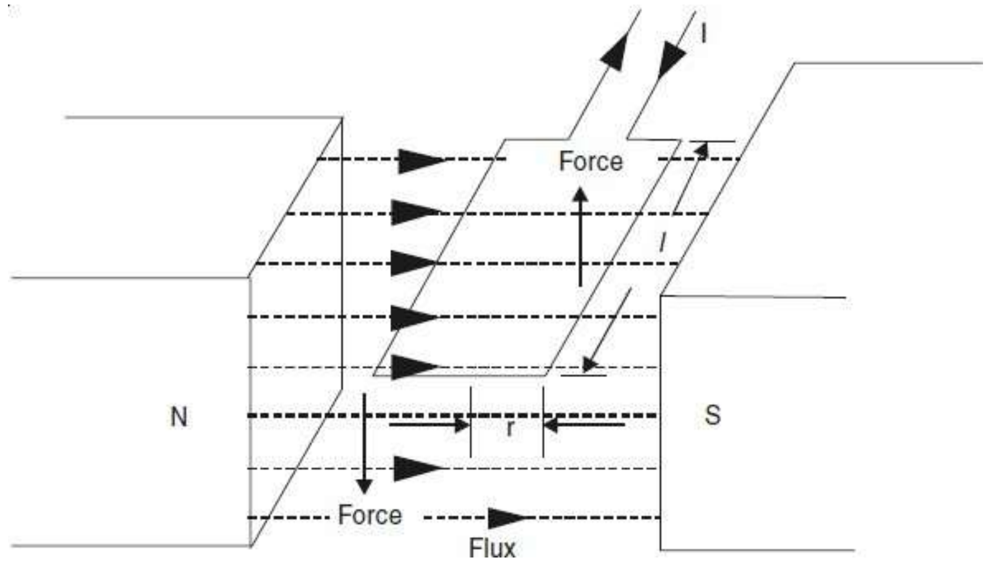


Figure 1.5.1 Torque on a coil in a magnetic field

[Source: "Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 72]*

$$F = 2B\,I\,l \text{ newtons}$$

If the coil has N turns, the total force is

$$F = 2N\,B\,I\,l \text{ newtons}$$

The torque is acting at a radius of r metres and is given by

$$\text{Torque} = 2N\,BI\,lr \text{ newtons–metres}$$

TheconfigurationofFig.1.8isthebasicmovingpartinanelectricalmeasuring instrument. An electric motor also works on this principle.

Properties of Magnetic Materials

Magnetic materials are classified based on the property called permeability as

1. Dia Magnetic Materials
2. Para Magnetic Materials
3. Ferro Magnetic Materials

1. Dia Magnetic Materials

The materials whose permeability is below unity are called Dia magnetic materials. They are repelled by magnet.

Ex. Lead, gold, copper, glass, mercury

2. Para Magnetic Materials

The materials with permeability above unity are called Para magnetic materials. The force of attraction by a magnet towards these materials is low. Ex.: Copper Sulphate, Oxygen, Platinum, Aluminum.

3. Ferro Magnetic Materials

The material s with permeability thousands of times more than that of paramagnetic materials are called Ferro magnetic materials. They are very much attracted by themagnet.

Ex. Iron, Cobalt, Nickel.

1.8 TRANSFORMER AS A MAGNETICALLY COUPLED CIRCUIT

Staticallyinducedemf(alsoknownastransformeremf)isinducedbyvariationof flux. It may be (a) mutually induced or (b) self induced.A mutually induced emf is set up in a coil whenever the flux produced by a neighbouring coil changes. However, if a single coil carries alternating current, its flux will follow the changes in the current. This change in flux will induce an emf known as self-induced emf in the coil, the word 'self'signifying that it is induced due to a change in its own current. It is also known as transformer emf, since it is induced in the windings of a transformer can also be put in a more general form. The total flux linkages λ of a coil is equal to the integral of the normal component of flux density B over the surface bounded by the coil, or

The surface over which the integration is carried out is the surface bounded by the periphery of the coil. Thus, induced emf

$$\lambda = \iint B \cdot ds$$

When the coil is stationary or fixed

$$e = \frac{d\lambda}{dt} = \frac{d}{dt}\iint B \cdot ds$$

$$e = \frac{d}{dt}\int_s B \cdot ds$$

$$e = \int_s \frac{\partial B}{\partial t} \cdot ds$$

where

e = emf induced, volts

B = flux density, tesla ds

=elementofarea,m2 t =

time, seconds.