Electronics Engineering

Basic Electrical Engineering

Comprehensive Theory

with Solved Examples and Practice Questions

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Basic Electrical Engineering

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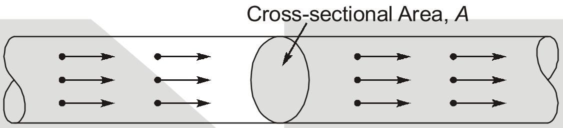
CHAPTER

1

Electromagnetism

1.1 Electric Current

Electric current may be defined as the time rate of net motion of an electric charge across a cross-sectional area. A random motion of electrons in a metal does not constitute a current unless there is a net transfer of charge with time



i.e., electric current, i = Rate of transfer of electric charge

$$= \frac{\text{Quantity of electric charge transferred during a given time duration}}{\text{Time duration}}$$

$$= \frac{dQ}{dt}$$

Coulomb is the practical as well as SI unit for measurement of electric charge. One coulomb is approximately equal to sum of 624 × 10^{16} electrons charge.

Since current is the rate of flow of electric charge through a conductor and coulomb is the unit of electric charge, the current may be specified in coulombs per second or Ampere.

1.2 Electromotive Force and Potential Difference

Electromotive force (emf) is the force that causes an electric current to flow in an electric circuit while the potential difference between two points in an electric circuit is that difference in their electrical state which tends to cause flow of electric current between them.

Volt is a unit of electromotive force as well as potential difference in practical as well as in SI system of units.

The volt is defined as that potential difference between two points of a conductor carrying a current of one ampere when the power dissipated between these points is equal to one watt.

1.3 Resistance

Resistance may be defined as that property of a substance which opposes (or restricts) the flow of an electric current (or electrons) through it.

The SI unit of resistance is ohm (Ω), which is defined as resistance between two points of a conductor when a potential difference of one volt, applied between these points, produces in this conductor a current of one ampere, the conductor not being a source of any emf.

For insulators having high resistance, much bigger units kilo ohm or kΩ(10^3 ohm) and mega ohm or MΩ (10^6 ohm) are used. In case of very small resistances smaller units like milli-ohm (10^{-3} ohm) or micro ohm (10^{-6} ohm) are employed.

1.4 OHM's Law

The current flowing through a conductor is directly proportional to the potential difference across the ends of the conductor and inversely proportional to the conductor resistance. This relation was discovered by German physicist George Simon Ohm and so it is known as Ohm's law.

If I is the current flowing through a conductor of resistance R across which a potential difference V is applied then according to Ohm's law

$$I \propto V \text{ and } I \propto \frac{1}{R} \quad \text{or} \quad I \propto \frac{V}{R} \quad \text{or} \quad I = \frac{V}{R}$$

where V is in volt. R is in ohm and I is in ampere.

Ohm's law may be defined as follows:

Physical state i.e., temperature etc. remaining the same, the current flowing through a conductor is directly proportional to the potential difference applied across its ends.

or

The ratio of potential difference applied across a conductor and current flowing through it remains constant provided physical state i.e., temperature etc. of the conductor remains unchanged.

i.e. $$\frac{V}{I} = \text{constant} = R$$

where R is known as the resistance of the conductor.

Ohm's law may be alternatively expressed as

$$V = IR$$

Ohm's law cannot be applied to circuits consisting of electronic tubes or transistors because such elements are not bilateral i.e., they behave in different way when the direction of flow of current is reversed as in case of a diode. Ohm's law also cannot be applied to circuits consisting of nonlinear elements such as powdered carbon, thyrite, electric arc etc. For example, for silicon carbide, the relationship between applied voltage (for potential difference) V and current flowing I is given as $V = KI^m$ where K and m are constants and m is less than unity.

1.5 SI System of Units

SI stands for "System International d' Unites" in French. This abbreviation is now adopted by the International Standardising Organization as the abbreviated name of this new system of units in all languages.

The SI system is a comprehensive, logical and coherent system, designed for use in all branches of science, engineering and technology.

This system derives all the units from the following seven base units.

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Intensity of electric current	ampere	A
Thermodynamic temperature	Kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

The SI system besides seven base units, has following supplementary units.

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

Recommended prefixes for formation of multiples and submultiples of units are given below:

Multiple	Prefix	Multiple	Prefix
10	deca	10^{-1}	deci
10^2	hecto	10^{-2}	centi
10^3	kilo (K)	10^{-3}	milli (m)
10^6	mega (M)	10^{-6}	micro (μ)
10^9	giga (G)	10^{-9}	nano (n)
10^{12}	tera (T)	10^{-12}	pico (p)

1.6 Work, Power and Energy

Work : Work is said to be done by or against a force, when its point of application moves in or opposite to the direction of the force and is measured by the product of the force and the displacement of the point of application in the direction of force.

i. e., Work done, $W =$ Force $[F] \times$ distance $[d]$

The SI or MKS unit of work is the joule, which is defined as the work done when a force of one newton acts through a distance of one metre in the direction of the force. Hence, if a force F acts through distance d in its own direction,

$$W = F\,[\text{newtons}] \times d\,[\text{metres}] = Fd \text{ joules}$$

Power : Power is defined as the rate of doing work or the amount of work done in unit time.

The MKS or SI unit of power is the joule/second or watt. In practice, the watt is often found to be inconveniently small and so a bigger unit, the kilowatt is frequently used.

$$1 \text{ kilowatt} = 1{,}000 \text{ watts}$$

Energy : Energy is defined as the capacity of doing work. Its units are same as those of work, mentioned above. If a body having mass m, in kg, is moving with velocity v, in metres/second,

$$\text{Kinetic energy} = \frac{1}{2}mv^2 \text{ J}$$

If a body having mass m, in kg, is lifted vertically through height h, in metres, and if g is the gravitational acceleration, in metres/second^2 in that region, potential energy acquired by the body

$$= \text{Work done in lifting the body} = mgh \text{ joule}$$

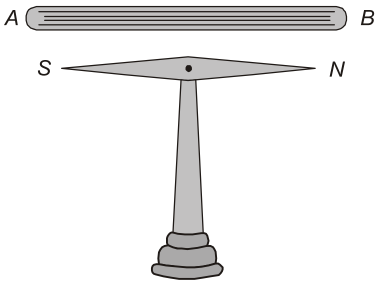
As already stated, in SI system the unit of energy of all forms is joule. Bigger unit of energy is mega joules (MJ) where 1 MJ = 10^6 J.

Calorie : It is the amount of heat required to raise the temperature of one gram of water through 1°C.

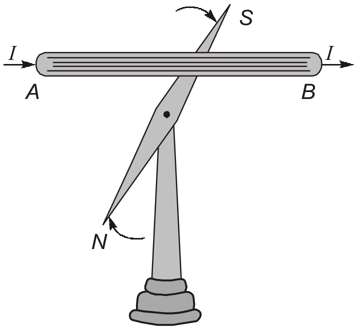
$$1 \text{ calorie} = 4.18 \text{ J} = 4.2 \text{ J}$$

1.7 Magnetic Field due to a Current Carrying Conductor

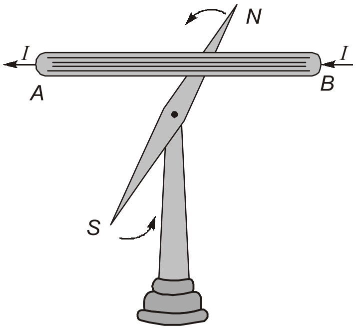
In 1819 it was discovered by a Danish Physicist, Hans Christian Oersted that an electric current is always accomplished by certain magnetic effects.



(a) No current flow



(b) Current flowing from *A* to *B*

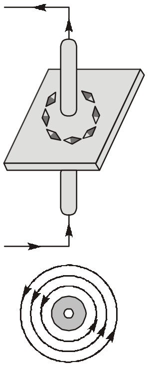


(c) Current flowing from *B* to *A*

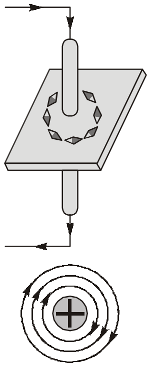
Oersted found that when current is passed through a conductor placed above the magnetic needle, the needle turns in a certain direction, as shown in figures above. He also found that when the direction of flow of current is reversed the magnetic needle also deflects in opposite direction.

Further investigation showed that the field around the current carrying conductor consists of lines of force, which encircles the conductor. It can be proved experimentally by passing a current carrying conductor AB in the card board and plotting the field with the help of magnetic needle on it, as shown in figures below.

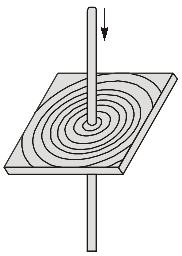
It is observed that when the current is passed through conductor in upward direction, the direction of lines of force is counterclockwise direction (observed from the top of the conductor) and when the current is passed through the conductor in downward direction, the direction of lines of force is clockwise (observed from the top of the conductor).



(d)



(e)



Magnetic field around
A current carrying counductor

The properties of the lines of magnetic induction around a current carrying conductor are summarized as below:

(i) Lines of magnetic induction are circles, symmetrical about, and concentric with, the axis of the conductor.

(ii) The spacing between the lines of induction decreases as we move closer to the conductor.

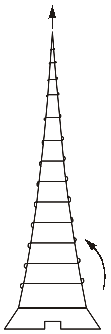
(iii) The direction of lines of magnetic induction depends on the direction of flow of current through the conductor.

(iv) Magnetic induction or flux density depends upon the strength (or magnitude) of the current flowing through the conductor.

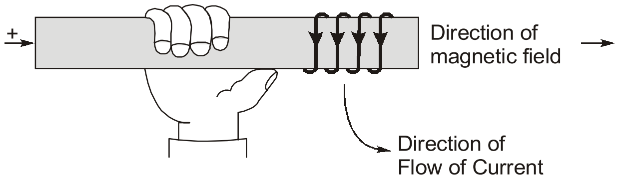
1.8 Determination of Direction of Magnetic Field Around a Current Carrying Conductor

The direction of lines of force (magnetic field) around a straight current carrying conductor may be determined by any of the following rules :

1. **Corkscrew Rule :** If the right handed corkscrew is held with its axis parallel to the conductor pointing the direction of flow of current and the head of the screw is rotated in such a direction that the screw moves in the direction of flow of current then the direction in which the head of screw is rotated, will be the direction of magnetic lines of force.
2. **Right Hand Rule :** If the current carrying conductor is held in right hand by the observer so that it is encircled by fingers stretching the thumb at right angle to the fingers in the direction of flow of current then finger tips will point the direction of magnetic lines of force, as shown in figure (b).



(a) Corkscrew Rule

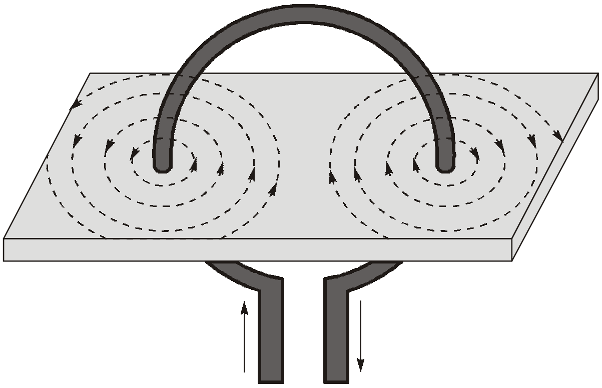


(b) Right hand rule

1.9 Magnetic Field due to a Circular Loop

If a single turn wire carrying current is bent in the form of a loop (or ring) as shown in figure. The lines of magnetic induction around it will be concentric circles, leaving the plane of the loop (or ring) on one side and entering on the other. The loop acts as the true magnet having north and south poles.

The direction of magnetic field may be determined by applying either of the two rules namely (i) right hand rule or (ii) corkscrew rule.

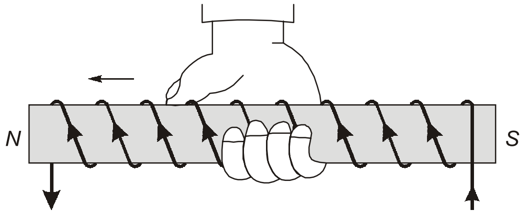


Magnetic Field due to A Circular Loop

1.10 Solenoid

The current carrying wire wound spirally in the form of helix about an axis, as shown in figure, is known as solenoid or coil. Magnetic field produced due to current carrying solenoid is fairly uniform over a small region in the middle of the coil. It acts just like a bar magnet having north and south poles.

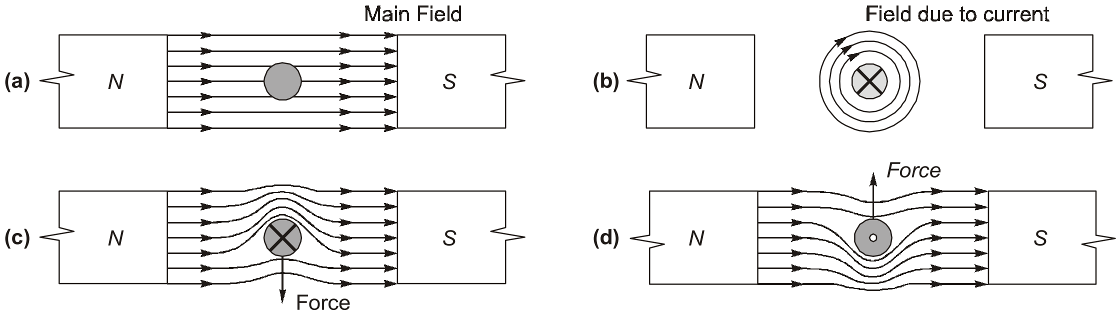
There are several methods used to determine the polarity of the solenoid.



1. **By Use of Compass Needle :** If one of the poles (say north pole) of the compass needle be brought into close proximity to one of the poles of the current carrying solenoid of unknown polarity the action of the compass needle will immediately classify the pole as north or south depending upon whether the needle is repelled or attracted.
2. **Helix Rule :** If the helix is held in right hand in such a manner that the finger tips point in the direction of flow of current and thumb is outstretched longitudinally along the coil, it will point towards north pole.

1.11 Force on a Current Carrying Conductor Lying in The Magnetic Field

In figure (a) a uniform magnetic field between the two opposite poles is shown.



In figure (b) the cross section of a conductor carrying current in inward direction placed between the two magnets, the field being temporarily removed, is shown. By applying the right hand thumb rule, the direction of the field around the conductor is found to be clockwise.

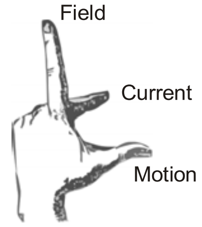
If the current carrying conductor shown in figure (b) is placed in the magnetic field shown in figure (a), the resultant magnetic field would be similar to that shown in figure (c).

The lines of force above the conductor are strengthened, since they are in same direction but the lines of force below the conductor are weakened because the two fields below the conductor are opposite in directions and hence tends to destroy each other. Magnetic lines like rubber bands have a tendency to strengthen out and, therefore, a force is experienced on the conductor in the downward direction, as shown in figure (c).

If the direction of current is reversed in the conductor, as shown in figure (d), the direction of force experienced is reversed. In this case the lines of force above the conductor are weakened while those below the conductor are strengthened.

Hence, it is observed that when a current carrying conductor is placed at right angle to the direction of magnetic field, a mechanical force is experienced on the conductor in a direction perpendicular to both the direction of magnetic field and flow of current.

The direction of this force can be determined by applying **Fleming's Left Hand Rule** which states that if the thumb, forefinger and middle finger of the left hand are stretched in such a way that they are at right angles to each other mutually and forefinger points towards the direction of the magnetic field, middle finger towards the direction of the flow of current then thumb will point the direction of force acting on the conductor (figure).



Fleming's Left Hand Rule

If the current in the conductor is reversed, keeping the direction of magnetic field unchanged the direction of force will reverse.

Similarly, if the direction of the magnetic field is reversed, keeping the direction of flow of current in the conductor unchanged, the direction of force will reverse.

Note: It should be noted that no force is exerted on a conductor when it lies parallel to the magnetic field.

The force experienced on the conductor is directly proportional to

1. Flux density (field strength), B
2. The current flowing through the conductor, I and
3. The length of the conductor, l

The magnitude of the force is given by, $F = BIl$

where F is the force in newtons, B is in tesla (Wb/m^2), I is in amperes and l is in metres.

In general, if the conductor lies at an angle θ with a magnetic field of flux density B weber/metre^2 then mechanical force experienced on a current carrying conductor is given by

$$F = BIl \sin\theta \qquad \text{Newtons}$$

where l is the length of the conductor in metres and I is the current carried by the conductor in ampere.

1.12 Magnetically Induced EMFS (or Voltages)

A very important effect of a magnetic field on an electric circuit is that when the flux linking the circuit changes, an emf is induced. Electromagnetic induction of emf (or voltage) is basic to the operation of transformers, generators (ac or dc) and motors (ac or dc). The effect is described by **Faraday's law**, which states that the magnitude of emf (or voltage) is directly proportional to the rate of change of flux linkage or to the product of number of turns and rate of change of flux linking the coil.

i.e., induced emf, $$e = N\frac{d\phi}{dt} \qquad \text{...(i)}$$

where $N\frac{d\phi}{dt}$ is the product of number of turns and rate of change of linking flux and is termed as rate of change of flux linkage.

The direction of induced emf is governed by Lenz's law which states that the direction of induced emf or voltage is such that the current produced by it sets up a magnetic field opposing the flux change.

A minus (–) sign is required to be placed before the right hand side quantity of Eq. (i) just to indicate the phenomenon explained by Lenz's law. Thus the expression for induced emf becomes as

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

where ϕ is in webers and time t is in second.

1.12.1 Dynamically Induced EMF

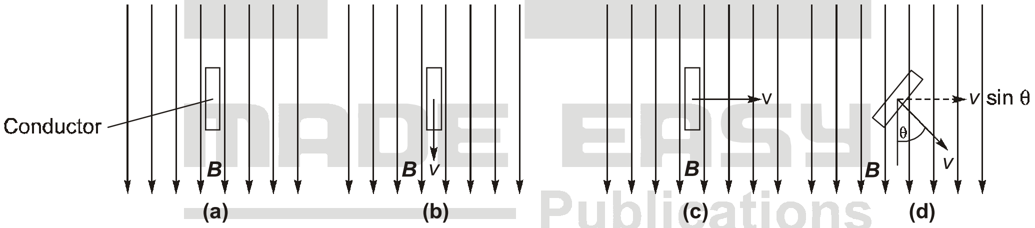
We have learn that when the flux linking with the coil or circuit changes, an emf is induced in the coil or circuit.

EMF can be induced by changing the flux linking in two ways :

(i) By increasing or decreasing the magnitude of the current producing the linking flux. In this case there is no motion of the conductor or of coil relative to the field and, therefore, emf induced in this way is known as statically induced emf.

(ii) By moving a conductor in a uniform magnetic field and emf produced in this way is known as dynamically induced emf.

Consider a conductor of length l metres placed in a uniform magnetic field of density B Wb/m^2, as shown in figure (a).



Fleming's right hand rule

Let this conductor be moved with velocity vm/s in the direction of the field, as shown in figure (b). In this case no flux is cut by the conductor, therefore, no emf is induced in it.

Now if this conductor is moved with velocity v m/s in a direction perpendicular to its own length and perpendicular to the direction of the magnetic field, as shown in figure (c) flux is cut by the conductor, therefore, an emf is induced in the conductor.

Area swept per second by the conductor = $l \times v$ m^2/s

Flux cut per second = Flux density x area swept per second = Bl v

Rate of change of flux, $\frac{d\phi}{dt}$ = Flux cut per second = Blv Wb/s

Induced emf, $e = \frac{d\phi}{dt} = Blv$ volts

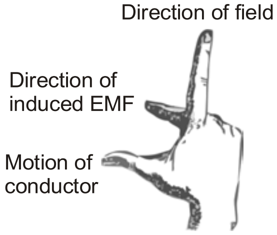
If the conductor is moved with velocity v metres per second in a direction perpendicular to its own length and at an angle to the direction of magnetic field, as shown in figure (d).

The magnitude of emf induced is proportional to the component of the velocity in a direction perpendicular to the direction of the magnetic field and induced emf is given by

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

The direction of this induced emf is given by Fleming's right hand rule.

If the thumb, forefinger and middle finger of right hand are held mutually perpendicular to each other, forefinger pointing into the direction of the field and thumb in the direction of motion of conductor then the middle finger will point in the direction of the induced emf as shown in figure below.



Fleming's right hand rule

1.12.2 Statically Induced EMF

Statically induced emf may be

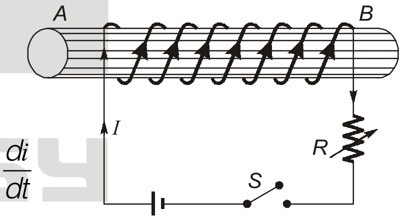
1. Self-induced emf 2. Mutually induced emf

1. Self Induced EMF : When the current flowing through the coil is changed, the flux linking with its own winding changes and due to the change in linking flux with the coil, an emf, known as self-induced emf, is induced.

Since according to Lenz's law, an induced emf acts to oppose the change that produces it, a self induced emf is always in such a direction as to oppose the change of current in the coil or circuit in which it is induced. This property of the coil or circuit due to which it opposes any change of the current in the coil or circuit, is known as **self-inductance**.

Consider a solenoid of N turns, length l metres, area of x-section a square metres and of relative permeability μ_r. When the solenoid carries a current of i amperes, a magnetic field of flux $\frac{Ni}{l/\mu_0\mu_r a}$ webers is set up around the solenoid and links with it.

If the current flowing through the solenoid is changed, the flux produced by it will change and, therefore, an emf will be induced.



Self-induced emf, $$e = -N\frac{d}{dt}\left[\frac{Ni}{l/\mu_r\mu_0 a}\right]$$

$$= -N\frac{N}{l/\mu_r\mu_0 a}\frac{di}{dt} = -\frac{N^2\mu_r\mu_0 a}{l}\cdot\frac{di}{dt}$$

The quantity $\frac{N^2\mu_r\mu_0 a}{l}$ is a constant for any given coil or circuit and is called coefficient of self-inductance. It is represented by symbol L and is measured in Henry (H).

Hence self-induced emf, $e = -L\frac{di}{dt}$ where $L = \frac{N^2\mu_r\mu_0 a}{l}$ H

Coefficient of Self-Induction : The coefficient of self-induction (L) can be determined from any one of the following three relations.

First Method : In case the dimensions of the solenoid are given, the coefficient of self-induction may be determined from the relation

$$L = \frac{N^2 a\mu_r\mu_0}{l} \text{ H}$$

Second Method : In case the magnitude of induced emf in a coil for a given rate of change of current in the coil is known, self-inductance of the coil may be determined from the following relation.

$$e = L\frac{di}{dt}$$

or
$$L = \frac{e}{di/dt}$$

Third Method : In case the number of turns of the coil and flux produced per ampere of current in the coil is known, the self-inductance of the coil may be determined from the following relation

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

The above relation can be derived as follows :

Magnetic flux produced in a coil of N turns, length l metres, area of x-section a metres^2 and relative permeability μ_r when carrying a current of i amperes is given by

$$\phi = \frac{Ni}{l/\mu_r\mu_0 a} = \frac{N}{l/\mu_r\mu_0 a}i$$

and self-inductance of the coil

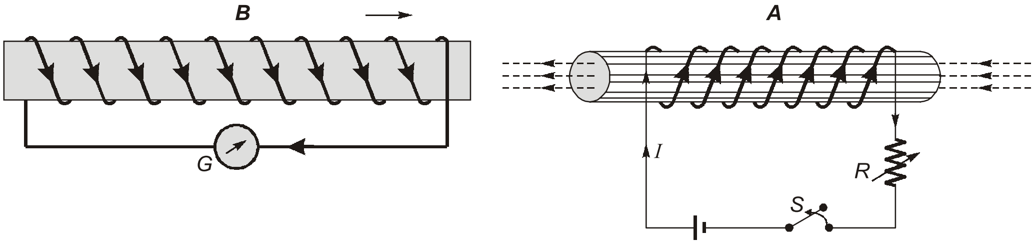
$$L = \frac{N^2 a\mu_r\mu_0}{l} = \frac{N}{i}\frac{Na\mu_r\mu_0}{l}i = \frac{N\phi}{i}$$

From the above relation it is obvious that the self-inductance of a coil or circuit is equal to weber-turns per ampere in the coil or circuit.

In the above relation if $N\phi = 1$ Wb-turn and $i = 1$ A then $L = 1$ H

Hence, a coil is said to have a self-inductance of one henry if a current of 1 A, when flowing through it, produces flux linkage of 1 Wb-turn in it.

2. **Mutually Induced EMF :** Consider two coils *A* and *B* placed closed together so that the flux created by one coil completely links with the other coil. Let coil *A* have a battery and switch *S* and coil *B* be connected to the galvanometer *G*.



When switch *S* is opened, no current flows through coil *A*, so no flux is created in coil *A*, i.e., no flux links with coil *B*, therefore, no emf is induced across coil *B*, the fact is indicated by galvanometer zero deflection. Now when the switch *S* is closed current in coil *A* starts rising from zero value to a finite value, the flux is produced during this period and increases with the increase in current of coil *A*, therefore, flux linking with the coil *B* increases and an emf, known as **mutually induced emf**, is produced in coil *B*, the fact is indicated by galvanometer deflection. As soon as the current in coil *A* reaches its finite value, the flux produced or flux linking with coil *B* becomes constant, so no emf is induced in coil *B*, and galvanometer pointer returns back to zero position. Now if the switch *S* is opened, current will start decreasing, resulting in decrease in flux linking with coil *B*, an emf will be again induced but in direction opposite to previous one, this fact will be shown by the galvanometer deflection in opposite direction.

Hence, **whenever the current in coil *A* changes, the flux linking with coil *B* changes and an emf, known as mutually induced emf, is induced in coil *B*.**

Consider coil *A* of turns N_1 wound on a core of length l metres, area of cross section a square metres and relative permeability μ_r. When the current of i_1 amperes flows through it, a flux of $\frac{N_1 i_1}{l/\mu_r\mu_0 a}$ is set up around the coil. Let whole of the flux produced due to flow of current in coil *A* be linked with the coil *B* having N_2 turns and placed near by coil *A*.

Mutually induced emf,

$$e_m = \text{Rate of change of flux linkage of coil } B$$

$$= -N_2 \times \text{rate of change of flux in coil } A$$

$$= -N_2\frac{d}{dt}\left[\frac{N_1 i_1}{l/\mu_0\mu_r a}\right] = -\frac{N_1 N_2 a\mu_0\mu_r}{l} i = \frac{di_1}{dt}\times M$$

The quantity $\frac{N_1 N_2 a\mu_0\mu_r}{l}$ weber is called the coefficient of mutual induction of coil *B* with respect to coil *A*. It is represented by symbol *M* and is measured in henrys.

Hence mutually induced emf,

$$e_m = -M\frac{di_1}{dt} \quad \text{where} \quad M = \frac{N_1 N_2 a\mu_0\mu_r}{l}\ \text{H}$$

Coefficient of Mutual Induction : Mutual inductance may be defined as the ability of one coil or circuit to induce an emf in a nearby coil by induction when the current flowing in the first coil is changed. The action is also reciprocal i.e., the change in current flowing through second coil will also induce an emf in the first coil. The ability of reciprocal induction is measured in terms of the coefficient of mutual induction *M*.

The coefficient of mutual induction (*M*) can be determined from any one of the following three relations.

First Method: In case the dimensions of the coils are given, the coefficient of mutual induction may be determined from the relation

$$M = \frac{N_1 N_2 a\mu_0\mu_r}{l}\ \text{Henry}$$

Second Method: In case the magnitude of induced emf in the second coil for a given rate of change of current in the first coil is known, mutual inductance between the coil may be determined from the following relation

$$e_m = M\frac{di_1}{dt}$$

or

$$M = \frac{e_m}{di_1/dt}$$

Third Method: In case the number of turns of the coil and flux linking with this coil per ampere of current in another coil is known, the mutual inductance of the coil may be determined from the following relation

$$M = N_2\frac{\phi_2}{i_1}\ \text{Henry}$$

1.13 Definitions Concerning Magnetic Circuit

1. **Magnetomotive force (m.m.f.) :** It drives or tends to drive flux through a magnetic circuit and corresponds to electromotive force (e.m.f.) in an electric circuit.
   M.M.F. is equal to the work done in joules in carrying a unit magnetic pole once through the entire magnetic circuit. It is measured in **ampere-turns**.
   In fact, as p.d. between any two points is measured by the work done in carrying a unit charge from one points to another, similarly, m.m.f. between two points is measured by the work done in joules in carrying a unit magnetic pole from one point to another.

2. **Ampere-turns (AT) :** It is the unit of magnetomotive force (m.m.f.) and is given by the product of number of turns of a magnetic circuit and the current in amperes in those turns.

3. **Reluctance :** It is the name given to that property of a material which opposes the creation of magnetic flux in it. It, in fact, measures the opposition offered to the passage of magnetic flux through a material and is analogous to resistance in an electric circuit even in form. Its units is AT/Wb.

   $$\text{reluctance} = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A}$$

   Like,
   $$\text{resistance} = \rho \frac{l}{A}$$

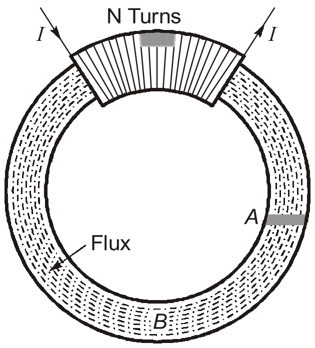
   In other words, the reluctance of a magnetic circuit is the number of amp-turns required per weber of magnetic flux in the circuit. The unit of reluctance is “reciprocal henry.”

4. **Permeance :** It is reciprocal of reluctance and implies the case or readiness with which magnetic flux is developed. It is analogous to conductance in electric circuits. It is measured in terms of Wb/AT or Henry.

1.14 Magnetic Circuit

It may be defined as the path which is followed by magnetic flux. The law of magnetic circuit are quite similar to (but not the same as) those of the electric circuit.

Consider a solenoid or a toroidal iron ring having a magnetic path of l metre, area of cross section A m^2 and a coil of N turns carrying I amperes wound anywhere on it as in figure below.



field strength inside the solenoid is

$$H = \frac{NI}{l} \text{ At/m}$$

Now
$$B = \mu_0 \mu_r H = \frac{\mu_0 \mu_r NI}{l} \text{ Wb/m}^2$$

Total flux produce
$$\Phi = B \times A = \frac{\mu_0 \mu_r ANI}{l} \text{ Wb}$$

$\therefore$
$$\Phi = \frac{NI}{l / \mu_0 \mu_r A} \text{ Wb}$$

The numerator M which produces magnetization in the magnetic circuit is known as magnetomotive force (m.m.f.). Obviously, its unit is ampere-turn (AT). It is analogous to e.m.f. in an electric circuit.

The denominator $l/\mu_0\mu_r A$ is called the reluctance of the circuit and is analogous to resistance in electric circuits.

$$\therefore \qquad \text{flux} = \frac{\text{m.m.f}}{\text{reluctance}}$$

or

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

Sometimes, the above equation is called the **Ohm's Law of Magnetic Circuit** because it resembles a similar expression in electric circuits i.e.

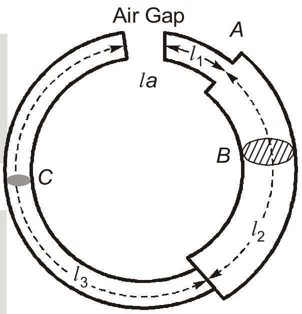
$$\text{current} = \frac{\text{e.m.f}}{\text{resistance}}$$

or

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

1.15 Composite Series Magnetic Circuit

In figure below is shown a composite series magnetic circuit consisting of three different magnetic materials of different permeabilities and lengths and one air gap ($\mu_r = 1$). Each path will have its own reluctance. The total reluctance is the sum of individual reluctances as they are joined in series.



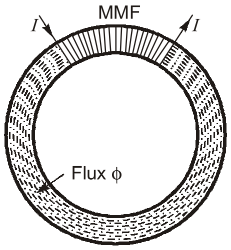
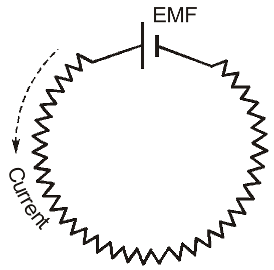
$$\therefore \qquad \text{total reluctance} = \Sigma \frac{1}{\mu_0\mu_r A}$$

$$= \frac{l_1}{\mu_0\mu_{r_1} A_1} + \frac{l_2}{\mu_0\mu_{r_2} A_2} + \frac{l_3}{\mu_0\mu_{r_3} A_3} + \frac{l_a}{\mu_0 A_g}$$

$$\therefore \qquad \text{flux } \Phi = \frac{\text{m.m.f}}{\dfrac{l}{\mu_0\mu_r A}}$$

1.16. Comparison between magnetic and electrical circuits

Similarities :

Magnetic Circuit	Electric Circuit
	
1. Flux = $\dfrac{\text{m.m.f}}{\text{reluctance}}$	Current = $\dfrac{\text{e.m.f}}{\text{resistance}}$
2. M.M.F (Ampere-turns)	E.M.F. (Volt)
3. Flux Φ (Weber)	Current I (Ampere)
4. Flux density B (Wb/m^2)	Current density (A/m^2)

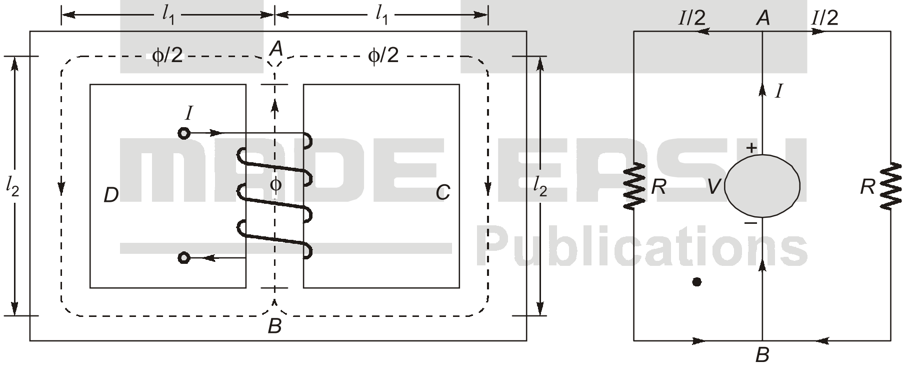
5.	Reluctance, $S = \frac{l}{\mu A}\left(=\frac{l}{\mu_0\mu_r A}\right)$	Resistance, $R = \rho\frac{l}{A}$
6.	Permeance (= 1/reluctance)	Conductance (= 1/resistance)
7.	Reluctivity	Resistivity
8.	Permeability (= 1/reluctivity)	Conductivity (= 1/resistivity)
9.	Total m.m.f. $= \Phi S_1 + \Phi S_2 + \Phi S_3 + ...$	Total e.m.f. $= IR_1 + IR_2 + IR_3 + ...$

Differences :

1. Strictly speaking, flux does not actually 'flow' in the sense in which an electric current flows.
2. If temperature is kept constant, then resistance of an electric circuit is constant and is independent of the current strength (or current density). On the other hand, the reluctance of a magnetic circuit does depend on flux (and hence flux density) established in it. It is so because μ (which equals the slope of B/H curve) is not constant even for a given material as it depends on the flux density B. Value of μ is large for low value of B and vice-versa. Hence, reluctance is small ($S = l/\mu A$) for small values of B and large for large values of B.
3. Flow of current in an electric circuit involves continuous expenditure of energy but in a magnetic circuit, energy is needed only creating the flux initially but not for maintaining it.

1.17 Parallel Magnetic Circuits

Figure (a) shown a parallel magnetic circuit consisting of two parallel magnetic paths *ACB* and *ADB* acted upon by the same m.m.f. Each magnetic path has an average length of $(2l_1 + l_2)$. The flux produced by the coil wound on the central core is divided equally at point *A* between the two outer parallel paths. The reluctance offered by the two parallel paths is equal to half the reluctance of each path.

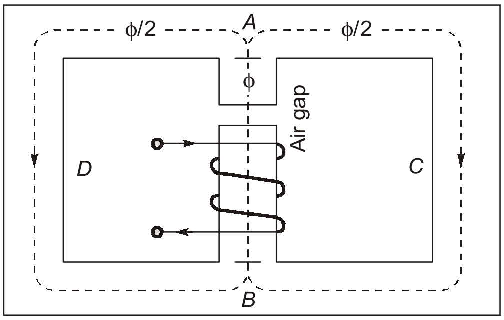


(a) **(b)**

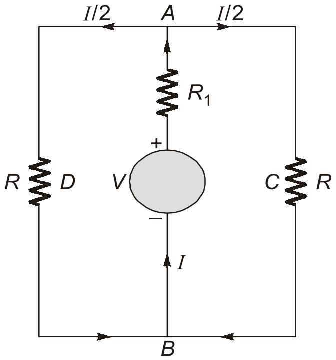
Figure (b) shows the equivalent electrical circuit where resistance offered to the voltage source is $= R \| R = R/2$. It should be noted that reluctance offered by the central core *AB* has been neglected in the above treatment.

1.18 Series-Parallel Magnetic Circuits

Such a circuit is shown in Figure (a). It shows two parallel magnetic circuits *ACB* and *ACD* connected across the common magnetic path *AB* which contains an air-gap of length l_g. As usual, the flux Φ in the common core is divided equally at point *A* between the two parallel paths which have equal reluctance.



(a)



(b)

The reluctance of the path *AB* consists of (i) air gap reluctance and (ii) the reluctance of the central core which comparatively negligible. The equivalent electrical circuit is shown in figure (b) where the total resistance offered to the voltage source is = $R_1 + R \| R = R_1 + R/2$.

1.19 Leakage Flux and Hopkinson's Leakage Coefficient

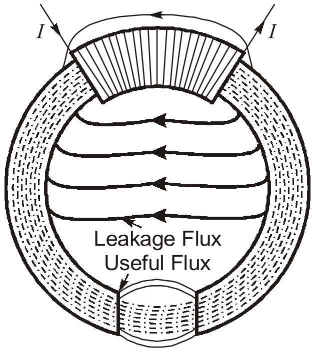
Leakage flux is the flux which follows a path not intended for it. In figure is shown an iron ring wound with a coil and having an air-gap. The flux in the air-gap is known as the useful flux because it is only this flux which can be utilized for various useful purposes.

It is found that it is impossible to confine all the flux to the iron path only, although it is usually possible to confine most of the electric current to a definite path, say a wire, by surrounding it with insulation. Unfortunately, there is no known insulator for magnetic flux. Air, which is a splendid insulator of electricity, is unluckily a fairly good magnetic conductor. Hence, as shown, some of the flux leaks through air surrounding the iron ring. The presence of leakage flux can be detected by a compass. Even in the best designed dynamos, it is found that 15 to 20% of the total flux produced leaks away without being utilised usefully.

If Φ = total flux produced ; Φ = useful flux available in the air-gap, then

$$\text{leakage coefficient } \lambda = \frac{\text{total flux}}{\text{useful flux}}$$

or $$\lambda = \frac{\Phi_T}{\Phi}$$



In electric machines like motors and generators, magnetic leakage is undesirable, because, although it does not lower their power efficiency, yet it leads to their increased weight and cost of manufacture. Magnetic leakage can be minimised by placing the exciting coils or windings as close as possible to the air-gap or to the points in the magnetic circuit where flux is to be utilized for useful purposes.

It is also seen from figure above that there is fringing or spreading of lines of flux at the edges of the air-gap. This fringing increases the effective area of the air-gap.

Note: The value of λ for modem electric machines varies between 1.1 and 1.25.

Example 1.1 A laminated soft iron ring of relative permeability 1000 has a mean circumference of 800 mm and a cross-sectional area 500 mm^2. A radial air-gap of 1 mm width is cut in the ring which is wound with 1000 turns. Calculate the current required to produce an air-gap flux of 0.5 mWb if leakage factor is 1.2 and stacking factor 0.9. Neglect fringing.

Solution:

$$\text{Total AT reqd.} = \Phi_g S_g + \Phi_i S_i = \frac{\Phi_g l_g}{\mu_0 A_g} + \frac{\Phi_i l_i}{\mu_0 \mu_r A_i B}$$

Now, air-gap flux $\Phi_s = 0.5$ mWb $= 0.5 \times 10^{-3}$ Wb, $l_g = 1$ mm $= 1 \times 10^{-3}$ m; $A_g = 500$ mm^2 $= 500 \times 10^{-6}$ m^2

Flux in the iron ring, $\Phi_i = 1.2 \times 0.5 \times 10^{-3}$ Wb

Net cross-sectional area $= A_i \times$ stacking factor $= 500 \times 10^{-6} \times 0.9$ m^2

$$\therefore \quad \text{Total AT reqd.} = \frac{0.5 \times 10^{-3} \times 1 \times 10^{-3}}{4\pi \times 10^{-7} \times 500 \times 10^{-6}} + \frac{1.2 \times 0.5 \times 10^{-3} \times 800 \times 10^{-3}}{4\pi \times 10^{-7} \times 1000 \times (0.9 \times 500 \times 10^{-6})}$$

$$= \frac{1644}{1000} = 1.64\ A$$

$$\therefore \quad I = \frac{1644}{1000} = 1.64 \text{ A}$$

Example 1.2 A ring has a diameter of 21 cm and a cross-sectional area of 10 cm^2. The ring is made up of semicircular sections of cast iron and cas steel, with each joint having a reluctance equal to an air-gap of 0.2 mm. Find the ampere-turns required to produce a flux of 8×10^{-4} Wb. The relative permeability of cast steel and cast iron are 800 and 166 respectively. Neglect fringing and leakage effects.

Solution:

$\Phi = 8 \times 10^{-4}$ Wb

$A = 10$ cm^2 $= 10^{-3}$ m^2

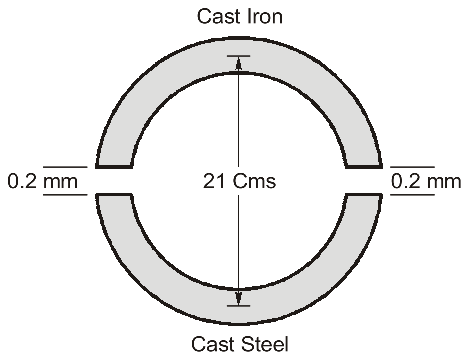
$B = 8 \times 10^{-4}/10^{-3} = 0.8$ Wb/m^2

Air gap $H = B/\mu_0 = 0.8/4\pi \times 10^{-7} = 6.366 \times 10^5$ AT/m

Total air-gap length $= 2 \times 0.2 = 0.4$ mm $= 4 \times 10^{-4}$ m

$\therefore$ AT required $= H \times l = 6.366 \times 10^5 \times 4 \times 10^{-4} = 255$

Cast Steel Path



$$H = \frac{B}{\mu_0 \mu_r} = \frac{0.8}{4\pi \times 10^{-7} \times 800} = 796 \text{ AT/m}$$

$$\text{Path} = \pi \frac{D}{2} = 21\frac{\pi}{2} = 33 \text{ cm} = 0.33 \text{ m}$$

$$\text{AT required} = H \times l = 796 \times 0.33 = 263$$

Cast Iron Path,

$$H = \frac{0.8}{4\pi \times 10^{-7} \times 166} = 3835 \text{ AT/m; path} = 0.33 \text{ m}$$

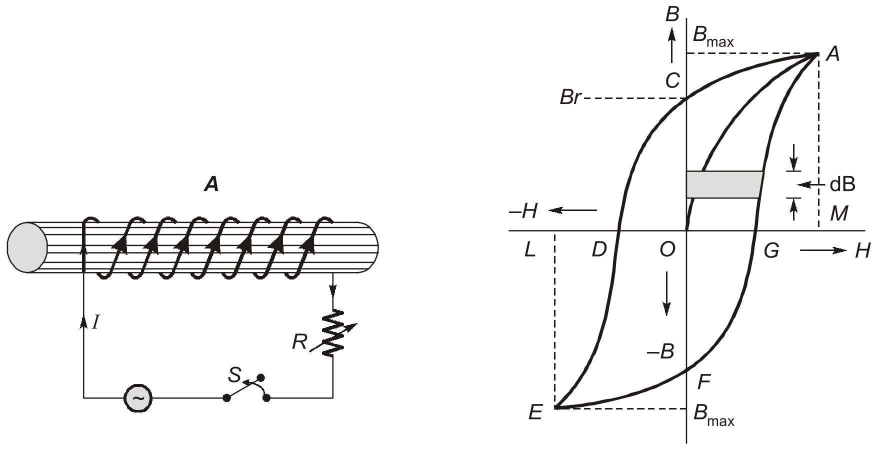
$$\text{At required} = 3835 \times 0.33 = 1265$$

$$\text{Total At required} = 255 + 263 + 1265 = \mathbf{1783\ AT}$$

1.20 Magnetic Hysteresis

It may be defined as the lagging of magnetisation or induction flux density (B) behind the magnetising force (H). Alternatively, it may be defined as that quality of a magnetic substance, due to which energy is dissipated in it, on the reversal of its magnetism.

Let us take an unmagnetised bar of iron *AB* and magnetise it by placing it within the field of a solenoid, shown in figure (a). The field $H (= NI/l)$ produced by the solenoid is called the magnetising force. The value of H can be increased or decreased by increasing or decreasing current through the coil. Let H be increased in steps from zero up to a certain maximum value and the corresponding values of flux density (B) be noted. If we plot the relation between H and B, a curve like *OA*, as shown in figure, is obtained. The material becomes magnetically saturated for $H = OM$ and has at that time a maximum flux density of B_{max} established through it.



(a) (b)

If H is now decreased gradually (by decreasing solenoid current), flux density B will not decrease along *AO*, as might be expected, but will decrease less rapidly along *AC*. When H is zero, B is not but has a definite value $B_r = OC$. It means that on removing the magnetising force H, the iron bar is not completely demagnetised. This value of $B (= OC)$ measures the **retentivity** or **remanence** of the material and is called the **remanent** or **residual flux density** B_r.

To demagnetise the iron bar, we have to apply the magnetising force in the reverse direction. When H is reversed (by reversing current through the solenoid), then B is reduced to zero at point D where $H = OD$. This value of H required to wipe off residual magnetism is known as coercive force (H_c) and is a measure of the coercivity of the material.