Magnetic terms, magnetic material and properties of magnet

Objectives: At the end of this lesson you shall be able to
- **state the different kinds of magnets and state the classification of magnetic material.**
- **state the molecular theory of magnetism**
- **describe the earth as a magnet**
- **state the classifications of magnets.**

Magnetism and magnets: Magnetism is a force field that acts on some materials and not on other materials. Physical devices which possess this force are called magnets. Magnets attract iron and steel, and when free to rotate, they will move to a fixed position relative to the north pole.

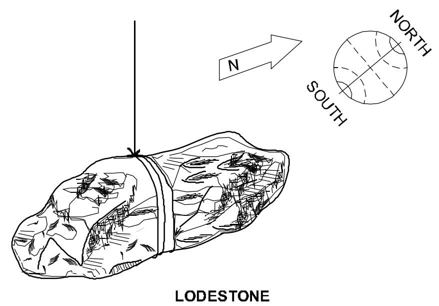
Classification of magnets

Magnets are classified into two groups.

- Natural magnets
- Artificial magnets

Lodestone (an iron compound) is a natural magnet which was discovered centuries ago. (Fig 1)

Fig 1



There are two types of artificial magnets. Temporary and permanent magnets.

Temporary magnets or electromagnets: If a piece of magnetic material, say, soft iron is placed in a strong magnetic field of a solenoid it becomes magnetised by induction. The soft iron itself becomes a temporary magnet as long as the current continues to flow in the solenoid. As soon as the source producing the magnetic field is removed, the soft iron piece will loose its magnetism.

Permanent magnets: If steel is substituted for soft iron in the same inducing field as in the previous case, due to the residual magnetism, the steel will become a permanent magnet even after the magnetising field is removed. This property of retention is termed retentivenes. Thus, permanent magnets are made from steel, nickel, alnico, tungsten all of which have higher retentiveness.

Molecular theory of magnetism: In magnetic materials such as iron, steel, nickel, cobalt and their alloys, which are ferromagnetic materials, the molecules themselves are tiny magnets, each of them having a north pole and south pole. This is basically due to their special crystalline structure and to the continuous movements of electrons in their atoms.

Under ordinary conditions, these molecules arrange themselves in a disorderly manner, the north and south pole of these tiny magnets pointing in all directions and neutralizing one another. Thus a non-magnetized ferromagnetic bar is one in which there is no definite arrangement of the magnetic poles as shown in Fig 2. When iron or steel is magnetized, the molecules are moved into a new arrangement as shown in Fig 3, which is caused by the force used to magnetize them.

Fig 2

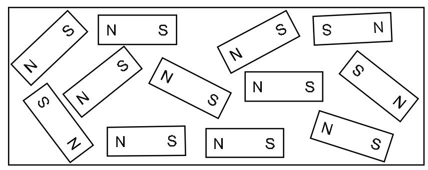
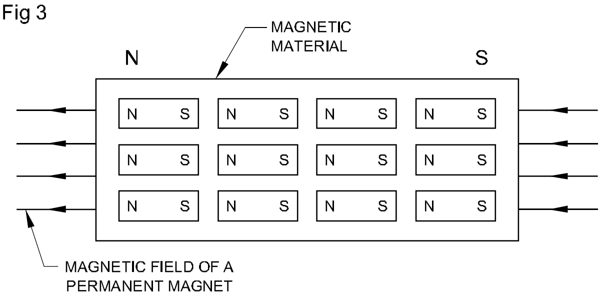


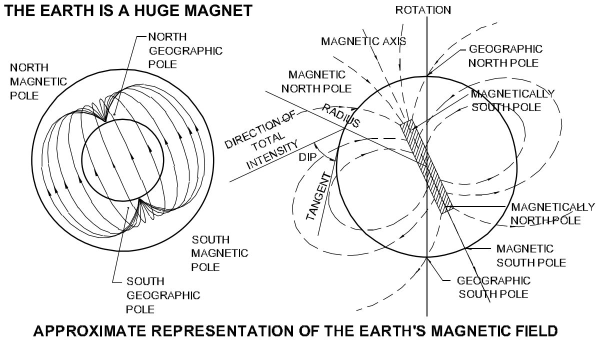
Fig 3



The earth's magnetic field: Since the earth itself is a large spinning mass, it too produces a magnetic field. The earth acts as though it has a bar magnet extending through its centre, with one end near the north geographic pole and the other end near the south geographic pole. (Fig 4)

Fig 4

THE EARTH IS A HUGE MAGNET



APPROXIMATE REPRESENTATION OF THE EARTH'S MAGNETIC FIELD

Classification of magnetic substances

Materials can be classified into three groups as follows.

Ferromagnetic substances: Those substances which are strongly attracted by a magnet are known as ferromagnetic substances. Some examples are iron, nickel, cobalt, steel and their alloys.

Paramagnetic substances: Those substances which are slightly attracted by a magnet of common strength are called paramagnetic substances. Their attraction can easily be observed with a powerful magnet. In short, paramagnetic substances are similar in behaviour to ferromagnetic materials. Some examples are aluminium, manganese, platinum, copper etc.

Diamagnetic substances: Those substances which are slightly repelled by a magnet of powerful strength only are known as diamagnetic substances. Some examples are bismuth, sulphur, graphite, glass, paper, wood, etc. Bismuth is the strongest of the diamagnetic substances.

There is no substance which can be properly called non-magnetic. It may also be noted that water is a diamagnetic material, and air is a paramagnetic substance.

Magnetic terms and properties of magnet

Objectives: At the end of this lesson you shall be able to
- **define the terms magnetic field, magnetic line, magnetic axis, magnetic neutral axis and unit pole**
- **explain the properties of a magnet**
- **describe magnetic shielding**
- **describe the shape of magnets and the method of magnetizing**
- **state the application, care and maintenance of a permanent magnet.**

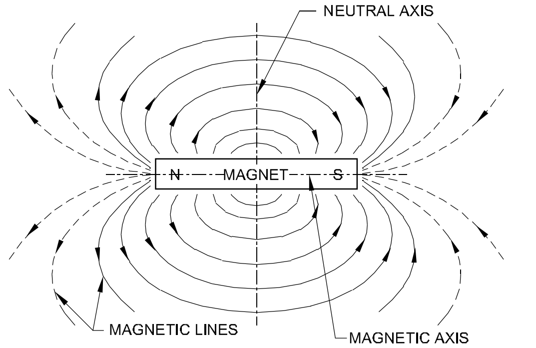
Magnetic fields: The force of magnetism is referred to as a magnetic field. This field extends out from the magnet in all directions, as illustrated in Fig 1. In this figure, the lines extending from the magnet represent the magnetic field.

The space around a magnet in which the influence of the magnet can be detected is called the magnetic field.

Magnetic lines: Magnetic lines of force (flux) are assumed to be continuous loops, the flux lines continuing on through the magnet. They do not stop at the poles.

The magnetic lines around a bar magnet are shown in Fig 1.

Fig 1

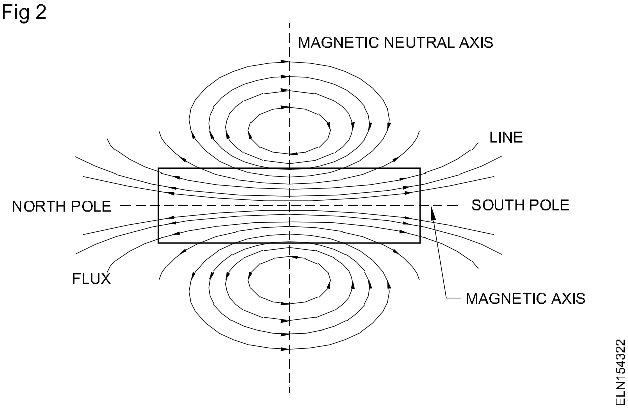


MAGNETIC FIELD OF A MAGNET. THE FLUX IS MOST DENSE AT THE POLES.

Magnetic axis: The imaginary line joining the two poles of a magnet are called the magnetic axis. It is also known as the magnetic equator.

Magnetic neutral axis (Fig 2): The imaginary lines which are perpendicular to the magnetic axis and pass through the centre of the magnet are called the magnetic neutral axis.

Fig 2



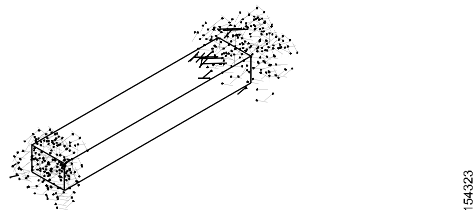
Unit pole: A unit pole may be defined as that pole which, when placed one metre apart from an equal and similar pole, repels it with a force of 10 newtons.

Properties of a magnet

The following are the properties of magnets.

Attractive property : A magnet has the property of attracting magnetic substances (such as iron, nickel and cobalt) and its power of attraction is greatest at its poles. (Fig 3)

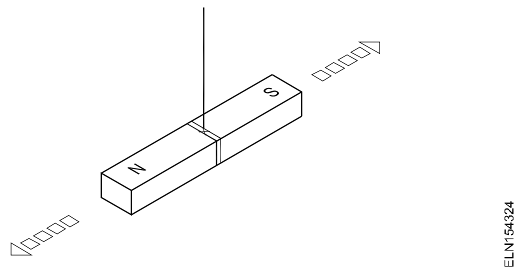
Fig 3



BAR MAGNET

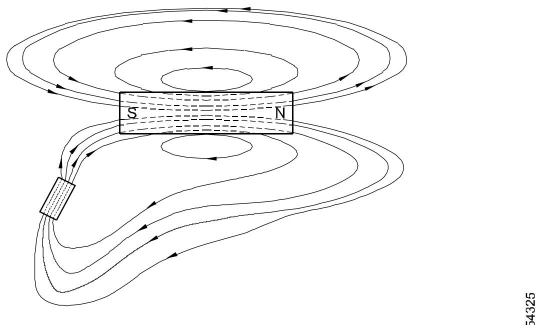
Directive property: If a magnet is freely suspended, its poles will always tend to set themselves in the direction of north and south. (Fig 4)

Fig 4



Induction property: A magnet has the property of producing magnetism in a nearby magnetic substance by induction. (Fig 5)

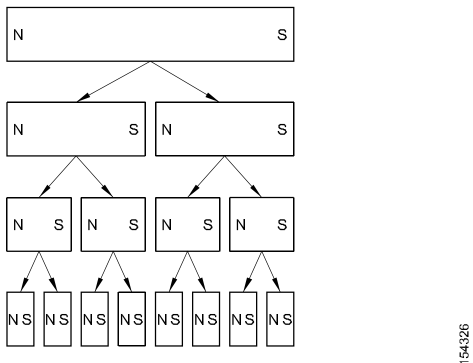
Fig 5



SOFT IRON PROVIDES A PATH FOR MAGNETIC LINES OF FORCE.

Poles-existing property: A single pole can never exist in a magnet. If it is broken into its molecules, each molecule will have two poles. (Fig 6)

Fig 6



MAGNET WHEN DIVIDED

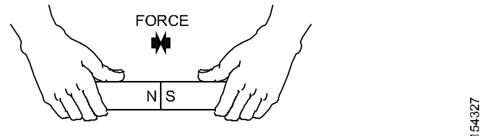
Demagnetising property: If a magnet is handled roughly by heating, hammering, etc. it will lose its magnetism.

Property of strength: Every magnet has two poles. The two poles of a magnet have equal pole strength.

Saturation property: If a magnet of higher strength is further subjected to magnetization, it will never acquire more magnetization due to its being already saturated.

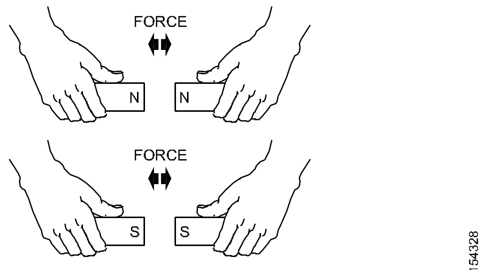
Property of attraction and repulsion: Unlike poles (i.e. north and south) attract each other, (Fig 7) while like poles (north/north and south/south) repel each other. (Fig 8)

Fig 7



ATTRACTION

Fig 8



REPULSION

Assumed physical properties of magnetic lines of force: The lines of force always travel from the north to the south pole outside the magnet through air and from the south to the north pole inside the magnet.

All the magnetic lines of force complete their circuit (form a loop).

The magnetic lines do not cross each other. The lines of force travelling in one direction have a repulsive force between them, and, therefore, do not cross.

The magnetic lines prefer to pass and complete their circuit through a magnetic material.

They behave like a magnetic elastic band.

Magnetic shielding: Magnetic flux lines can pass through all materials. Magnetic materials have a very low reluctance to flux lines. The lines of flux will be attracted through a magnetic material even if they have to take a longer path. (Fig 9) This characteristic allows us to shield things from magnetic lines of force by enclosing them with a magnetic material. This is the way anti-magnetic watches are made. Measuring instruments which are to be shielded are enclosed inside an iron case. (Fig 10)

Shapes of magnets: Magnets are available in various shapes, with the magnetism concentrated at their ends known as poles. The common shapes are listed here.

– Bar magnet

– Horseshoe magnet

– Ring magnet

– Cylindrical type magnet

– Specially shaped magnets

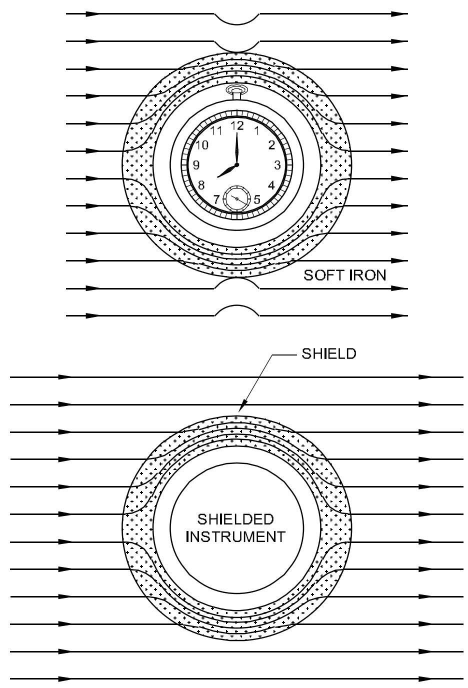
Bar magnet: It is in the form of a rectangular block with the magnetism concentrated at the ends, north pole and south pole. (Fig 11a)

Horseshoe magnet : A rectangular iron rod bent to the shape of a horseshoe with the magnetism concentrated at their ends forming the north pole and south pole. (Fig 11b)

Ring magnet: A ferrous metal formed into a ring as shown in Fig 11c is a ring magnet.

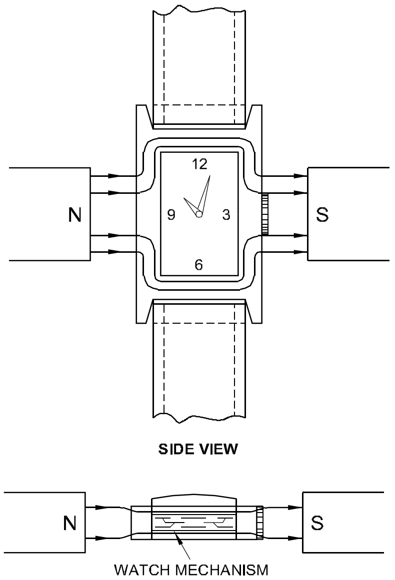
Cylindrical type magnet: It is formed by a cylindrical iron rod with concentration of magnetism at the north and south pole ends as shown in Fig 11d.

Fig 9



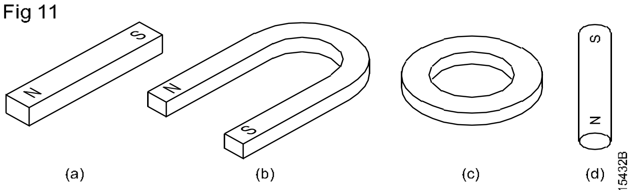
MAGNETIC SHIELD. THE SHIELD PROVIDES A LOW- RELUCTANCE PATH AROUND THE PROTECTED AREA.

Fig 10



MAGNETIC MATERIALS SHIELD A WATCH FROM MAGNETIC FIELDS. THE SHIELD BECOMES ONLY TEMPORARILY MAGNETIZED. THE FLUX LINES CANNOT REACH THIS WATCH MECHANISM.

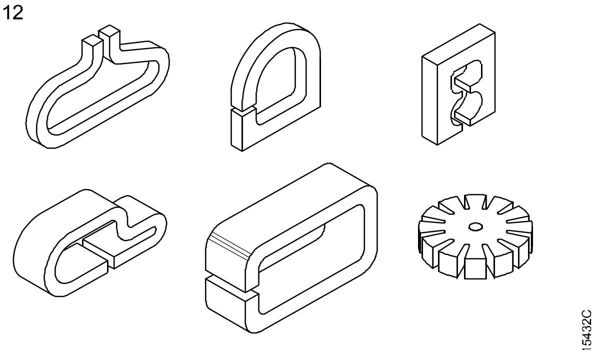
Fig 11



SHAPES OF PERMANENT MAGNETS

Specially shaped magnets: Permanent magnets for special purposes like, for the use of magnet in automobiles, cycle dynamos, electrical instruments and energy meters, are made to special shapes depending upon the purpose for which they are needed. (Fig 12)

Fig 12



SPECIAL SHAPES OF MAGNET

Methods of magnetizing: There are three principal methods of magnetizing a material.

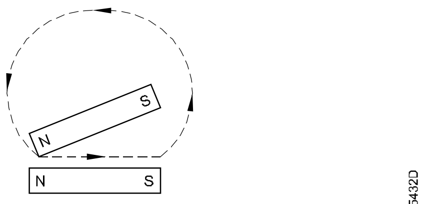
- Touch method
- By means of electric current
- Induction method.

Touch method: This method can be further divided into:

- single touch method
- double touch method, and
- divided touch method

Single touch method: In the single touch method, the steel bar to be magnetized is rubbed with either of the poles of a magnet, keeping the other pole away from it. Rubbing is done only in one direction as shown in Fig 13. The process should be repeated many times for inducing magnetization of the bar.

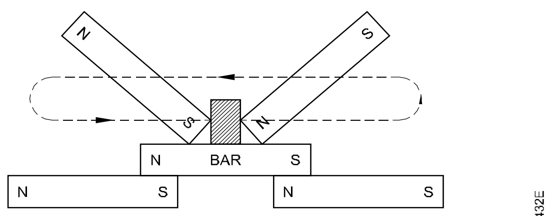
Fig 13



STEEL BAR

Double touch method: In this method the steel bar to be magnetized is placed over the two opposite pole ends of a magnet, and the rubbing magnets are placed together over the centre of the bar with a small wooden piece in between, as shown in Fig 14. They are never lifted off the surface of the steel bar, but rubbed again and again from

Fig 14

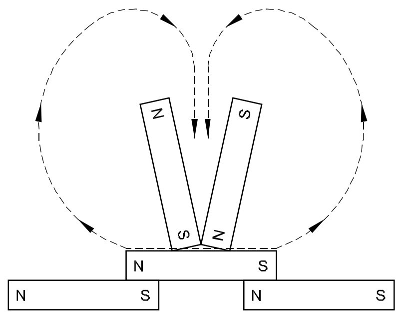


DOUBLE-TOUCH METHOD

end to end, finally ending at the centre where the rubbing was started.

Divided touch method: Here the two different poles of the rubbing magnets are placed as in the previous case. They are then moved along the surface of the steel bar to the opposite ends. The rubbing magnets are then lifted off the surface of the steel bar and placed back in the centre of the bar. The whole process is repeated again and again as shown in Fig 15.

Fig 15



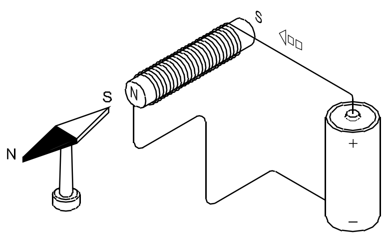
DIVIDED-TOUCH METHOD

ELN15432F

The steel bar thus magnetized becomes a permanent magnet but the degree of magnetization is very low.

By electric current: The bar to be magnetized is wound with an insulated copper wire, and then a strong electric current (DC) from a battery is passed through the wire for some time. The steel bar then becomes highly magnetized. If the bar is of soft iron, the magnetism remains as long as the current continues but almost completely disappears as soon as the current ceases. The magnet made by such an arrangement is called an electromagnet and is generally used in laboratories. (Fig 16)

Fig 16



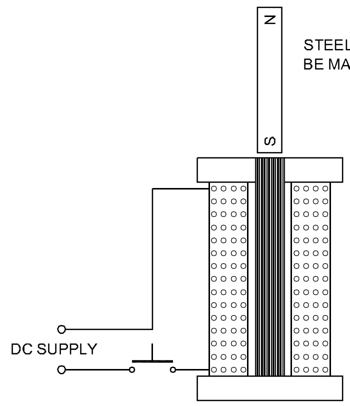
ELN15432G

Induction method: This is a commercial method of making permanent magnets. In this method a pole charger is used which has a coil of many turns and an iron core inside it as shown in Fig 17. The direct current supply is fed to the coil through a push-button switch.

The steel piece to be magnetized is placed on the iron core kept inside the coil, and direct current is passed through the coil. The iron core now becomes a powerful magnet, and thus the steel piece is magnetised by induction. The magnetised piece is then removed after switching off the supply.

This is a commercial process for making permanent magnets for speakers, telephones, microphones, earphones, electrical instruments, magnets,compasses etc.

Fig 17

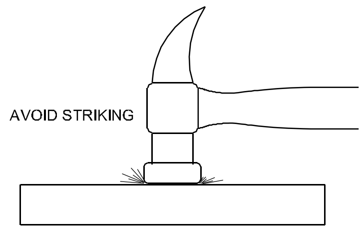


ELN15432H

Care and maintenance of permanent magnets: Permanent magnets should not be thrown or dropped.

They should not be hammered. (Fig 18)

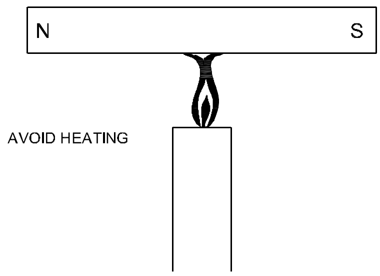
Fig 18



ELN15432I

They should not be heated. (Fig 19)

Fig 19

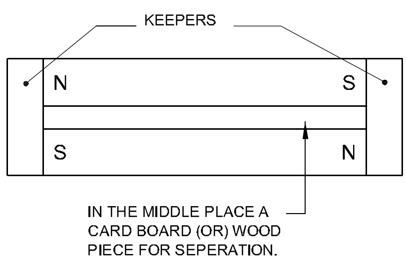


ELN15432J

Bar magnets should be placed side by side with their ends facing opposite polarity, with keepers at their ends.

Keepers should be used while storing the magnets. (Fig 20)

Fig 20



ELN15432K

As far as possible, the north and south poles of the magnet should be kept in the direction of the south and north directions of the earth respectively.

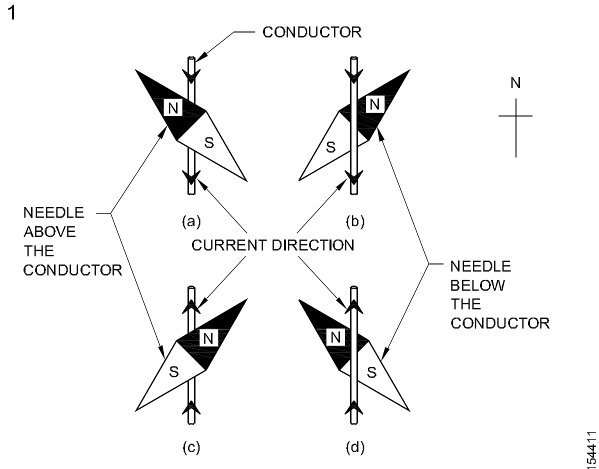
Principles and laws of electro magnetism

Objectives: At the end of this lesson you shall be able to
- **state the oersted principle**
- **explain what is meant by electromagnetism**
- **describe the magnetic field in current-carrying conductors, loop, coil, magnetic core -**
- **state right Hand Grip rule, Corkscrew rule and Right Hand palm rule**
- **state the interaction of the magnetic field**
- **state the magnetic materials for a temporary magnet.**

Oersted's experiment: Oersted, a Danish scientist discovered in 1819, while giving a demonstration lecture, that there is a close relationship between electricity and magnetism. He observed that when a magnetic needle is placed under and parallel to a conductor, and then the current switched on, the needle tends to deflect at right angles to the wire.

Suppose, a wire in which the current is to be passed, is arranged in the direction north to south by placing the needle above the wire as in Fig 1a. Then the north pole of the needle will be deflected to the west, nearly perpendicular to the wire. The deflection will be to the east, as in Fig 1b by placing needle below the wire. When the direction of the flow of current is reversed, the deflections of the needle will be in the opposite direction as shown in Fig 1c and 1d.

Fig 1



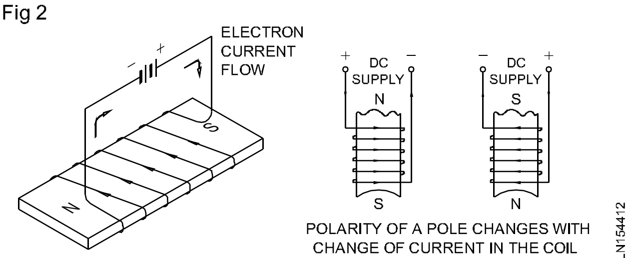
DEFLECTION OF MAGNETIC NEEDLE BY AN ELECTRIC CURRENT

In these cases the deflection of the needle shows that the lines of force are produced around the current-carrying conductor as shown in Fig 3.

Electromagnetism: On passing a current through a coil of wire, a magnetic field is set up around the coil. If a soft iron bar is placed in the coil of wire carrying the current, the iron bar becomes magnetized. This process is known as `electromagnetism'. The soft iron bar remains as a magnet as long as the current is flowing in the circuit. It loses its magnetism when the current is switched off from the coil.

The polarity of this electromagnet depends upon the direction of the current flowing through it. If the direction of the current is altered, the polarity of the magnetic field will also be changed as shown in Fig 2.

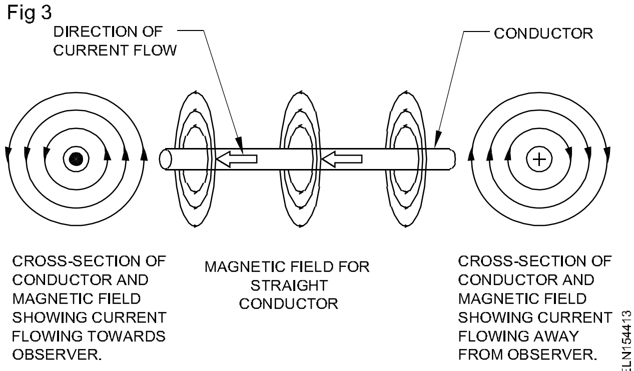
Fig 2



POLARITY OF A POLE CHANGES WITH CHANGE OF CURRENT IN THE COIL

Electromangetism in a wire (current-carrying conductor): A magnetic field is formed around a conductor carrying current. The field is so arranged around the conductor as to form a series of loops. (Fig 3)

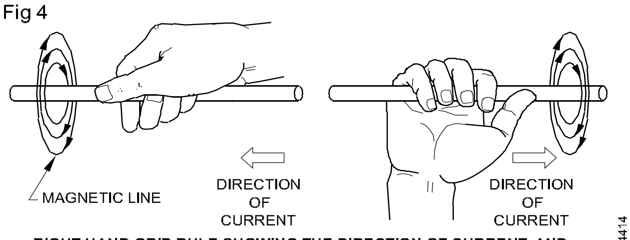
Fig 3



The direction of the magnetic field depends on the direction of the current flow. A compass moved around the wire will align itself with the flux lines.

The Right Hand Grip Rule can be used to determine the direction of the magnetic field. If you wrap your fingers around the wire with your thumb pointing in the direction of current flow, your fingers will point in the direction of the magnetic field as shown in Fig 4.

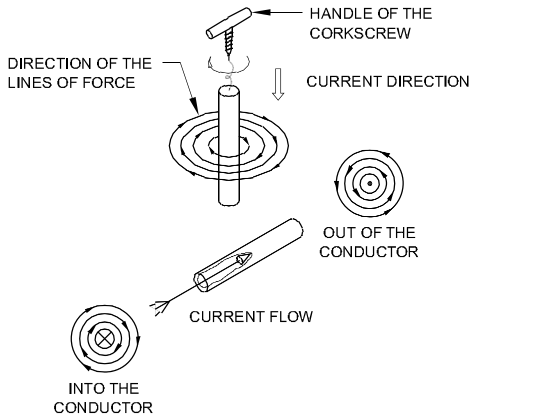
Fig 4



RIGHT HAND GRIP RULE SHOWING THE DIRECTION OF CURRENT AND DIRECTION OF MAGNETIC LINES

Assume a right handed corkscrew to be along the wire so as to advance in the direction of the current. The motion of the handle gives the direction of magnetic lines of force around the conductor (Fig 5)

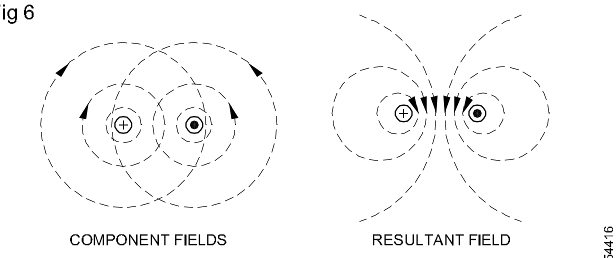
Fig 5



CORKSCREW RULE

If two wires carrying current in opposite directions are brought close to each other, their magnetic fields will oppose one another, since the flux lines are going in the opposite directions. The flux lines cannot cross, and the fields move the wires apart. (Fig 6)

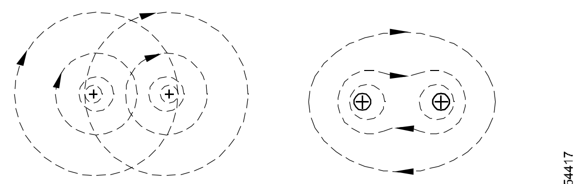
Fig 6



PARALLEL CONDUCTORS CARRYING CURRENT IN OPPOSITE DIRECTION

When wires carrying current in the same direction are brought together, their magnetic fields will aid one another, since the flux lines are going in the same direction. The flux lines join and form loops around both the wires, and the fields bring the wires together. The flux lines of both wires add to make a stronger mangetic field. Three or four wires put together in this way would make a still stronger field. (Fig 7)

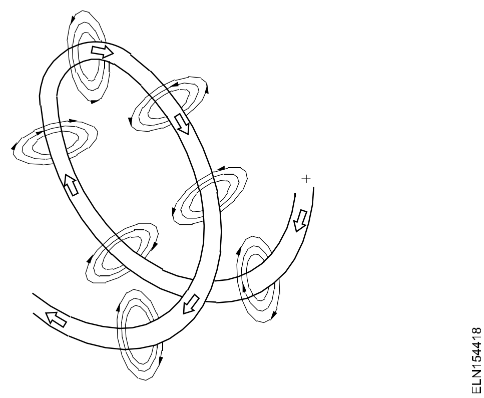
Fig 7



PARALLEL CONDUCTORS CARRYING CURRENT IN SAME DIRECTION

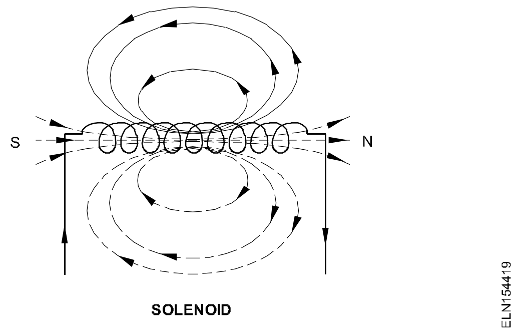
Electromagnetism in a loop: If the wire is made to form a loop, the magnetic fields around the wire will all be so arranged that they each flow into the loop on one side, and come out on the other side. In the centre of the loop, the flux lines are compressed to create a dense and strong field. This produces magnetic poles, with north on the side that the flux lines come out and south on the side that they go in as shown in Fig 8.

Fig 8



Electromagnetism in a coil: If a number of loops are wound in the same direction to form a coil, more fields will add to make the flux lines through the coil even more dense. The magnetic field through the coil becomes even stronger. The greater the number of loops, the stronger the magnetic field becomes. If the coil is compressed tightly, the fields would join even more to produce an even stronger electromagnet as shown in Fig 9.

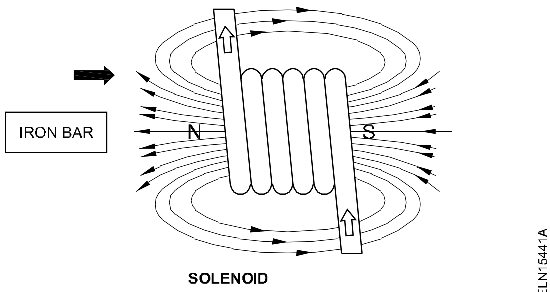
Fig 9



SOLENOID

A helically wound coil that is made to produce a strong magnetic field is called a solenoid. The flux lines in a solenoid act in the same way as in a magnet. They leave the N pole and go around to the S pole. When a solenoid attracts an iron bar, it will draw the bar inside the coil. (Fig 10)

Fig 10

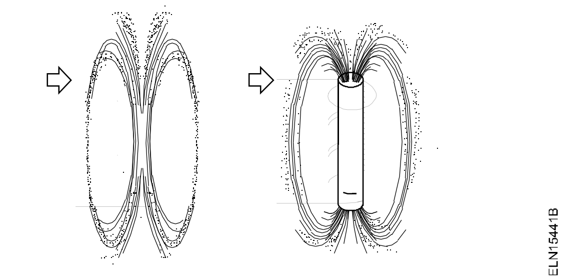


SOLENOID

The magnetic core: The magnetic field of a coil can be made stronger still by keeping an iron core inside the coil of wire. Since the soft iron is magnetic and has a low reluctance, it allows more flux lines to be concentrated in it than it would in the air. The greater the number of flux lines, the stronger the magnetic field. (Fig 11)

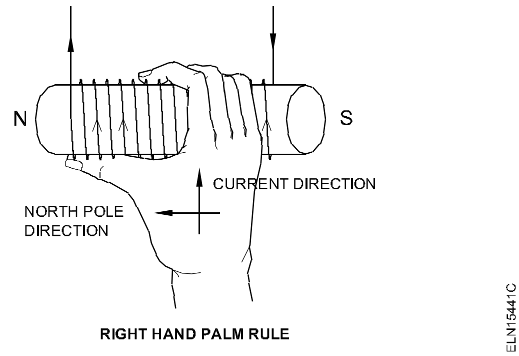
Soft iron is used as a core in an electromagnet because hard steel would become permanently magnetized.

Fig 11



The direction of the magnetic field can be found from palm rule right hand palm rule. (Fig 12)

Fig 12



RIGHT HAND PALM RULE

The Right Hand Palm Rule : Hold the right hand palm over the solenoid in such a way the fingers point in the direction of current in the solenoid conductors then the thumb indicates the direction of magnetic field (North Pole) of the solenoid.

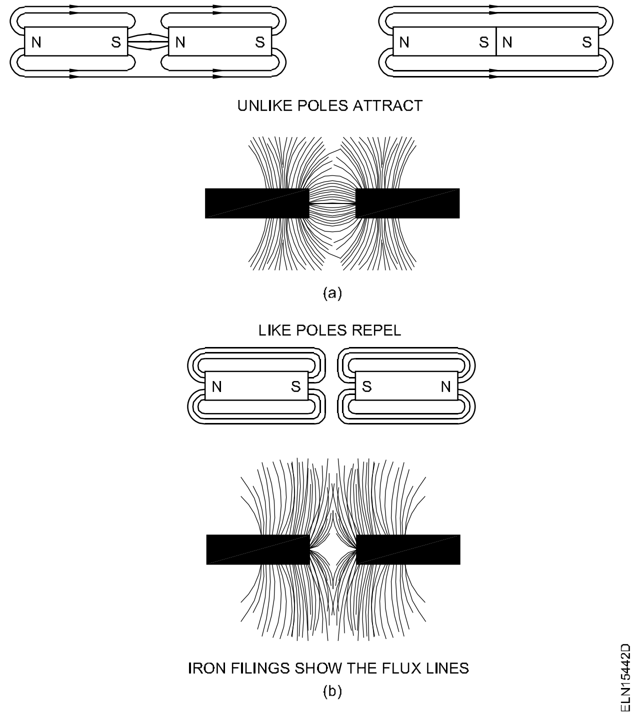
Interaction of magnetic fields: When two magnets are brought together, their fields interact. The magnetic lines of force will not cross one another. This fact determines how the fields act together.

If the lines of force are going in the same direction, they will attract each other and join together as they approach each other. This is why unlike poles attract. (Fig 13a)

If the lines of force are going in opposite directions, they cannot combine. And, since they cannot cross, they apply a force against each other. This is why like poles repel.

The interaction of the flux lines can also be shown with iron filings. (Fig 13b)

Fig 13



Magnetic materials for temporary magnets: Electromagnets are generally known as temporary magnets. The magnetic strength of such magnets can be varied by varying the current passing through them. Soft iron is used in electromagnets as a magnetic core. Silicon steel is very much used in bigger magnets (steel with 2.4% silicon). Nowadays other metals like permalloy, mumetal are also used for some applications.

Permalloy is an alloy of iron and nickel which can be magnetized by a very weak magnetic field and is useful for telephones.

Mumetal is an alloy of nickel, copper, chromium and iron. It has very high permeability and resistivity. Eddy current loss is very low. It is used in instrument transformers and for screening magnetic fields.

The magnetic circuits - self and mutually induced emfs

Objectives: At the end of this lesson you shall be able to
- **define the magnetic terms in a magnetic circuit (like M.M.F., reluctance, flux, field strength, flux density, permeability, relative permeability)**
- **state hysterisis and explain hysterisis loop**
- **describe pulling power of magnet.**

MagnetoMotive Force (MMF): The amount of flux density set up in the core is dependent upon five factors - the current, number of turns, material of the magnetic core, length of core and the cross-sectional area of the core. More current and the more turns of wire we use, the greater will be the magnetising effect. We call this product of the turns and current the magnetomotive force (mmf), similar to the electromotive force (emf). (Fig 1 & 2)

Fig 1

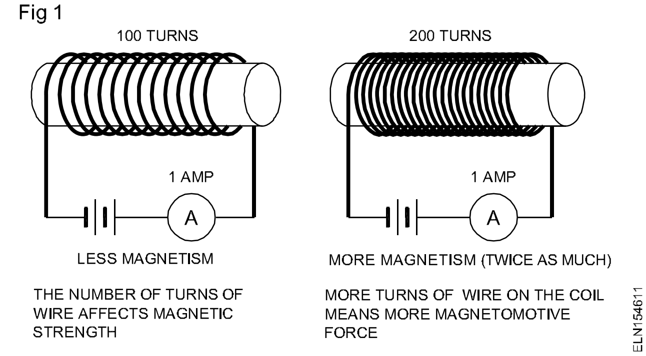
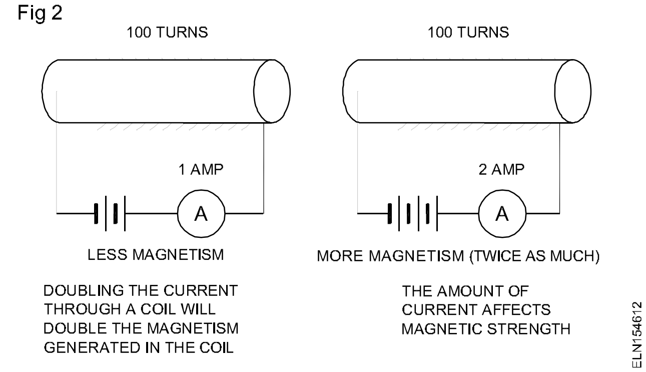


Fig 2



MMF = NI ampere-turns

where mmf - is the magnetomotive force in ampere turns

N - is the number of turns wrapped on the core

I - is the current in the coil, in amperes, A.

If one ampere current is flowing through a coil having 200 turns then the mmf is 200 ampere turns.

Reluctance: In the magnetic circuit there is something analogous to electrical resistance, and is called reluctance, (symbol S). The total flux is inversely proportional to the reluctance and so if we denote mmf by ampere turns. we can write

$\phi = \frac{NI}{S}$ Where ϕ is flux and reluctances $S = \frac{\ell}{\mu_o \mu_r a}$

where S - reluctance

l - length of the magnetic path in metres

μ_o - permeability of free space

μ_r - relative permeability

a - cross-sectional area of the magnetic path in sq.mm.

The unit of reluctance is ampere turns/Wb.

Magnetic flux:The magnetic flux in a magnetic circuit is equal to the total number of lines existing on the cross-section of the magnetic core at right angle to the direction of the flux. Its symbol is Ø and the SI unit is weber.

$$\phi = \frac{NI}{S}$$

$$= \frac{NIa\mu_o\mu_r}{\ell}$$

where

ϕ - total flux

N - number of turns

I - current in amperes

S - reluctance

μ_o - permeability of free space

μ_r - relative permeability

a - magnetic path cross-sectional area in m^2

ℓ - length of magnetic path in metres.

Magnetic field strength: This is also known sometimes as field intensity, magnetic intensity or magnetic field, and is represented by the letter H. Its unit is ampere turns per metre.

$$H = \frac{M.M.F}{\text{Length of coil in meters}} = \frac{NI}{\ell}$$

Flux density (B): The total number of lines of force per square metre of the cross- sectional area of the magnetic core is called flux density, and is represented by the symbol B. Its SI unit (in the MKS system) is tesla (weber per metre square).

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

where ϕ - total flux in webers

A - area of the core in square metres

B - flux density in weber/metre square.

Permeability: The permeability of a magnetic material is defined as the ratio of flux created in that material to the flux created in air, provided that mmf and dimensions of the magnetic circuit remain the same. It's symbol is μ and

$\mu = B/H$

where B is the flux density

H is the magnetising force.

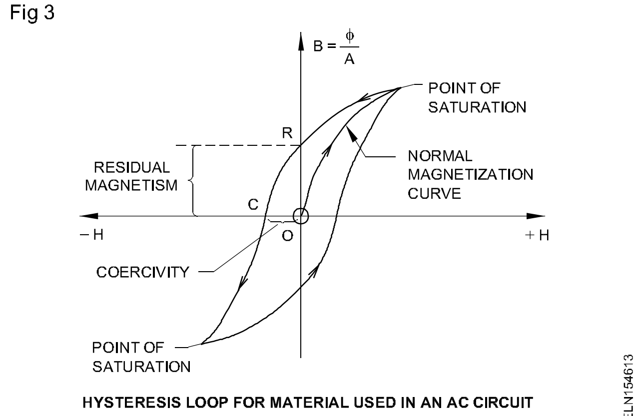
Being a ratio it has no unit and it is expressed as a mere number. The permeability of air μ air = unity. The relative permeability μr of iron and steel ranges from 50 to 2000. The permeability of a given material varies with its flux density.

Hysteresis: Consider the graphical relation between B and H for a magnetic material. Since μ = B/H, the graphical relationship shows how the permeability of a material varies with the magnetizing intensity H.

Assume that the magnetic core is initially completely demagnetised. As we increase the current, $H = \frac{NI}{\ell}$ increases and there will be an increase in the flux density, B. Since the number of turns and the length of core of a coil are fixed, H is directly proportional to the current or ammeter reading. The flux density can be measured by inserting the probe of a flux meter into a small hole drilled in the core.

A plot of the values of B and H gives the normal magnetization curve, as shown in Fig 3.There is evidently a linear portion where B is relatively proportional to H. But then a condition of saturation occurs when a very large increase in H is required to significantly increase B. This point in the curve is called as **saturation point.**

Fig 3



HYSTERESIS LOOP FOR MATERIAL USED IN AN AC CIRCUIT

If the current is now gradually reduced towards zero, H returns to zero, but B does not. The core exhibits retentiveness and retains some residual magnetism. The **retentiveness** is represented by the distance OR.

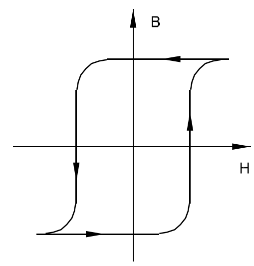
If the connections to the coil are reversed, and the current is again increased, it is found that a certain amount of H is required to bring the magnetism in the core down to zero. This is called the **coercivity** and is represented by the distance OC.

Further, any increase in the current in the opposite direction increases the magnetism in the core as before in the opposite direction, until once again saturation occurs.

Hysteresis loop: Reduction of the current and subsequent reversal of the direction will produce a closed figure called a B-H curve or hysteresis loop. The name comes from the Greek word `hysteros' meaning `to lag behind'. That is, the state of the flux density is always lagging behind the efforts of the magnetising intensity.

The shape of a B-H loop is an indication of the magnetic properties of the material. (Fig 4)

Fig 4



HYSTERSIS LOOP FOR PERMANENT MAGNET

Hysteresis results in the dissipation of energy which appears in the form of heat. The energy wasted in this manner is proportional to the area of the loop. Thus, the energy expanded, in joules per cubic metre of material in one cycle, is equal to the area of the loop in M.K.S. units.

Energy expended/cycle/m^2 in joules= Area of hysteresis loop in m^2.

The shape of the hysteresis loop depends on the nature of the iron or steel. Iron is subject to rapid reversal of magnetism and in this case the area of loop is very small.

Numerically the loss is given by the equation,energy dissipated per second = $\eta f B_m^{1.6}$ joules/m^3

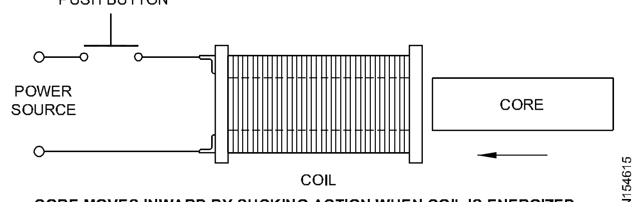
where η - constant, called hysteresis coefficient

B_m - maximum flux density

f - frequency.

Pulling power of solenoid: When the coil is energised, it produces a magnetic field which also magnetises the iron core. The iron core is attracted to the coil and they

Fig 5



CORE MOVES INWARD BY SUCKING ACTION WHEN COIL IS ENERGIZED snap together. Once the core is in the centre of the coil, the magnetic field is concentrated with that core and there is no room for further movement.

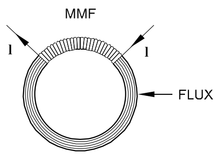
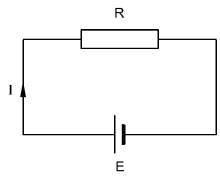
The pulling power of a solenoid depends on the number of turns of the coil, the current, material, flux density of the magnetic core, length and cross-sectional area of the core. The strength of an electromagnet depends upon its ability to conduct magnetism. The ability of conduction depends on mmf, reluctance and permeability of the magnetic path. (Fig 5)

Electromagnet applications - Electromagnetic induction

Objectives: At the end of this lesson you shall be able to
- **compare the magnetic circuit and electric circuit**
- **state the applications of an electromagnet (Bell & Buzzer tubelight choke)**
- **state the principle and laws of electromagnetic induction**
- **explain the energy stored in induction coil**
- **explain about the series and parallel connection of inductors and types of inductors**
- **state function of choke in a flourscent light circuit**
- **state the factors that contribute to induced voltage**
- **explain about the counter EMF-induced reactance-time constant.**

Comparison between magnetic and electric circuits

Similarities (Fig 1a & 1b)

	Magnetic Current	Electrical Current
1	Flux = $\frac{\text{mmf}}{\text{reluctance}}$  Fig 1a	Current = $\frac{\text{emf}}{\text{resistance}}$  Fig 1b
2	M.M.F. (Ampere-turns)	E.M.F. (Volts)
3	Flux ϕ (Webers)	Current I (amperes)
4	Flux density B (Wb/m^2)	Current density (A/m^2)
5	Reluctance $S = \frac{\ell}{\mu_A}$ or $S = \frac{\ell}{\mu_0 \mu_r a}$	Resistance $R = \frac{\rho L}{A}$
6	Permeance = (1/reluctance)	Conductance (= 1/resistance)
7	Reluctivity $\mu_o \mu_r A$	Resistivity
8	Permeability (=1/reluctivity)	Conductivity(=1/resistivity)

Practical applications of electromagnets: Electromagnets are used in the manufacture of all types of electrical machines, such as motors, generators, transformers, convertors, some electrical measuring instruments, protective relays, for medical purposes (like removing iron pieces from eyes) and in many other electrical devices like bells, buzzers, circuit-breakers, relays, telegraphic circuits, lifts and other industrial uses. (Figs 2, 3, 4, 5 & 6)

a Bells (Fig 2)

b Buzzers

c Circuit-breakers (Fig 3)

d Relays (Fig 4)

e Telegraphic circuits

f Lifts (Fig 5)

g Industrial uses (Fig 6)

Fig 2

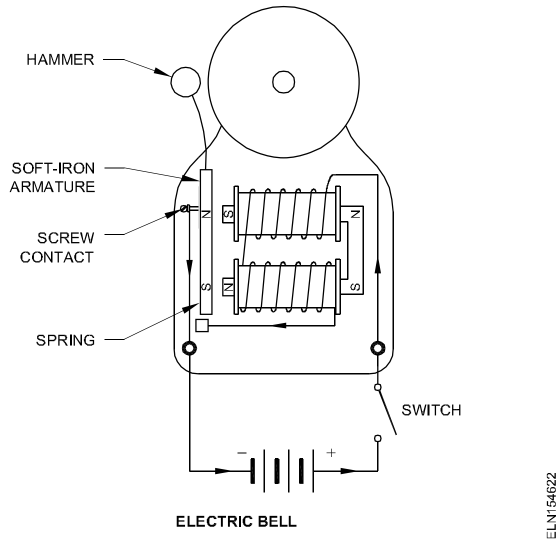


Fig 3

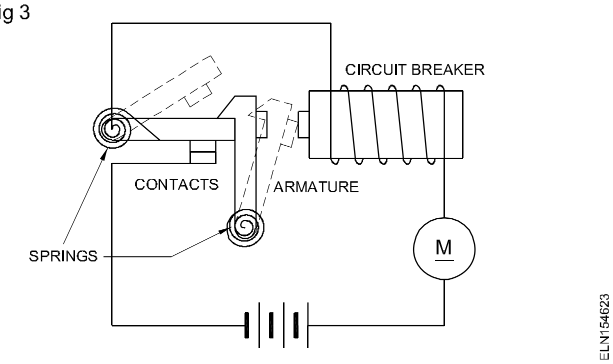


Fig 4

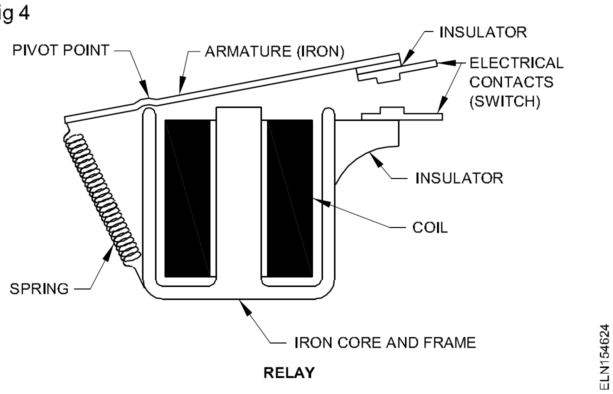


Fig 5

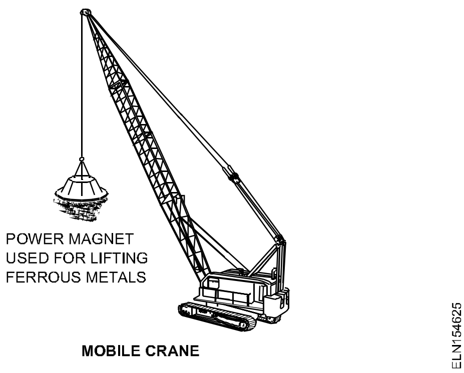
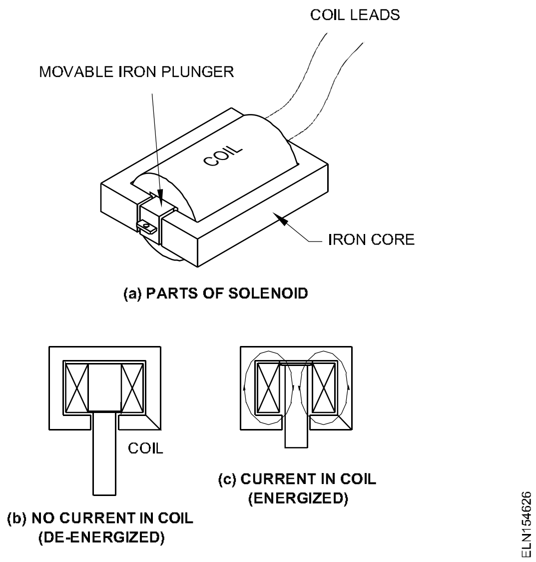


Fig 6



Principles and laws of electromagnetic induction

Faraday's Laws of Electromagnetic Induction are also applicable for conductors carrying alternating current.

Faradays' Laws of Electromagnetic Induction

Faraday's First Law states that whenever the magnetic flux is linked with a circuit changes, an emf is always induced in it.

The Second Law states that the magnitude of the induced emf is equal to the rate of change of flux linkage.

Dyanamically Induced EMF

Accordingly induced emf can be produced either by moving the conductor in a stationery magnetic field or by changing magnetic flux over a stationery conductor. When conductor moves and produces emf, the emf is called as dynamically induced emf Ex. generators.

Statically Induced EMF

When changing flux produces emf the emf is called as statically induced emf as explained below. Ex: Transformer.

Statically induced emf: When the induced emf is produced in a stationery conductor due to changing magnetic field, obeying Faraday's laws of electro magnetism, the induced emf is called as statically induced emf.

There are two types of statically induced emf as stated below:-

1 **Self induced emf** produced with in the same coil

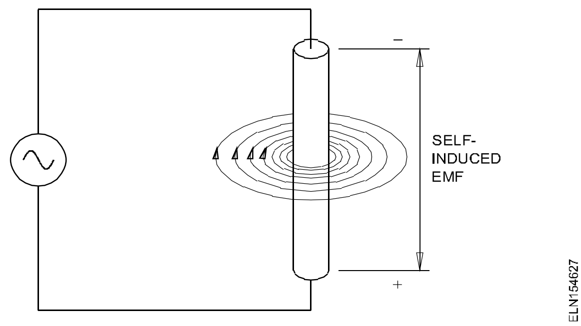
2 **mutually induced emf** produced in the neighbouring coil

Self-induction: The production of an electromotive force in a circuit, when the magnetic flux linked with the circuit changes as a result of the change in a current inducing in the same circuit.

At any instant, the direction of the magnetic field is determined by the direction of the current flow.

With one complete cycle, the magnetic field around the conductor builds up and then collapses. It then builds up in the opposite direction, and collapses again. When the magnetic filed begins building up from zero, the lines of force or flux lines expand from the centre of the conductor outward. As they expand outward, they can be thought of as cutting through the conductor.

Fig 7

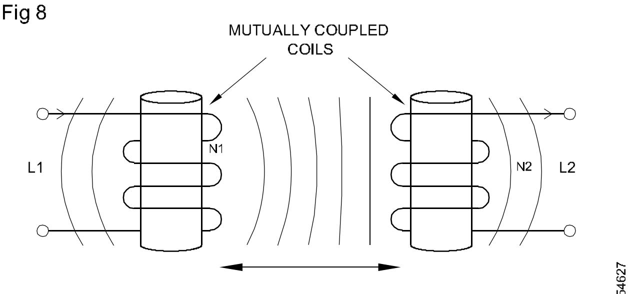


According to Faraday's Laws, an emf is induced in the conductor. Similarly, when the magnetic field collapses, the flux lines cut through the conductor again, and an emf is induced once again. This is called self-induction. (Fig 7)

Mutual Inductance: When two or more coils one magnetically linked together by a common magnetic flux, they are said to have the property of mutual inductance. It is the basic operating principal of the transformer, motor generaters and any other electrical component that interacts with another magnetic field. It can define mutual induction on the current flowing in one coil that induces a voltage in an adjacement coil.

In the Fig,8 current flowing in coil L1 sets up a magnetic field around it self with some of its magnetic field line passing through coil L2 giving in mutual inductance coil one L on has a current of I, and N, turns while coil two L2, has N2 turns therefore mutual inductance M, of coil two that exists with respect to coil one L, depend on their position with inspect to each other.

Fig 8



MUTUAL INDUCTANCE BETWEEN COILS

The mutual inductance M that exists between the two coils can be greately measured by positioning them on a common soft iron cone or by measuring the number of turns of either coil on would he found in a transformer.

The two coils are tightly wound one on top of the other over a common soft iron core unity in said to exist between them as any losses due to the leakage of flux will be extremely small. Then assuring a perfect flux leakage between the two coils the mutual inductance M that exists between them can be given on:

$$M = \frac{M_0 M_r N_1 N_2 A}{L}$$

Value

M_o is the permeability of free space $(4\pi \times 10^{-7})$

M_r - is the relative permability of soft iron cone

N is the no. of turns of coil

A is the cross sectional area in m^2

l is the coil length in meters

Inductance: Inductance (L) is the electrical property of an electrical circuit or device to oppose any change in the magnitude of current flow in a circuit.

Devices which are used to provide inductance in a circuit are called inductors. Inductors are also known as chokes, coils, and reactors. Inductors are usually coils of wire.

Factors determining inductance: The inductance of an inductor is primarily determined by four factors.

- Type of core permeability of the core m_r.
- Number of turns of wire in the coil 'N'.
- Spacing between turns of wire (Spacing factor).
- Cross-sectional area (diameter of the coil core) 'a' or 'd'.

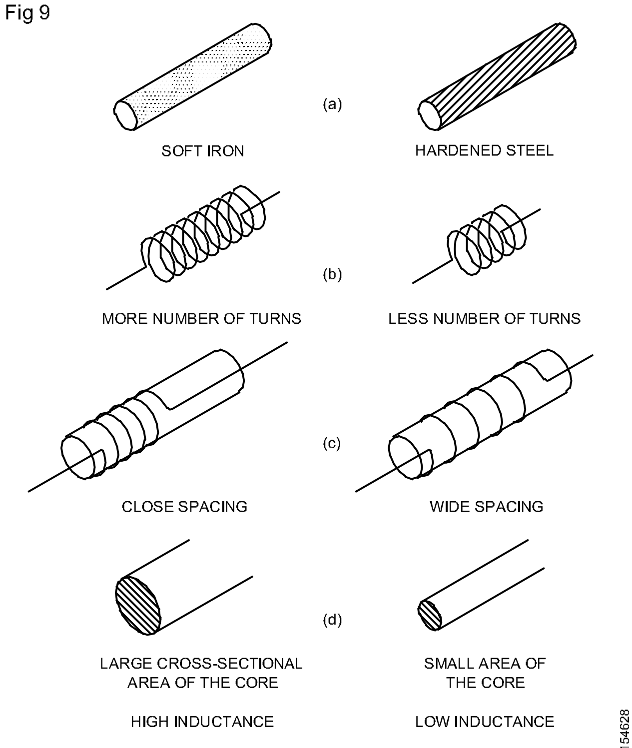
The amount of inductance in a coil of wire is affected by the physical make up of the coil. (Fig 8.)

Core (Fig 9a): If soft iron is used as a core material instead of hardened steel, the coil will have more inductance.

If all the factors are equal, an iron core inductor has more inductance than an air core inductor. This is because iron has a higher permeability, that is, it is able to carry more flux. With this higher permeability there is more flux change, and thus more counter induced emf (cemf), for a given change in current.

Number of turns (Fig 9b): Adding more turns to an inductor increases its inductance because each turn adds more magnetic field strength to the inductor. Increasing the magnetic field strength results in more flux to cut the conductors (turns) of the inductor.

Fig 9



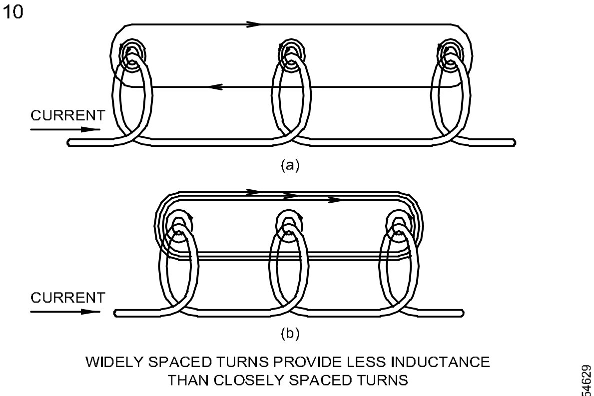
FACTORS DETERMINING INDUCTANCE

Spacing between turns of wire (Fig 9c): When the distance between the turns of wire in a coil is increased, the inductance of the coil decreases. Fig 10 illustrates why this is so. With widely spaced turns Fig 10 many of the flux lines from adjacent turns does not link to gether. Those lines that do not link together produce no voltage in other turns. As the turns come closer together Fig 10 only a fewer lines of flux fail to link up.

Cross sectional area (Fig 9d):For a given material having same number of turns, the inductance will be high with large cross-sectional area and will be low for smaller cross-sectional area.

Symbol and unit of Self-inductance: The property of a coil or conductor to self-induce an emf, when the current though it is changing, is called the coil's (conductor's) self-inductance of simply inductance. The letter symbol for inductance is L; its basic unit is henry, H.

Fig 10



EFFECT OF TURN SPACING

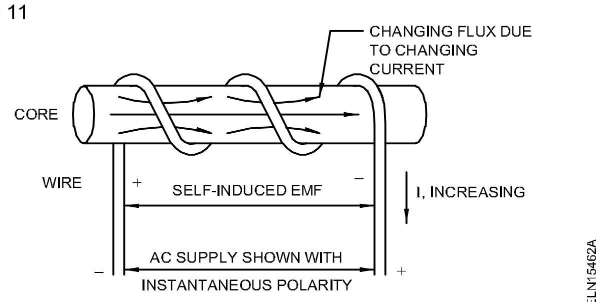
Henry: A conductor or coil has an inductance of one henry if a current that changes at the rate of one ampere per second produces a induced voltage (cemf) of 1 volt.

The inductance of straight conductors is usually very low, and for our proposes can be considered zero. The inductance of coiled conductors will be high, and it plays an important role in the analysis of AC circuits.

What will be the direction of the induced emf? (Lenz's Law): The direction of the self-induced emf is explained by Lenz's Law.

A change in current produces an emf whose direction is such that it opposes the change in current. In other words, when a current is decreasing, the induced emf is in the same direction as the current and tries to oppose the current from decreasing. And when a current is increasing, the polarity of the induced emf is opposite to the direction of the current and tries to prevent the current from increasing (Fig 11).

Fig 11



The magnitude of induced emf:The magnitude of self-induced emf depends on the rate at which the magnetic field changes. However magnetic field is proportional to current.

$$v = L \times \frac{di}{dt}$$

where

- v is the emf induced in volts, V (some times called as counter emf (cemf)
- L is the inductance in henrys, H
- di is the change in current in amperes, A.
- dt is the change in time in seconds s,

$\frac{di}{dt}$ is the rate of change of current in amperes/second, A/s.

Coefficient of self-inductance : It is defined as the flux linkage of weber turns per ampere in the coil.

By definition $L \times \frac{N\phi}{I}$ henry

where 'N' is the number of turns

'f' is the flux in webers

I is the current in amperes

Energy storage: An inductor stores energy in the magnetic field created by the current. The energy stored is expressed as follows.

$$W = \frac{1}{2} LI^2$$

where I is in amperes,

L is in henries and

W is energy in joules or watt-second

To obtain the desired value of inductors, some series and parallel combination of inductors can be used.

Series and Parallel Inductors

Series inductors: When inductors are connected in series, as in Fig 12a, the total inductance L_T is the sum of the individual inductances. The formula for L_T is expressed in the following equation for the general case of n inductors in series.

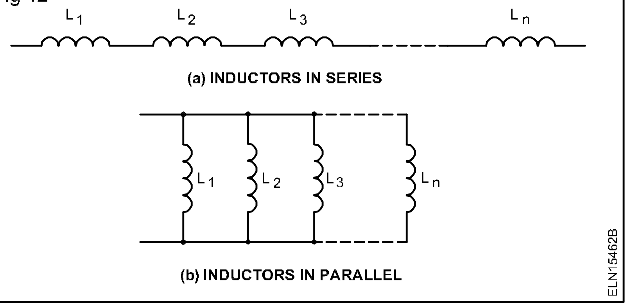
$$L_T = L_1 + L_2 + L_3 + ...L_n$$

Notice that inductance in series to resistance in series.

Parallel inductors: When inductors are connected in parallel, as in Fig 12b, the total inductance is less than the smallest inductance. The formula for total inductance in parallel is similar to that for total parallel resistance.

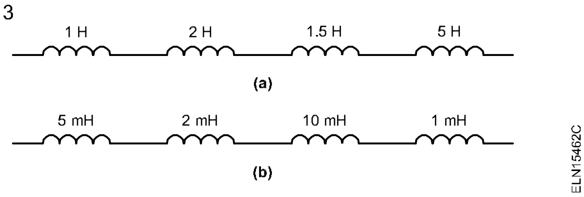
$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots\dots\dots\dots \frac{1}{L_n}$$

Fig 12



Example 1: Determine the total inductance for each of the series connections in Fig 13.

Fig 13



Solution

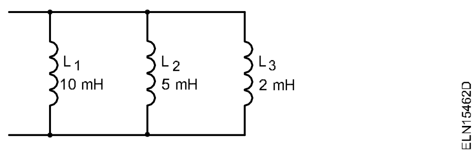
a) L_T = 1H + 2H + 1.5H + 5H = 9.5H

b) L_T = 5mH + 2mH + 10mH + 1mH = 18mH

Note 1000mH = 1 H

Example 2: Determine L_T in Fig 14.

Fig 14



Solution

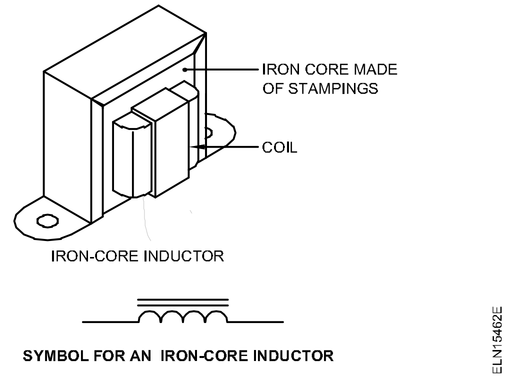
$$L_T = \frac{1}{\left(\frac{1}{10}\text{mH}\right) + \left(\frac{1}{5}\text{mH}\right) + \left(\frac{1}{2}\text{mH}\right)}$$

$$= \frac{1}{0.1 + 0.2 + 0.5}$$

$$L_T = \frac{1}{0.8} = 1.25 \text{ mH.}$$

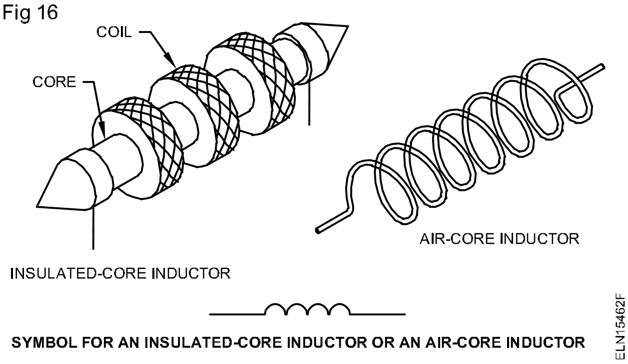
Types of Inductor: Basically, all inductors are made by winding a length of conductor around a core (Fig 15). The conductor is usually a solid copper or aluminum wire coated with enamel insulation, and the core is made either of magnetic material, such as powered iron, or of insulating material.

Fig 15



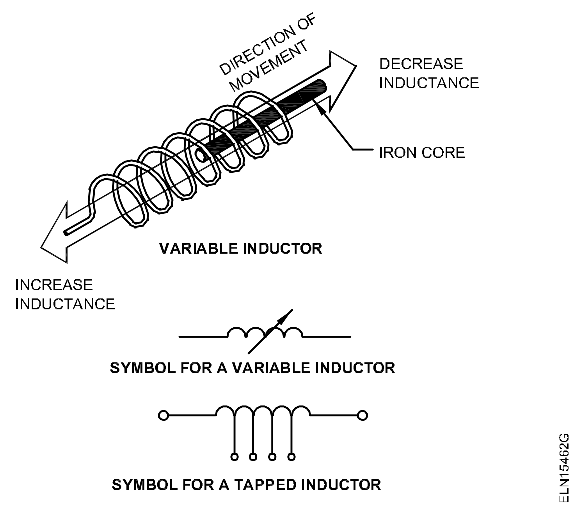
When an inductor is wound around an insulating core, the core is used only for a support, since it has no magnetic properties. If heavy wire is used in making the inductor, a core is actually not needed; the regid loops of wire support themselves. When a magnetic core is not used, the inductor is usually referred to as an air-core inductor. (Fig 16)

Fig 16



Inductor with set values of inductance that cannot be changed are called fixed inductors. Inductors whose inductance can be varied over some range are called variable inductors. Usually, variable inductors are made so that the core can be moved into and out of the winding. The position of the core will determine the inductance value. (Fig 17)

Fig 17



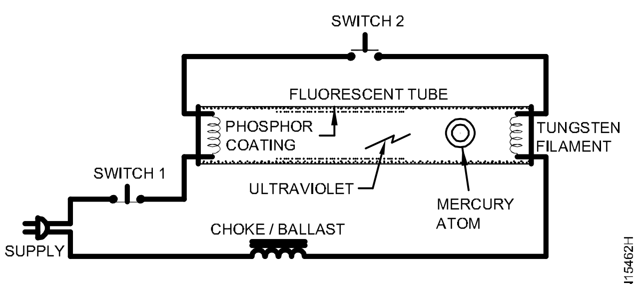
Inductors are also frequently called chokes or coils. All these three terms mean the same thing.

Fixed inductors are used as ballast in gas discharge lamps. They are also used in electronics as power supply filters. Variable inductors and tapped inductors are used for obtaining variation of current in welding transformers to suit the electrode size and weld material.

Function of choke in a fluorescent lamp circuit: Fig 18 shows a fluorescent lamp circuit. The inductor (ballast) is used to induce a momentary high voltage to fire the lamp. The ballast then limits the current through the lamp, after the lamp is lit, because of the coil's inductive reactance. The operation of the lamp circuit is as follows.

The fluorescent lamp is a glass tube with a tungsten filament sealed at each end. The inner surface of the tube is coated with a phosphor material this determines the colour of the light produced. Most of the air is removed during manufacture and a small amount of argon gas and mercury are admitted to the sealed tube.(Fig 18)

Fig 18



SCHEMATIC DIAGRAM OF FLUORESCENT TUBE LAMP

When the momentary contact of the switch 2 is pushed (CLOSED), and held closed for several seconds, a complete series path exists for current to flow through the two filaments to become heated, emitting electrons. A dull glow is observed at each end of the tube. When the switch 2 is released (OPEN), the current through the ballast is interrupted, causing a high voltage to be momentarily induced. This voltage, along with the 240V input, is sufficient to cause the lamp to 'fire'. This means that the current is conducted through the ionized gas in the tube from one filament to the other.

It should be noted that the ballast gets its name from the second function it provides. After the lamp is lit, a typical 40W lamp requires only 110V to maintain proper current through the lamp. The opposition to alternating current caused by the inductance, its inductive reactance, help in the applied 240V dropping to the required value across the lamp.

Flourecent lamps that use a single on/off switch1 in the supply line for control purposes employ a starter inplace of the switch 2.

When a fluorescent lamp circuit is connected to DC supply, the choke serves the first purpose only. An additional resistor is to be connected in series to limit the current through the lamp.

Disadvantage of Inductance:

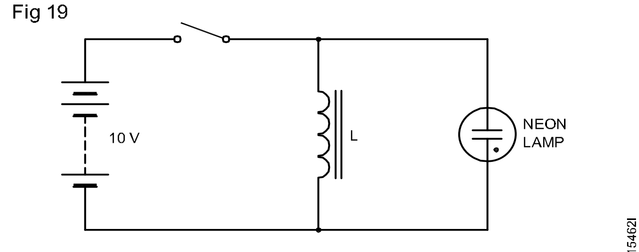
Inductance increases arcing in switch contact which is a major disadvantage. A large voltage across the contacts, while opening the switch of the inductive circuit, sets an arc, and the stored energy in the magnetic field increases the arcing. Additional measures are required to suppress the arc in such circuits.

Factors that contribute to induced voltage: The ability of a coil to induce high voltage can be observed by connecting a neon lamp across a coil as in Fig 19.

A neon lamp used as an indicator requires a minimum of about 70V to 'fire' or light. It is observed that a battery does not light the lamp as the voltage is only 10V at the time of switching ON. But when the switch is opened the lamp flashes indicating the presence of high voltage, more than 70 V.

A major application of the high voltage induced in a coil by interrupting the current through the coil is in fluorescent lamp circuits and ignitors of petrol engines.

Fig 19



L - CHOKE OF 40W FLUORESCENT TUBELIGHT

Counter emf - inductive reactance - time constant

Objectives: At the end of this lesson you shall be able to
- **explain the term Counter EMF (CEMF)**
- **explain about the inductive reactance**
- **state the reasons for the difference between ohmic resistance and impedance of a coil**
- **explain time constant of an inductive circuit.**

Counter EMF and LENZ's law: The voltage induced in a conductor or coil by its own magnetic field is called a counter electromotive force (cemf). Since the induced emf (voltage) is always opposing, or countering, the action of the source voltage, it is known as cemf. Counter electromotive force is sometimes referred to as back electromotive force (bemf).

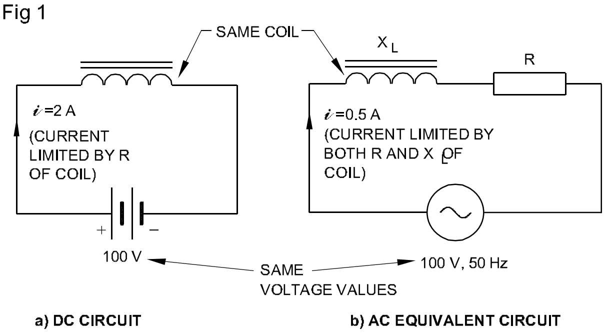
In any type of inductive circuit there is an important relationship between the direction of the current change and the induced voltage. Lenz's law states that a cemf always has a polarity which opposes the force that created it.

The inductance rating of an inductor refers to its ability to generate a counter voltage to a change in current flow. One henry (1H - the SI unit) represents the inductance of a coil in which a current change of one ampere per second (1 A/s) will produce a cemf of one volt (1V).

Inductive reactance:The opposition offered to an AC current flow by the inductive effect is called inductive reactance. Inductive reactance is the result of the cemf of the inductor. The inductor cemf is just equal to (and opposite) the source voltage.

Current flow through a coil connected to a DC source is limited by the wire resistance of the coil only (Fig 1a) Current flow through the same coil connected to an AC source is limited by the wire resistance and the inductive reactance (Fig 1b)

Fig 1



INDUCTANCE CONNECTED TO AN AC AND DC SOURCE

The reactance of an inductor can be calculated with the following formula

$X_L = 2\pi fL = 6.28\ fL$

The inductive reactance is in ohms while the frequency is in hertz and the inductance is in henrys.

From the above formula it can be seen that inductive reactance is directly proportional to both frequency and inductance.

This direct proportional relationship makes sense when one recalls two things.

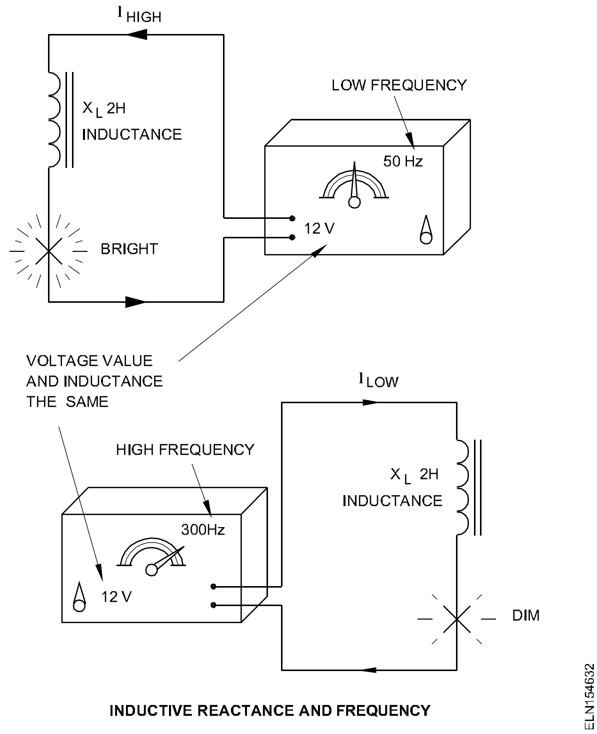
- The higher the frequency, the more rapidly the current is changing. Thus more cemf and more reactance are produced (Fig 2)
- The higher the inductance, the more the flux change per unit of current change. Again more cemf and reactance are produced.(Fig 3)

OHMIC resistance: The DC resistance is the resistance measured with a very accurate ohmmeter. It is the total resistive effect to pure DC.

Effective resistance: In general, a pure resistive circuit reacts in much the same way for both AC or DC. There are, however, some differences that must be considered. These differences vary with the frequency of AC and are generally negligible at low frequencies.

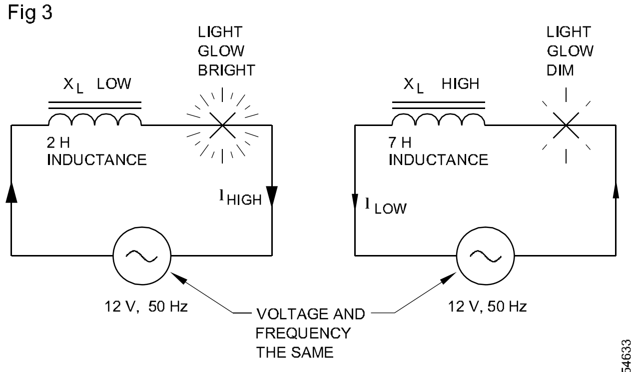
The following five factors affect the amount of current flow in a pure resistive circuit.

Fig 2



INDUCTIVE REACTANCE AND FREQUENCY

Fig 3



COIL-INDUCTANCE AND INDUCTIVE-REACTANCE

- DC resistance
- Skin effect
- Eddy currents
- Hysteresis
- Dielectric stress

The DC resistance is the resistance offered by the conductor (element) to pure DC. The fact that the alternating current changes in value and direction tends to make it flow along the outer surface of the conductor. This phenomenon, known as skin effect, reduces the inner conductive effect of the conducting material and increases the circuit resistance.

Alternating current produces a magnetic flux which changes its polarity with each reversal of current flow. The change in polarity causes the molecules in the metal parts near the circuit to be in motion, thus producing heat. The heat either radiates back into the circuit conductors or retards the dissipation of heat produced by the current flowing in the conductors. The hysteresis effect increases the effective resistance of the circuit.

Eddy currents are caused by voltages induced into the conductors and other surrounding metal parts. They are directly proportional to the frequency of the supply. The heat produced by these currents tends to increase the effective resistance of the circuit.

As the alternating voltage varies in strength, the stress on the conductor insulation increases and decreases. This variation in electric stress also produces heat which increases the circuit resistance.

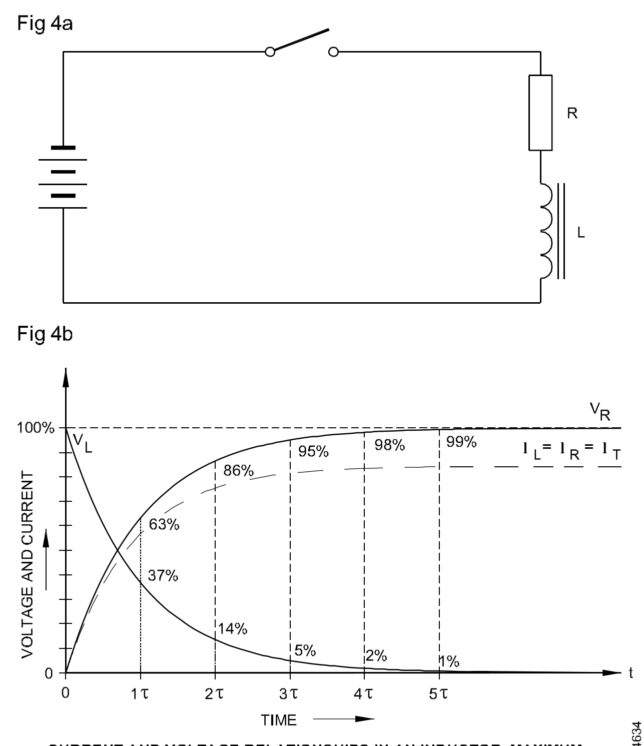
Effect of inductance present in a AC circuit: Coils have various uses in electrical engineering such as

- excitation coils in electric machines or magnets
- relay coils in switching devices
- choke coils for limiting current etc.

If a coil with the current passing through it is compared to a vehicle being moved, then the momentary value of the coil's current I can be compared to the velocity V of the vehicle. An increase in the current corresponds to accelerating the vehicle and a decrease in the current corresponds to braking (retarding) the vehicle. Due to the inertia of the vehicle's mass the velocity cannot suddenly change. The same applies to the coil's current, where a sudden change is prevented by the self-induced emf (voltage).

Time constant for inductors: When a coil with inductance L and resistance R_L is fed by a direct voltage (Fig 4a) the flux increasing with the current induces cemf, so that the current only increases to its final value $I = \frac{V}{R_L}$ with a time delay Fig 4b. The time constant for an RL circuit is defined as the time required for the current through the resistor-inductor to rise to 63.2% of its final value. The time constant of an RL circuit can be calculated using the formula $t = \frac{L}{R}$.

The time constant is in seconds when L is in henry and R is in ohms. The current after the time t = t has reached 63.2% of its final value. The table shows after five time constants have elapsed (t=5t), the current has reached 99.3% of its final value, i.e. it has practically reached its final value.



CURRENT AND VOLTAGE RELATIONSHIPS IN AN INDUCTOR. MAXIMUM INDUCTIVE VOLTAGE OCCURS BEFORE MAXIMUM CURRENT IS REACHED.

Time t =	τ	2τ	3τ	4τ	5τ	6τ	7τ	8τ
Current value I =	63.2%	86.46	95.02	98.10	99.33	99.75	99.9	99.966