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INSTITUTE OF SCIENCE AND TECHNOLOGY

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**SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING**

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**

# UNIT - I

# Electrical Technology – SEEA1102

# I. INTRODUCTION TO ELECTRICAL STANDARDS

Indian Standard Electricity Rules - Domestic Wiring - Wiring Materials and Accessories - Staircase Wiring - Fluorescent Tubes – Earthing - Types of Earthing - Benefits of Earthing

## Major codes & standard followed in India

- Indian Electricity rules, 1956 as amended up to 25TH Nov., 2000
- Bureau of Indian standards
- Central electricity authority guidelines
- CPCB norms (central pollution control board)
- National building code
- CBIP manuals (Central board of irrigation & power)
- Oil Industry safety directorate (OISD) for oil & gas industry
- IE rules & IS takes precedence over all the standards. None of the Indian standard contradicts each other, they only supplement each other in a way that what is not mentioned in one standard is available in another**.**

## What is IER?

- ✓ The Indian Electricity Rules, 1956 was made under section 37 of the Indian Electricity Act, 1910.
- ✓ Now redefined after enactment of The Electricity Act, 2003

## Who is the governing body of IER?

- ✓ CEAR namely *Central Electricity Authority (Measures relating to Safety and Electric Supply) Regulations, 2010 came into effect from 20th September 2010*, in place of The Indian Electricity Rules, 1956.
- ✓ These rules themselves were been allowed to be in force till rules under section 53 of new Act

**IE rules**

- The rules regarding the safety in construction and use of electrical installations / plants / equipment's are framed by Central Electricity Board.
- The I.E. rules were first framed in 1922 and amended in 1937 and 1956.
- The Indian Electricity Act,deals with the provisions relating to supply and use of electrical energy and the rights and obligations of persons licensed under part II of that act to supply energy.

**Objectives of IE rules**

- ✓ To regulate the relation between the Electricity Supplier and Consumer.
- ✓ To make the generation, transmission, distribution and the use of electricity as safe as possible.

**IE rules mainly deals with**

- ❖ Appointment of inspectors & their duties.
- ❖ Licensing provisions.
- ❖ General safety requirements.
- ❖ Conditions relating to supply and use of energy.
- ❖ Electric supply lines and systems for LV & MV.
- ❖ Electric supply lines and systems for HV & EHV.
- ❖ Overhead lines, underground cables and generating stations.
- ❖ Electric traction.
- ❖ Precautions in mines & oil fields.

**Indian electricity Rules are expected to serve the interests of**

• project administrators,

• licensees,

• electrical engineers,

• works managers,

• licensed contractors,

• electricians,

• wireman and

• indeed all those who have to deal with generation ,transmission, conversion, distribution, supply and use of electrical energy including consumers.

**INDIAN ELECTRICITY RULES 1956**

- ✓ Rules 1 to 3 Preliminary
- ✓ Rules 4 to 10 Inspectors
- ✓ Rules 11 to 28 License
- ✓ Rules 29 to 46 General Safety Precautions
- ✓ Rules 47 to 59 General conditions relating to supply and use of energy
- ✓ Rules 60 to 62 Electric supply lines, systems and apparatus for low and medium voltages.
- ✓ Rules 63 to 73 Electric supply lines, systems and apparatus for high and extra high voltages.
- ✓ Rules 74 to 93 Overhead lines
- ✓ Rules 94 to 108Electric Traction
- ✓ Rules 109 to 132 Additional precautions to be adopted in Mines and oil fields
- ✓ Rules 133 to 143 Miscellaneous

**Indian Electricity Rules have been covered in 11 Chapters**

**Rules 1 to 3**

It covers preliminaries, such as definitions of different expressions used in Rules, Authorization to person to work on live mains etc.

**Rules 4 to 10**

It deals with appointment of Electrical Inspector, his qualification and experience.

Powers of Electrical Inspector to enter the premises and to serve order for compliance of defects, provision of appeals against the order of Electrical Inspector etc.

**Rules 11 to 28**

It deals with granting of license for supply of electricity. As per the provision of the Electricity Act:2003, such license shall be issued by the Gujarat Electricity Regulatory Commission ( GERC ) , constituted under the new Act.

**Rules 29 to 46**

This chapter deals with General Safety requirement. All these Rules are described below in detail .

**Rules 47 to 59**

It deals with general conditions relating to supply and use of energy. It covers general Rules for applicable to all class of installation.

**Rules 60 to 62**

It covers the Rules applicable to low and medium voltage installation's supply and use.

**Rules 63 to 73**

It covers the Rules applicable to high and extra high voltage installations.

**Rules 74 to 93**

It deals with the provision of Rules applicable to Overhead lines and under ground cables.

**Rules 94 to 108**

This contains specific safety provisions which apply only to a Electrical energy used for the purpose of Traction.

**Rule 109 to 132**

It deals with precautions to be adopted in mines and oil fields.

**Rules 133 to 143**

Miscellaneous – Contain mainly penalty for breaking Rules

**INDIAN ELECTRICITY RULES FOR WIRING**

The Indian electricity Rules have been framed by a competent body to ensure a satisfactory operation of equipment and apparatus and also to safeguard the consumers from electric shocks.

Some of the important rules are listed below.

**RULE No.29**

All electric supply lines and apparatus shall be sufficient in power and size and of sufficient mechanical strength for the work they may required to do and so far as is practicable, shall be constructed, installed, protected worked and maintained in accordance with standards for the Indian standards institution as to prevent danger.

**RULE No .30**

Service line placed by the supplier on the premises of a consumer which are underground or which are accessible shall be so insulated and protected by the supplier as to be secured under all ordinary conditions against , electrical, mechanical, chemical or other injury to the insulation.

The consumer shall take precaution for the safe custody of the equipment of this premises belonging to the supplier and also ensure that the installation under his control is maintained in a safe condition.

**RULE No.33**

The consumer shall take all reasonable precautions to prevent mechanical damage to the earthed and its lead belonging to the supplier

**Rule No.34**

Where bare conductors are used in a building ,the owner of such conductors shall ensures that they are inaccessible and shall provide switches for rendering them dead whenever necessary.

**Rule No.45**

No electrical installation , alteration , repairs ( except such replacement of lamps, fans, fuses, switches which does not alter the capacity) shall be carried out except by an electric contractor licensed in this behalf by the state government.

**Rule No.46**

Every installation shall be periodically inspected and checked at intervals not exceeding five years either by inspector or by the supplier.

**Rule No.56**

A supplier may affix seal or cut out to any meter or apparatus placed upon as consumer's premises and no person other than the supplier shall break any such seal

**Rule No.77**

No conductor of an overhead line, including services lines, erected across a street shall at any part thereof be at a height less than 19 feet for low and medium voltages and 20 feet for high voltages.

When erected along a street, the minimum ground clearance shall be 18 feet for low and medium voltages 19 feet for high voltages.

**Rule No.77**

Clearance from buildings of low and medium voltages lines and service lines for flat roof, when the line passes above the building a vertical clearance of 2.439 meters or 8 feet from the highest point and when the line passes adjacent to the building horizontal clearance of 1.219 meter or 4 feet from the nearest point.

**Rule No.80**

Clearance from buildings or high and extra high voltage line is around 3.658 meter or 12 feet and plus 1 foot for every additional 33 KV.

**Rule No.89**

No service line or trapping shall we taken of from on over head lines, except at the point of support.

**Introduction to Domestic Wiring**

- A building whether used as a home, as a godown, as a factory, as a cafeteria, as a hotel, as a research laboratory or as an educational institute, needs electrical installations.
- Electrical power is required to run various appliances, equipment and machinery.

**Domestic Wiring Definitions**

Wiring is systematic laying of wires for the smooth flowing of electricity current at different

utility places with utmost safety and precautions.

- Electrical wiring done in residential and commercial buildings to provide power for lights,

fans, pumps and other domestic appliances is known as domestic wiring.

**Single line diagram of Transmission and Distribution System**

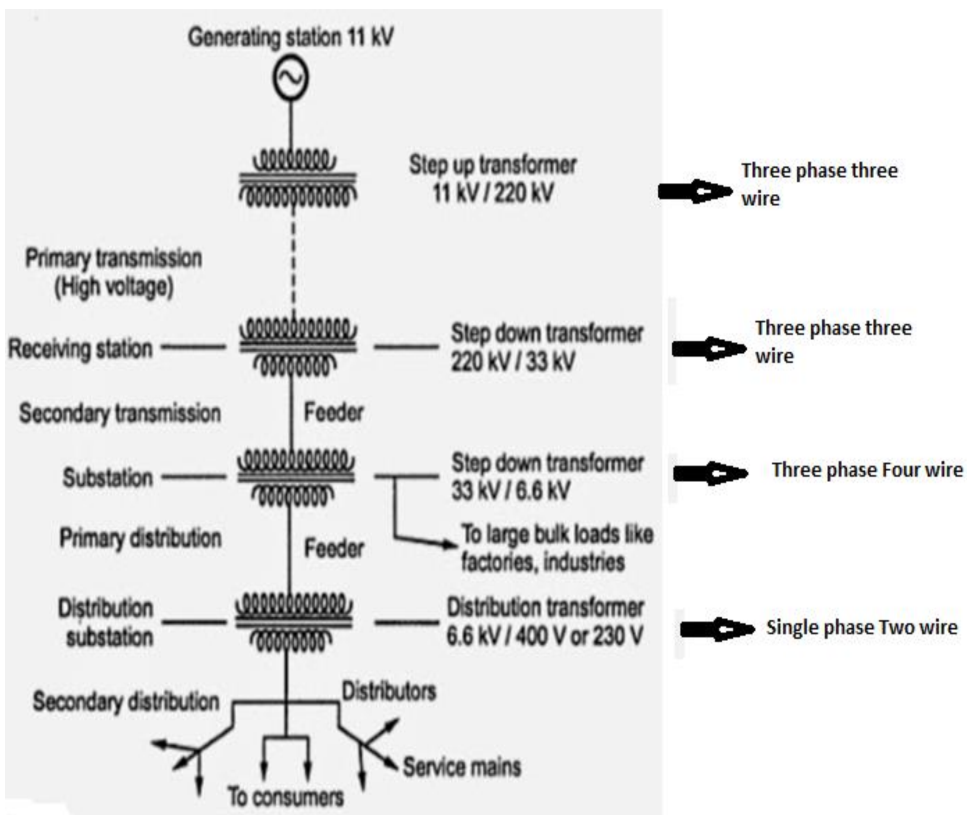



**Fig 1.1 Single line Diagram of Power system network**

**Distribution of electrical power to consumers**

1. Single phase two wire
2. Three phase three wire
3. Three phase four wire

**1. Single phase Two Wire (Domestic Wiring)**

For Domestic consumers, the most commonly used system is single phase 2 wire system. It is derived from a 400V, 3 phase 4 wire system. Group of consumers are connected between one phase line conductor and neutral conductor, thus providing 230V, 50Hz, single phase supply.

**2. Three phase Four wire ( Industrial wiring)**

For large industrial consumers, having heavy motor load and drawing more than 1 MVA, the power is supplied from a three phase system at high voltage, such as 6.6kV,11kV or 33kV. The consumer has its own substation to distribute power at appropriate voltages at different location within its premises.

**3. Three Phase Three Wire (Transmission wiring)**

This system used for transmitting power to receiving and substation. This system used as primary or as secondary transmission system. This system does not require neutral wire , hence saves material cost and less power loss.

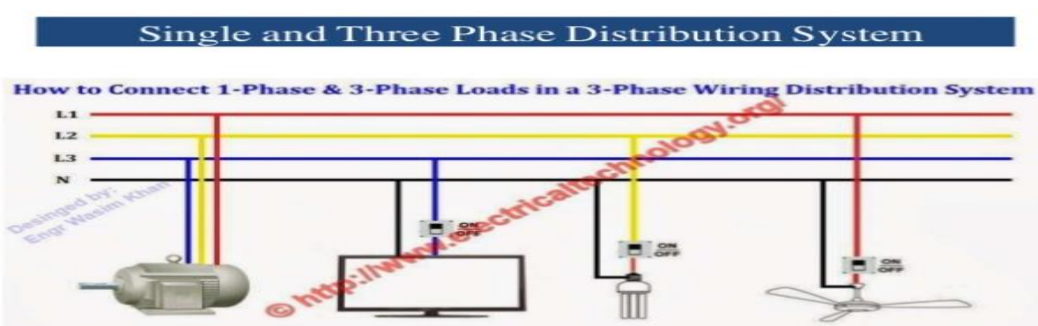



**Fig 1.2 Distribution system**

## Wiring materials and Accessories

### Wiring materials

Electrical wire is made of materials like copper, aluminium and silver. As silver is expensive, mostly copper and aluminium are used in wiring. Materials are classified into three types according to their properties:

- 1. Conducting materials
- 2. Insulating materials

### Conducting Material

**(a) Copper**

- Copper It is a good conductor of electricity.
- It is used in wiring materials in cables.
- Its has low resistance and is used for conduction of electricity at high, medium and low voltage.
- It is used in wiring and cable making.

**(b) Aluminium**

- It is light weight and cheaper in comparison to copper.
- Therefore, this type of conducting material is mostly used in electrical wiring.
- It is silvery–white in colour and it has a soft texture. It is often used in wiring and making cable .

**Insulating Materials**

- Insulating materials are used for insulating purpose.
- These types of materials are bad conductors of current.
- For example rubber, paper, mica, wood, glass and cotton.

**Wiring Accessories**

**(a) Switch**

A switch is used to make or break an electrical circuit. It is used to switch 'on' or 'off ' the supply of electricity to an appliance. There are various switches such as

- surface switch
- flush switch
- ceiling switch
- pull switch
- push button switch
- bed switch

**Surface switch:**

It is mounted on wooden boards fixed on the surface of a wall.

It is of three types

1. One-way switch

2. Two-way switch

3. Intermediate switch

**One-way switch:** It is used to control single circuits and lamp

*One-way switch*

**Two-way switch**: It is used to divert the flow of current to either of two directions. The two-way switch can also be used to control one lamp from two different places as in the case of staircase wiring.

*Two-way switch*

**Intermediate switch:** It is used to control a lamp from more than two locations

*Intermediate switch*

**(i) Flush switch:** It used for decorative purpose .

**(ii) Bed switch:** As the name indicates, it is used to switch 'on' the light from any place, other than switch board or from near the bed. This switch is connected through a flexible wire

Bed switch

Flush Switch

**(b) Holders**

It is used to hold the lamp required for lighting purpose. Normally available with Bakelite exterior and porcelain interior or Brass exterior with porcelain interior.

**Types**

1. Pendant holder
2. Batten holder

Pendant holder

Batten holder

**(c) Ceiling rose**

It is used to provide a tapping to the pendant lamp– holder through the flexible wire or a connection to a fluorescent tube

**(d) Socket Outlet**

The socket outlet has an insulated base with the moulded or socket base having three terminal sleeves

**(e) Plug**

Used for tapping power from socket outlets.

Available as two or three pin plugs

**(f) Main switch**

To control the electrical circuit a main switch is used. Through the main switch, the power in a building is controlled completely.

Ceiling rose

Socket

Main switch/
Main MCB

**(g) PVC casing-capping wiring**

PVC capping is done in order to cover the wires. It includes casing also.

This casing-capping wiring is also known as open wiring, as it is done outside the wall.

**(h) Fuses**

Safety device

Used to isolate the circuit in the event of any overload or fault.

Fuse base is porcelain and fuse wire is made up of copper or tin or lead.

**(i) Cables**

It consists of a conductor made of copper or aluminium surrounded by insulation and a sheath.

Cables used for domestic wiring

- Vulcanised Indian Rubber
- Poly Vinyl Chloride
- Tough Rubber Sheathed
- Cab Tyre Sheather
- Lead Sheathed
- Weather Proof

**(j) Junction Box**

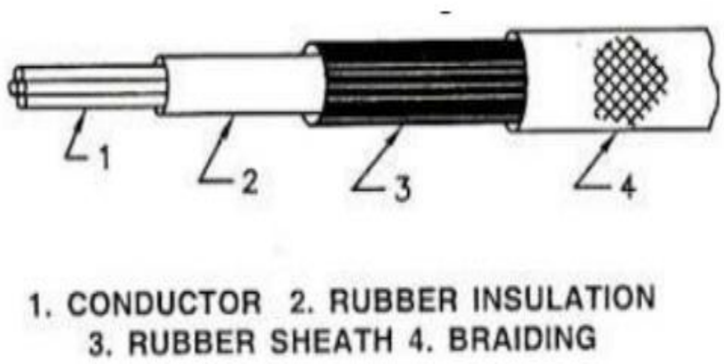
Used to join some conductors and provide different paths for different conductors.

**Types of Wires used for domestic wiring**

a) C.T.S (Cabe Tyre Sheath) wires
b) VIR ( Vulcanized India Rubber ) wires
c) PVC (Polyvinyl chloride) wires
d) Lead alloy sheathed wires
e) Flexible wires
f) Weather proof wires

**C.T.S (cabe tyre sheath) wires**

- It consists of ordinary rubber coated conductors with an additional tough rubber .
- These conductors are covered by red and black color rubber.
- It is then coated with a layer of hard rubber.
- It is available in sizes 1/18, 3/20, 7/22 etc.
- It does not absorb moisture.
- It is used in batten wiring service lines and short distance overhead lines.
- It is available in 250/440 voltage grade only.

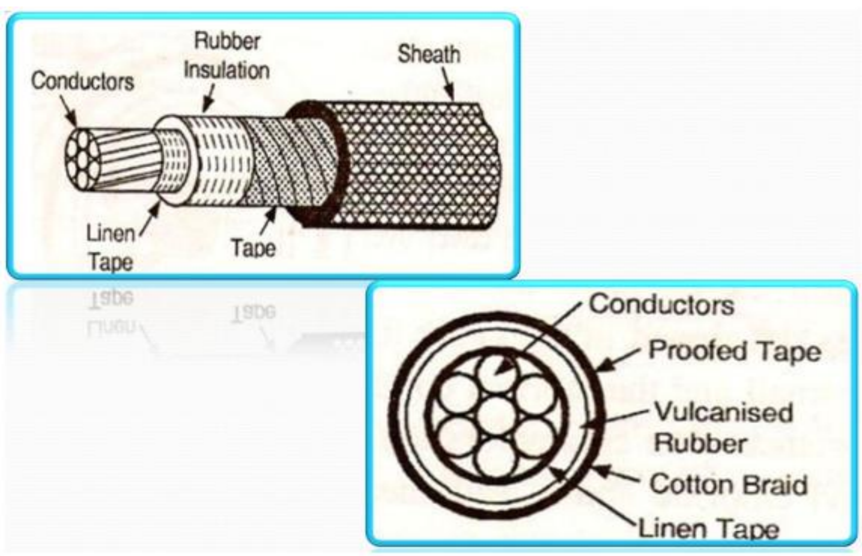



**VIR ( Vulcanized India Rubber ) wires**

- A VIR wire mainly consists of a tinned conductor having rubber coating .Tinning of conductor

prevents the sticking of rubber to the conductor and also avoid corrosion.

- Cotton bradding is done over rubber insulation protect against moisture.
- It is available in 1/18, 3/20, 3/22, 7/20, 7/22, 7/16, 19/22, 19/16 sizes.
- It is suitable for indoor conduct wiring, casing capping wiring and cleat wiring.



**PVC (Polyvinyl chloride) wires**

- PVC insulation is normally used for household wiring.
- Previously for household purposes, rubber insulated wires are used but it was replaced by
  PVC insulation.
- PVC wires are easier to process and they are much more cost-effective.
- They have a much longer life.
- PVC insulation is highly used in the cable industry while manufacturing wires and cables.
- Because of its resistance to fire and ease of use these wires have been most widely used for
  cable production.
- It is available in sizes 1 $mm^2$, 1.5 $mm^2$, 2.5 $mm^2$ , 4 $mm^2$. 0.75 $mm^2$, copper wire
- It is available in 600, 660, 1100 Voltage grade.

**Lead sheathed wires**

- Lead covered cables are used in places exposed to sun and rain.
- Advantage:
  - Long life time
  - Prevents from mechanical injury
  - Prevents from entry of moisture and other gases
- Disadvantage:
  - Costly
  - Not suitable where alkalies, acids or fumes

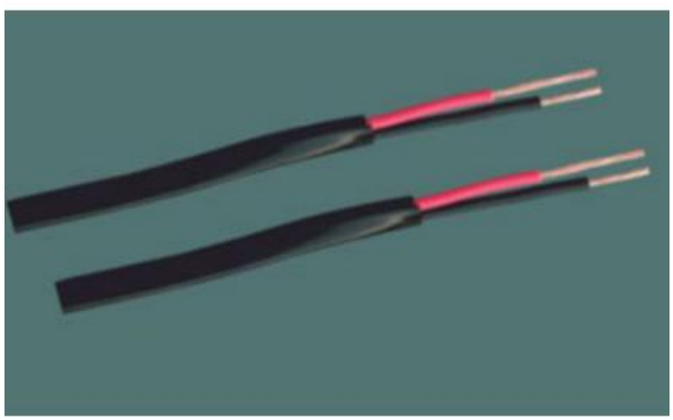
are present

**Flexible wires**

- Flexible wires are very useful for household portable Appliances where flexibility of wire is more important.
- These wire consists of number of strands instead of a single conductor .
- The conductor is insulated with PVC material.

**Weather proof wires**

- It is made of waterproof by drooping it into water -proof compound.
- These sorts of wires are used outdoors.



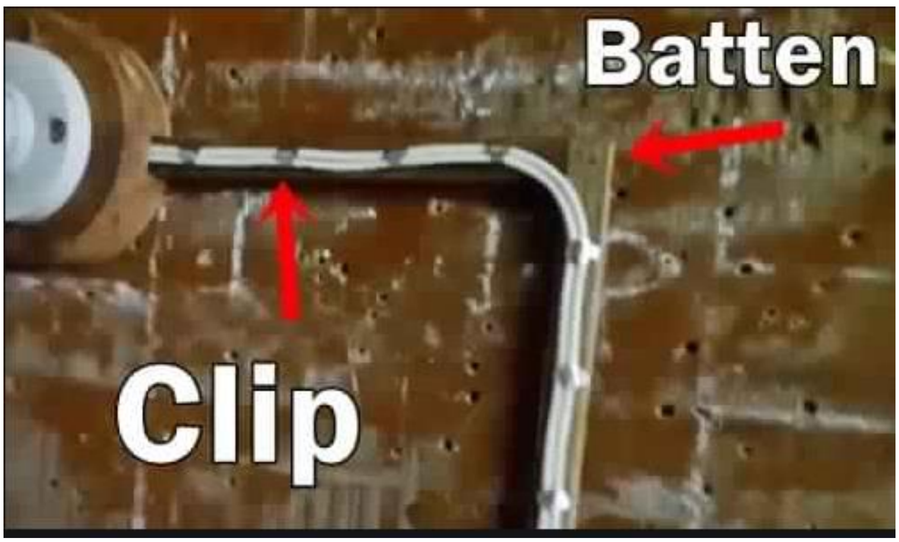
**Types of Wiring**

- Cleat Wiring
- Batten Wiring
- Casing- caping wiring
- Conduit wiring

- **Cleat wiring**
  - VIR conductors are supported in porcelain cleats.
  - Procelain cleats are spaced every 60cm .
  - VIR or PVC insulated wires are used as conductors
  - This wiring is suitable for temporary installation where cost in the main criteria but not the  ppearance.
  - Advantage – Faults can be identified easily
  - Disadvantage-
    - maintaintance cost is high,
    - lot of dust may collect over the wire,
    - no protection from mechanical injury, fire or gas.

**Batten Wiring**

- ✓ These wiring are not suitable for outdoor ,they can be use for Damp climate
- ✓ In this wiring system ,wire sheathed in tough rubber are used which are quite flexible .They are clipped on wooden battens With Brass clips(link or joint )are fixed on to walls or ceilings by flat head screws.
- ✓ The sheath is earthed at each junction to provide a path to ground for leakage current.
- ✓ The cables are moisture and chemical proof.




**Wooden casing- capping wiring**

- – Used for residential buildings
- – Consists of rectangular wooden blocks called casing, made from first class seasoned teak wood or any other wood free from any defect.
- – Has two grooves into which the wires are laid.
- – Casing at the top is covered by means of capping which is rectangular strip of wood of the same width as that of casing and is screwed to it.
- – Advantage:
    - Sufficient mechanical protection is given to the cable.
- – Disadvantage:
    - High cost

- More risk of fire
- Difficult to identify the faults.



**Conduit wiring**

- VIR conductors run in metallic tubes are called conduit wiring.
  - **Surface Conduit**
    - Wiring system with conduit on the surface of the wall
    - In this wiring method, they make holes on the surface of wall on equal distances and conduit is installed then with the help of plugs
  - **Concealed conduit**
    - Layout of the wiring done under the plaster of the wall of the building
    - It is the most popular, beautiful, stronger and common electrical wiring system nowadays.


•

Advantages of concealed wiring

- Safe y Better appearance
- No risk of fire
- No risk of damage of cable insulation
- Safe from humidity, smoke, steam, etc.
- No risk

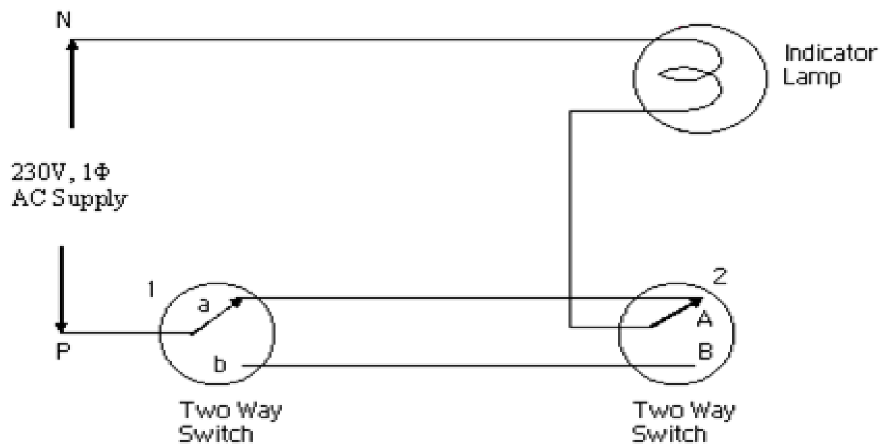
Disadvantages of concealed wiring

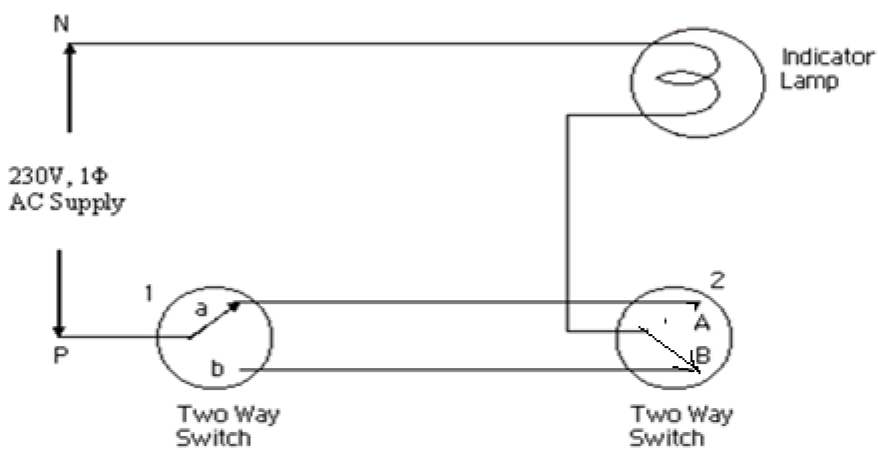
- Expensive
- Installation not easy
- Not easily customisable for future use
- Hard to detect faults of shock

**Staircase Wiring**

- Staircase wiring is a common multi-way switching or two-way light switching connection;
- one light two switches wiring.
- Here one lamp is controlled by two switches from two different positions.
- That is to operate the load from separate positions such as above or below the staircase, from inside or outside of a room, or as a two-way bed switch, etc

**CIRCUIT DIAGRAM:**



| POSITION OF SWITCHES | | LAMP CONDITION |
|---|---|---|
| S1 | S2 | |
| a | B | OFF |
| b | B | ON |
| b | A | OFF |
| a | A | ON |

- 

## Fluorescent Tubes

Works on the principle of low pressure mercury vapour discharge phenomena

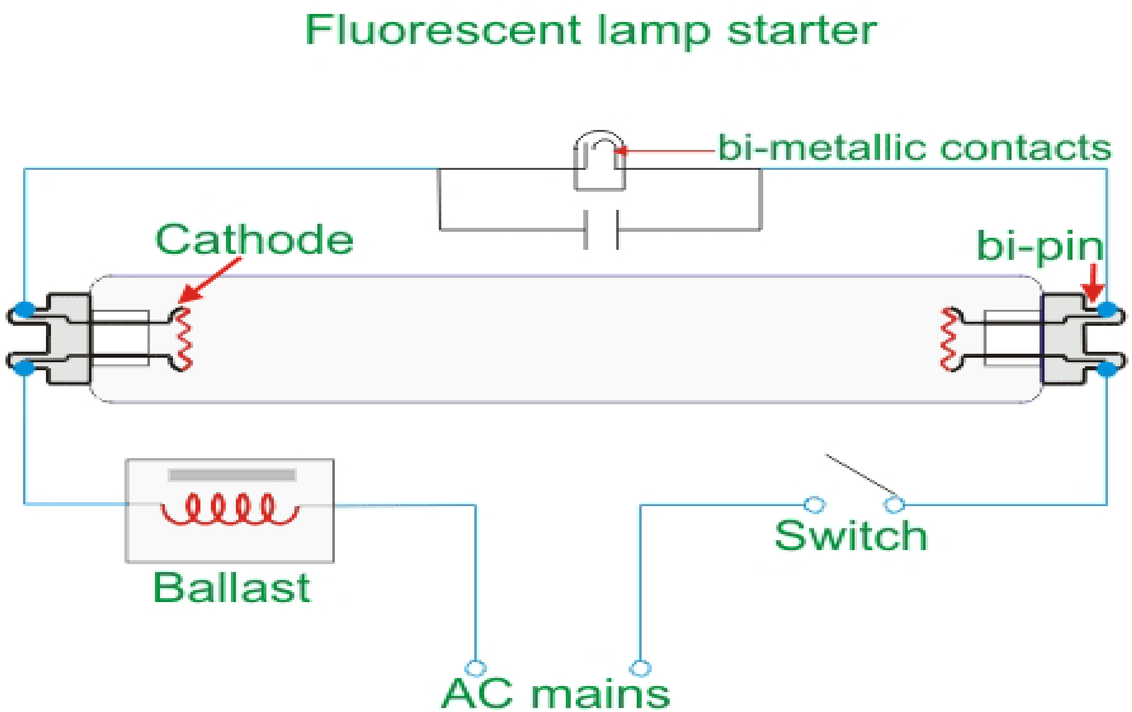
Converts ultra violet rays into visible rays with the help of phosphor coated on the glass tube.

### Inner Parts

- Filament
- Phosphor coated tubes ( When mercury vapour discharge takes place, the UV rays is converted in to Visible rays with the help of phosphor coating)
- Mercury vapour + Inert gas (Argon)

### Outer Parts

- Choke or Ballast
- Starter (Fixed contact,Bimetallic strip, capacitor)




- When we switch ON the supply, full voltage comes across the lamp and as well as across the starter through the ballast. But at that instant, no discharge happens, i.e., no lumen output from the lamp.
- At that full voltage first the glow discharge is established in the starter. This is because the electrodes gap in the neon bulb of starter is much lesser than that of the fluorescent lamp.
- Then gas inside the starter gets ionized due to this full voltage and heats the bimetallic strip. That causes to bend the bimetallic strip to connect to the fixed contact. Now, current starts flowing through the starter. Although the ionization potential of the neon is more than that of the argon but still due to small electrode gap, a high voltage gradient appears in the neon bulb and hence glow discharge gets started first in the starter.
- As soon as the current starts flowing through the touched contacts of the neon bulb of the starter, the voltage across the neon bulb gets reduced since the current, causes a voltage drop across the inductor(ballast). At reduced or no voltage across the neon

bulb of the starter, there will be no more gas discharge taking place and hence the bimetallic strip gets cool and breaks away from the fixed contact. At the time of breaking of the contacts in the neon bulb of the starter, the current gets interrupted, and hence at that moment, a large voltage surge comes across the inductor(ballast).

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

$$Where,\ L\ is\ inductance\ of\ inductor$$

$$and\ \frac{di}{dt}\ is\ rate\ of\ change\ of\ current.$$

- This high valued surge voltage comes across the fluorescent lamp (tube light) electrodes and strikes penning mixture (mixture argon gas and mercury vapor).
- Gas discharge process gets started and continues and hence current again gets a path to flow through the fluorescent lamp tube (tube light) itself. During discharging of penning gas mixture the resistance offered by the gas is lower than the resistance of starter.
- The discharge of mercury atoms produces ultraviolet radiation which in turn excites the phosphor powder coating to radiate visible light.

Starter gets inactive during glowing of fluorescent lamp (tube light) because no current passes through the starter in that condition

## EARTHING

Earthing is the Process of connecting metallic bodies of all the electrical apparatus and equipment to the earth by a wire having negligible resistance.

The process of transferring the immediate discharge of the electrical energy directly to the earth by the help of the low resistance wire is known as the electrical earthing.

copper wires are generally used as earthing lead, copper strips are preferred for high installation as it can carry higher values of fault current due to its wider area.

The earthing is essential because of the following reasons

- ✓ The earthing protects the personnel from the short circuit current.
- ✓ The earthing provides the easiest path to the flow of short circuit current even after the failure of the insulation.
- ✓ The earthing protects the apparatus and personnel from the high voltage surges and lightning discharge.

TYPES OF EARTHING

1. Plate Earthing
2. Pipe Earthing
3. Rod Earthing
4. Wire Earthing

Pipe Earthing and Plate Earthing are considered to be the best as they have low value of Earth resistance.

PIPE EARTHING

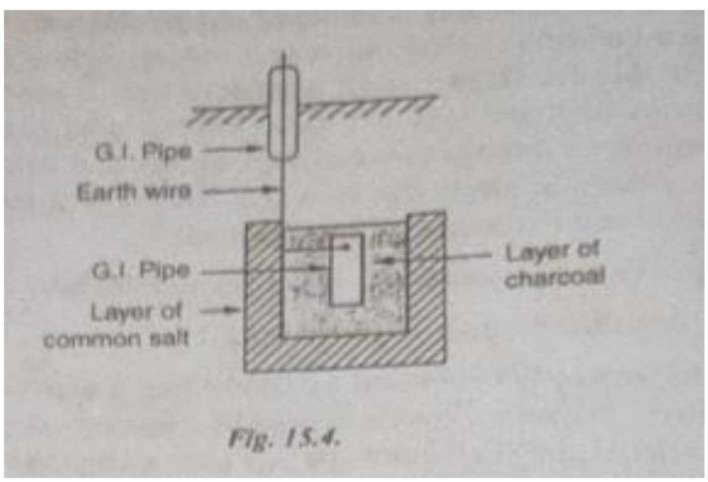



Figure 1.3 Pipe Earthing

A galvanized steel pipe of approved length and diameter is placed vertically in a wet soil in this kind of system of earthing. It is the most common system of earthing.

The dimension of the pipe is usually 40mm (1.5in) in diameter and 2.75m (9ft) in length for ordinary soil or greater for dry and rocky soil. The moisture of the soil will determine the length of the pipe to be buried but usually it should be 4.75m (15.5ft).

Alternate layers of Charcoal Powder and salt are arranged 15cm around the pipe . The Charcoal Powder and salt decrease the earth resistance. They increase the dampness and moisture.

Earth Pipe is covered with cement concrete for protection from Mechanical damage.

PLATE EARTHING

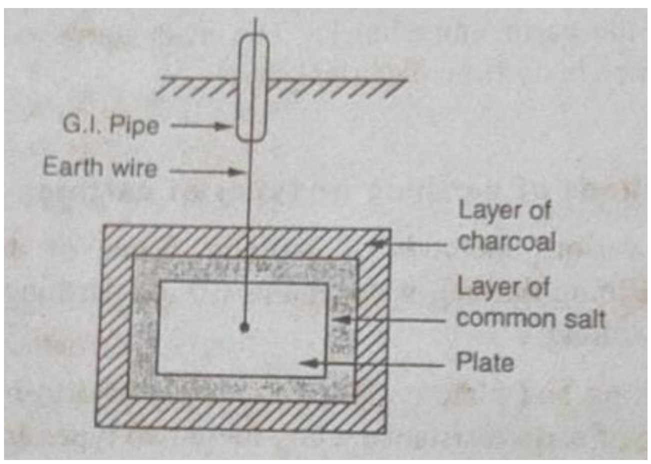



Figure 1.4 Plate Earthing

In this method of Earthing, earth plate is provided at the bottom of the earth rod in addition to the arrangement done in pipe earthing.

In plate earthing system, a plate made up of copper with dimensions 60cm x 60cm x 3.18mm (i.e. 2ft x 2ft x 1/8 in) or galvanized iron (GI) of dimensions 60cm x 60cm x 6.35 mm (2ft x 2ft x ¼ in) is buried vertical in the earth (earth pit) which should not be less than 3m (10ft) from the ground level.

Charcoal Layers are placed immediately after the plate.

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# UNIT - II

# Electrical Technology – SEEA1102

# II. MAGNETIC CIRCUITS

Definition of MMF, Flux and Reluctance - Leakage Factor - Reluctances in Series and Parallel (Series and Parallel Magnetic Circuits) - Electromagnetic Induction - Fleming's Rule - Lenz's Law - Faraday's laws - statically and dynamically induced EMF - Self and mutual inductance - Analogy of Electric and Magnetic Circuits.

## Definition of MMF, Flux and Reluctance - Leakage Factor

### Magneto motive force(MMF)

Magnetomotive force, also known as magnetic potential, is the property of certain substances or phenomena that gives rise to magnetic fields. Magnetomotive force is analogous

to electromotive force or voltage in electricity .The standard unit of magnetomotive force is the ampere-turn (AT), represented by a steady, direct electrical current of one ampere (1A) flowing in a single-turn loop of electrically conducting material in a vacuum .

$$\text{Magnetomotive force (mmf )}F = NI(\text{ampere} - \text{turns})$$

Sometimes a unit called the gilbert (G) is used to quantify magnetomotive force. The gilbert is defined differently, and is a slightly smaller unit than the ampere-turn. To convert from ampere-turns to gilberts, multiply by 1.25664. Conversely, multiply by 0.795773.

### Flux

**Magnetic flux** (most often denoted as $\Phi_m$), is the amount of **magnetic field** (also called "**magnetic flux**density") passing through a surface (such as a conducting coil). The SI unit of **magnetic flux** is the weber (Wb) (in derived units: volt-seconds). The CGS unit is the maxwell.

### Reluctance

**Magnetic reluctance**, or **magnetic resistance**, is a concept used in the analysis of magnetic circuits. It is analogous to resistance in an electrical circuit, but rather than dissipating electric energy it stores magnetic energy. In likeness to the way an electric field causes an electric current to follow the path of least resistance, a magnetic field causes magnetic flux to follow the path of least magnetic reluctance. It is a scalar, extensive quantity, akin to electrical resistance.

The unit for magnetic reluctance is inverse henry, $H^{-1}$.Reluctance depends on the dimensions of the core as well as its materials.

Reluctance =l/μA.(A-t/Wb)

**Leakage flux**

The total magnetic flux in an electric rotating machine or transformer divided by the useful flux that passes through the armature or secondary winding. Also known as leakage coefficient.

There are three categories of magnetic materials: *diamagnetic*, in which the material tends to exclude magnetic fields; *paramagnetic*, in which the material is slightly magnetized by a magnetic field; and *ferromagnetic*, which are materials that very easily become magnetized. The vast majority of materials do not respond to magnetic fields, and their permeability is very close to that of free space. The materials that readily accept magnetic flux—that is, ferromagnetic materials—are principally iron, cobalt, and nickel and various alloys that include these elements. The units of permeability are webers per amp-turn-meter (Wb/A-t-m).

The permeability of free space is given by

$$\text{Permeability of free space } \mu_0 = 4\pi \times 10{-}7 \text{ Wb/A-t-m}$$

Oftentimes, materials are characterized by their *relative permeability*, $\mu_r$, which for ferromagnetic materials may be in the range of hundreds to hundreds of thousands. As will be noted later, however, the relative permeability is not a constant for a given material: It varies with the magnetic field intensity. In this regard, the magnetic analogy deviates from its electrical counterpart and so must be used with some caution.

$$\text{Relative permeability} = \mu_r = \mu\mu_0$$

**Magnetic flux density**

Another important quantity of interest in magnetic circuits is the magnetic flux *density*, *B*. As the name suggests, it is simply the "density" of flux .Unit is Tesla.

Magnetic flux density $B = \varphi/A$ webers/$m^2$ or tesla (T)

**Magnetic field intensity**

The magnetic field intensity is defined as the magnetomotive force (mmf) per unit of length around the magnetic loop. With *N* turns of wire carrying current i, the mmf created in the circuit is *Ni* ampere-turns. With *l* representing the mean path length for the magnetic flux, the magnetic field intensity is therefore

Magnetic field intensity H =NI/L ampere-turns/meter

We arrive at the following relationship between magnetic flux density *B* and magnetic field intensity as B = μH

**Problems**:

1.Given a copper core with: Susceptibility as $-9.7*10^6$ ,Length of core L = 1 m, Gap length g = .01 m, Cross sectional area A = .1 m, Current I = 10A,N = 5 turns. Find: $B_g$

$\mu = \mu_0(1+\chi_m)$ , Now using the length, cross sectional area, and permeability of the core we can solve for reluctance $R_c$ by:

$$R_c = \frac{L}{\mu A} = \frac{1}{1.2566 \times 10^{-6} \times .1} = 7.96 \times 10^6$$

Similarly, to get the reluctance of the gap

$$R_g = \frac{g}{\mu_0(\sqrt{A}+g)^2} = \frac{.01}{4 \times \pi \times 10^{-7}(\sqrt{.1}+.01)^2} = 74.8 \times 10^3$$

Now recall the equation for the magnetic field of a gap as seen in

$$B_g = \frac{NI}{(R_g R_c)((\sqrt{A}+g)^2}$$

$$B_g = \frac{5 \times 10}{74.8 \times 10^3 \times 7.96 \times 10^6 \times (\sqrt{.1}+.01)^2} = .789 \times 10^{-9}$$

2.A coils of 200 turns is wound uniformly over a wooden ring having a mean circumference of 600 mm and a uniform cross sectional area of 500 mm2 . If the current through the coil is 4 A, calculate: (a) the magnetic field strength, (b) the flux density, and (c) the total flux

Answer: 1333 A/m, 1675×10-6 T, 0.8375 mWb

3.A mild steel ring having a cross sectional area of 500 m2 and a mean circumference of 400 mm has a coil of 200 turns wound uniformly around it. Calculate: (a) the reluctance of the ring and (b) the current required to produce a flux of 800 mWb in the ring. (Given that mr is about 380).

Answer: 1.677×106 A/Wb, 6.7 A.

**Reluctance in Series (Composite Magnetic Circuit)**

A magnetic circuit having a number of parts of different magnetic materials and different dimensions carrying the same magnetic field is called a Series Magnetic Circuit. It is also known as Composite Magnetic Circuit. One such circuit is shown in figure.

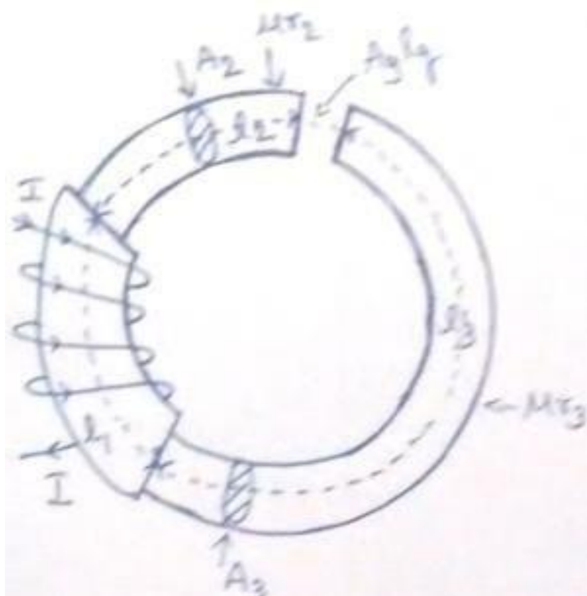



Figure2.1 Reluctance in series

It consist of 3 different magnetic material and one air gap . Since materials are different the permeability are different. Assume that the length and the areas of cross-section are also different . Then the reluctance of each path will be different.

As the reluctance are in series, the total reluctance is the sum of the reluctance of different paths.

Total reluctance = $S = S_1 + S_2 + S_3 + S_g$ Total

mmf = flux x reluctance

$$= \text{Ø} \times S = \text{Ø} \,(l_1/\mu_0\mu_{r1}A_1 + l_2/\mu_0\mu_{r2}A_2 + l_3/\mu_0\mu_{r3}A_3 + l_g/\mu_0A_g)$$

$$= l_1 \text{Ø} / A_1\mu_0\mu_{r1} + l_2 \text{Ø} / A_2\mu_0\mu_{r2} + l_3 \text{Ø} / A_3\mu_0\mu_{r3} + l_g \text{Ø} / A_g\mu_0$$

$$= l_1B_1/\mu_0\mu_{r1} + l_2 B_2/\mu_0\mu_{r2} + l_3 B_3/\mu_0\mu_{r3} + l_g$$

$B_g/\mu_0$ Total mmf = $H_1l_1 + H_2l_2 + H_3l_3 + H_gl_g$

Note: The following formulae are used in the above expression

1. Ø / A = B
2. $B/\mu_0\mu_r = H$

**Reluctance in Parallel ( Parallel Magnetic Circuits)**

If a magnetic circuit has 2 or more paths for the magnetic flux, it is called a parallel magnetic flux.

$L_2$

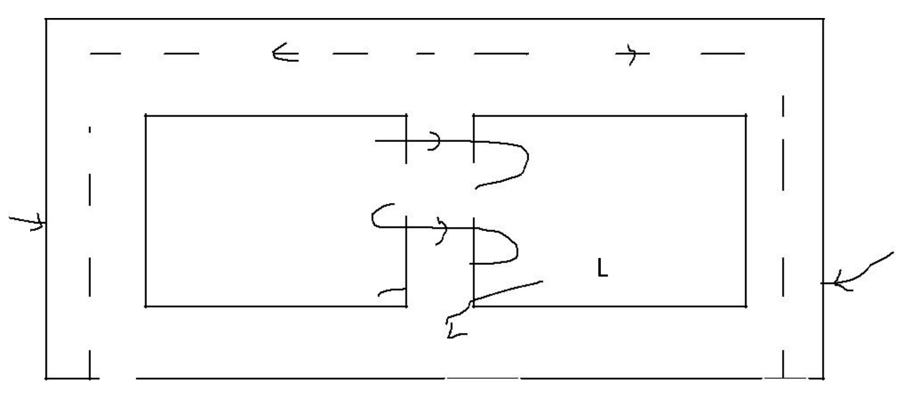



Figure 2.2 Reluctance in Parallel

On the central limb AB, a current carrying coil ia wound. The mmf in the coil sets up a magnetic flux Ø 1 in the central limb. It is further divided in to 2 paths. They are

1. The path ADCB which carries flux $\phi_2$ and
2. The path AFEB which carries flux $\phi_3$

These 2 path are in parallel. The ampere turns (mmf) for this circuit is equal to the ampere turns required for any one of these paths.

$$Ø_1 = Ø_2 + Ø_3$$

Reluctance of path BA = $S_1 = l_1/\mu_0\mu_{r1}A_1$

Reluctance of path ADCB = $S_2$ =

$l_2/\mu_0\mu_{r2}A_2$ Reluctance of path AFEB = $S_3$

= $l_3/\mu_0\mu_{r3}A_3$

Mmf required for path ADCB = $Ø_2 \times S_2$

Mmf required for path AFEB = $Ø_3 \times S_3$

Mmf for parallel path = $Ø_2 \times S_2 = Ø_3 \times S_3$
Mmf required for path BA = $Ø_1 \times S_1$

Total mmf required = mmf for path BA + mmf required for path ADCB or path

AFEB Total mmf (or) AT = $Ø_1 \times S_1 + Ø_2 \times S_2 = Ø_1 \times S_1 + Ø_3 \times S_3$

**Analogy of Electrical and Magnetic Circuits**

| S.No. | Magnetic Circuit | Electric Circuit |
|---|---|---|
| 1. | Magnetic Flux, ϕ webers | Electric current, I amperes |
| 2. | Magnetomotive force, NI | Electromotive force, V Volts |
| 3. | Reluctance, S AT/Wb | Resistance, R Ohms |
| 4. | Ø = NI/s | I = V/R |
| 5. | $S = l/ \mu_0\mu_r 2A$ | $R = \rho l/A$ |
| 6. | Magnetic Intensity H = NI/I AT/m | Electric Intensity, E = V/d Volts/m |
| 7. | Magnetic Flux Density, B $Wb/m^2$ | Current Density, J $A/m^2$ |
| 8. | Permeability $\mu = \mu_0\mu_r$ | Permitivity $\epsilon = \varepsilon_0\ \varepsilon_r$ |
| 9. | Magnetic flux does not flow. It only links with the coil. | Electric current flows through the coil. |
| 10. | Energy is required only for creating the magnetic flux, not for maintaining it. | Current flow involves continuous requirement for energy. |
| 11. | The reluctance varies with flux density. | The resistance remains practically constant with the current strength. |

**Worked Example**

1. Find the ampere turns required to produce a flux of 0.4 milliweber in the airgap of a circular magnetic circuit which has an airgap of 0.5mm. The iron ring has 4sq.cm cross section and 63cm mean length. The relative permeability of iron is 1800 and the leakage co-efficient is 1.15

**Sol.** Given Data:

Flux in the airgap = Øg= Øuseful= o.4 weber

Length of airgap lg = .5mm

Cross-section of the iron ring A = $4x10^{-4}m^2$ Mean length of iron ring = l = 63 cm

Relative permeability of iron = 1800

Leakage co-efficient λ = 1.15

This magnetic circuit has two materials airgap and iron Total mmf = mmf in airgap + mmf in iron

Flux = mmf/reluctance

Mmf = flux x reluctance

a) For airgap: mmf = Øuseful x $S_g$

$= 0.4x10^{-4}$ x $(lg/\mu_0 A)$

$= 0.4x10^{-4} ((0.5x10^{-3})/(4\pi x10^{-7}x4x10^{-4}))$

= 397.88 AT

b) For iron path flux = Øi = λ x Øuseful

$= 1.15 \times 0.4 \times 10^{-3}$

$= 0.46 \times 10^{-3}$ wb

Reluctance, Si = $(l/(\mu_0 \mu_r A))$

$= 0.63/(4\pi \times 10^{-7} \times 1800 \times 4 \times 10^{-4})$

$= 696302.876$ AT/Wb

Mmf = $Ø_i \times S_i$

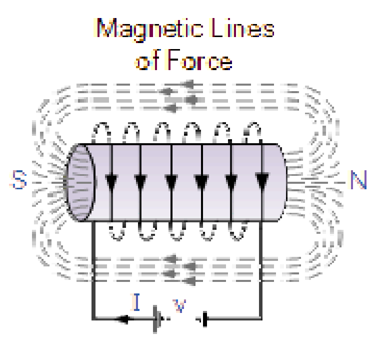
$= 0.46 \times 10^{-3} \times 696302.876$

$= 320.29$AT

Total ampere turns required : 397.88+320.29 = 718 AT

**Electromagnetic Induction**

We have seen previously that when a DC current pass through a long straight conductor a magnetising force, H and a static magnetic field, B is developed around the wire. If the wire is then wound into a coil, the magnetic field is greatly intensified producing a static magnetic field around itself forming the shape of a bar magnet giving a distinct North and South pole.




**Air-core Hollow Coil**

The magnetic flux developed around the coil being proportional to the amount of current flowing in the coils windings as shown. If additional layers of wire are wound upon the same coil with the same current flowing through them, the static magnetic field strength would be increased.

Therefore, the Magnetic Field Strength of a coil is determined by the *ampere turns* of the coil. With more turns of wire within the coil, the greater the strength of the static magnetic field around it.

But what if we reversed this idea by disconnecting the electrical current from the coil and instead of a hollow core we placed a bar magnet inside the core of the coil of wire. By moving this bar magnet "in" and "out" of the coil a current would be induced into the coil by the physical movement of the magnetic flux inside it.

Likewise, if we kept the bar magnet stationary and moved the coil back and forth within the magnetic field an electric current would be induced in the coil. Then by either moving the wire or changing the magnetic field we can induce a voltage and current within the coil and this process is known as **Electromagnetic Induction** and is the basic principal of operation of transformers, motors and generators.

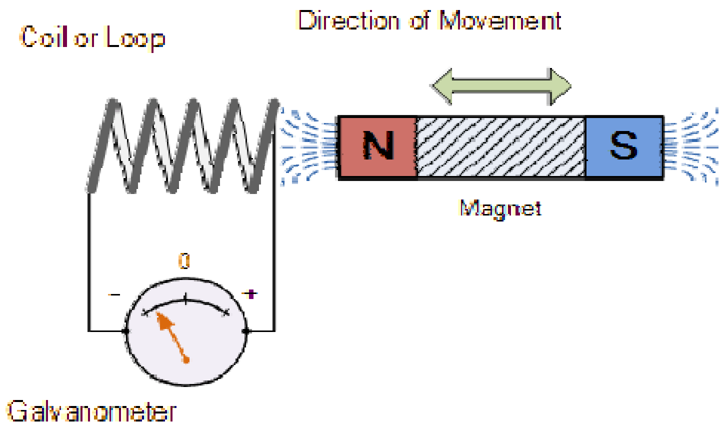
**Electromagnetic Induction** was first discovered way back in the 1830's by **Michael Faraday**. Faraday noticed that when he moved a permanent magnet in and out of a coil or a single loop of wire it induced an ElectroMotive Force or emf, in other words a Voltage, and therefore a current was produced.

So what Michael Faraday discovered was a way of producing an electrical current in a circuit by using only the force of a magnetic field and not batteries. This then lead to a very important law linking electricity with magnetism, **Faraday's Law of Electromagnetic Induction**. So how does this work?

When the magnet shown below is moved "towards" the coil, the pointer or needle of the Galvanometer, which is basically a very sensitive centre zero'ed moving-coil ammeter, will deflect away from its centre position in one direction only. When the magnet stops moving and is held stationary with regards to the coil the needle of the galvanometer returns back to zero as there is no physical movement of the magnetic field.

Likewise, when the magnet is moved "away" from the coil in the other direction, the needle of the galvanometer deflects in the opposite direction with regards to the first indicating a change in polarity. Then by moving the magnet back and forth towards the coil the needle of the galvanometer will deflect left or right, positive or negative, relative to the directional motion of the magnet.

**Electromagnetic Induction by a Moving Magnet**




Likewise, if the magnet is now held stationary and ONLY the coil is moved towards or away from the magnet the needle of the galvanometer will also deflect in either direction. Then the action of moving a coil or loop of wire through a magnetic field induces a voltage in the coil with the magnitude of this induced voltage being proportional to the speed or velocity of the movement.

Then we can see that the faster the movement of the magnetic field the greater will be the induced emf or voltage in the coil, so for Faraday's law to hold true there must be "relative motion" or movement between the coil and the magnetic field and either the magnetic field, the coil or both can move.

**Faraday's Law of Induction**

From the above description we can say that a relationship exists between an electrical voltage and a changing magnetic field to which Michael Faraday's famous law of electromagnetic induction states: "that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux".

In other words, **Electromagnetic Induction** is the process of using magnetic fields to produce voltage, and in a closed circuit, a current.

So how much voltage (emf) can be induced into the coil using just magnetism. Well this is determined by the following 3 different factors.

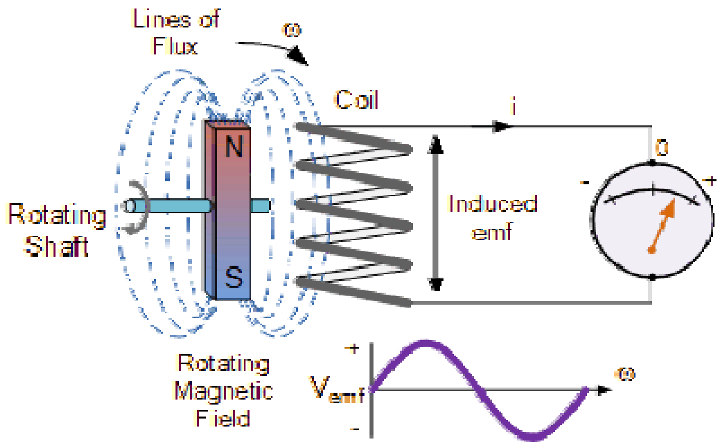
- 1). Increasing the number of turns of wire in the coil. – By increasing the amount of individual conductors cutting through the magnetic field, the amount of induced emf produced will be the sum of all the individual loops of the coil, so if there are 20 turns in the coil there will be 20 times more induced emf than in one piece of wire.
- 2). Increasing the speed of the relative motion between the coil and the magnet. – If the same coil of wire passed through the same magnetic field but its speed or velocity is increased, the wire will cut the lines of flux at a faster rate so more induced emf would be produced.
- 3). Increasing the strength of the magnetic field. – If the same coil of wire is moved at the same speed through a stronger magnetic field, there will be more emf produced because there are more lines of force to cut.

If we were able to move the magnet in the diagram above in and out of the coil at a constant

speed and distance without stopping we would generate a continuously induced voltage that would alternate between one positive polarity and a negative polarity producing an alternating or AC output voltage and this is the basic principal of how a **Generator** works similar to those used in dynamos and car alternators.

In small generators such as a bicycle dynamo, a small permanent magnet is rotated by the action of the bicycle wheel inside a fixed coil. Alternatively, an electromagnet powered by a fixed DC voltage can be made to rotate inside a fixed coil, such as in large power generators producing in both cases an alternating current.

**Simple Generator using Magnetic Induction**




The simple dynamo type generator above consists of a permanent magnet which rotates around a central shaft with a coil of wire placed next to this rotating magnetic field. As the magnet spins, the magnetic field around the top and bottom of the coil constantly changes between a north and a south pole. This rotational movement of the magnetic field results in an alternating emf being induced into the coil as defined by Faraday's law of electromagnetic induction.

The magnitude of the electromagnetic induction is directly proportional to the flux density, β the number of loops giving a total length of the conductor, l in meters and the rate or velocity, v at which the magnetic field changes within the conductor in meters/second or m/s, giving by the motional emf expression:

Faraday's Motional emf Expression

= –|- . . .

If the conductor does not move at right angles (90°) to the magnetic field then the angle θ° will be added to the above expression giving a reduced output as the angle increases:

**Lenz's Law of Electromagnetic Induction**

Faraday's Law tells us that inducing a voltage into a conductor can be done by either passing it through a magnetic field, or by moving the magnetic field past the conductor and that if this conductor is part of a closed circuit, an electric current will flow. This voltage is called an **induced emf** as it has been induced into the conductor by a changing magnetic field due to electromagnetic induction with the negative sign in Faraday's law telling us the direction of the induced current (or polarity of the induced emf).

But a changing magnetic flux produces a varying current through the coil which itself will produce its own magnetic field as we saw in the **Electromagnets** tutorial. This self-induced emf opposes the change that is causing it and the faster the rate of change of current the greater is the opposing emf. This self-induced emf will, by Lenz's law oppose the change in current in the coil and because of its direction this self-induced emf is generally called a **back-emf**.

**Lenz's Law** states that: " the direction of an induced emf is such that it will always opposes the change that is causing it". In other words, an induced current will always OPPOSE the motion or change which started the induced current in the first place and this idea is found in the analysis of **Inductance**.

Likewise, if the magnetic flux is decreased then the induced emf will oppose this decrease by generating and induced magnetic flux that adds to the original flux.

Lenz's law is one of the basic laws in electromagnetic induction for determining the direction of flow of induced currents and is related to the law of conservation of energy.

According to the law of conservation of energy which states that the total amount of energy in the universe will always remain constant as energy can not be created nor destroyed. Lenz's law is derived from Michael Faraday's law of induction.

One final comment about Lenz's Law regarding electromagnetic induction. We now know that when a relative motion exists between a conductor and a magnetic field, an emf is induced within the conductor.

But the conductor may not actually be part of the coils electrical circuit, but may be the coils iron core or some other metallic part of the system, for example, a transformer. The induced emf within this metallic part of the system causes a circulating current to flow around it and this type of core current is known as an **Eddy Current**.

Eddy currents generated by electromagnetic induction circulate around the coils core or any connecting metallic components inside the magnetic field because for the magnetic flux they are acting like a single loop of wire. Eddy currents do not contribute anything towards the usefulness of the system but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core. However, there are electromagnetic induction furnace applications in which only eddy currents are used to heat and melt ferromagnetic metals.

SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

# UNIT - III

# Electrical Technology – SEEA1102

## I. DC GENERATORS

Construction, Principles of operation of DC Machines - Types - EMF Equation - Performance Characteristics of Series and Shunt Generators - Applications.

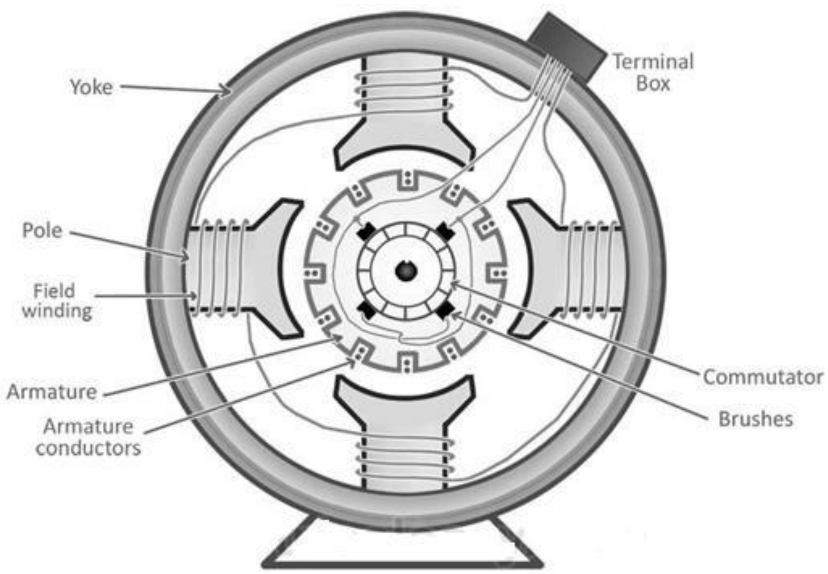



Figure 3.1 constructional details of a simple 4-pole DC machine

**DC Generator**

A dc generator is an electrical machine which converts mechanical energy into direct current electricity. This energy conversion is based on the principle of production of dynamically induced emf. This article outlines basic construction and working of a DC generator.

**Construction of A DC Machine:**

A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, a DC generator or a DC motor can be broadly termed as a DC machine. These basic constructional details are also valid for the construction of a DC motor. Hence, let's call this point as construction of a DC machine instead of just 'construction of a dc generator'.

The above figure shows the constructional details of a simple 4-pole DC machine. A DC

machine consists two basic parts; stator and rotor. Basic constructional parts of a DC machine are described below.

Yoke: The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.

Poles and pole shoes: Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.

Field winding: They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

Armature core: Armature core is the rotor of the machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.

Armature winding: It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

Commutator and brushes: Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

## Working Principle of A DC Generator

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with the closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of induced current is given by Fleming's right hand rule.

According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

## Types Of A DC Generator:

DC generators can be classified in two main categories, viz; (i) Separately excited and

(ii) Self-excited.

(i) Separately excited: In this type, field coils are energized from an independent external DC source.

(ii) Selfexcited: In this type, field coils are energized from the current produced by the generator itself. Initial emf generation is due to residual magnetism in field poles. The generated emf causes a part of current to flow in the field coils, thus strengthening the field flux and thereby increasing emf generation. Self excited dc generators can further be divided into three types -

(a) Series wound - field winding in series with armature winding

(b) Shunt wound - field winding in parallelwith armature winding

(c) Compound wound - combination of series and shunt winding

**EMF Equation of A DC Generator**

Consider a DC generator with the following parameters, P = number of field poles

Ø = flux produced per pole in Wb (weber) Z = total no. of armature conductors

A = no. of parallel paths in armature

N = rotational speed of armature in revolutions per min. (rpm)

Avg. emf generated per conductor= $\frac{d\text{Ø}}{dt}$ volts

and flux cut per conductor in one revolution= dØ= Ø.P (Wb)

no. of revolutions per second (speed)= N/60

∴. time for one revolution = dt = 60/N

∴. emf generated / conductor = $\frac{d\text{Ø}}{dt} = \frac{P\text{Ø}N}{60}$ volts

but generated emf (Eg) will be equal to generated emf in any parallel path

∴. Generated emf (Eg) = $\frac{P\text{Ø}N}{60} \quad \frac{Z}{A}$ volts

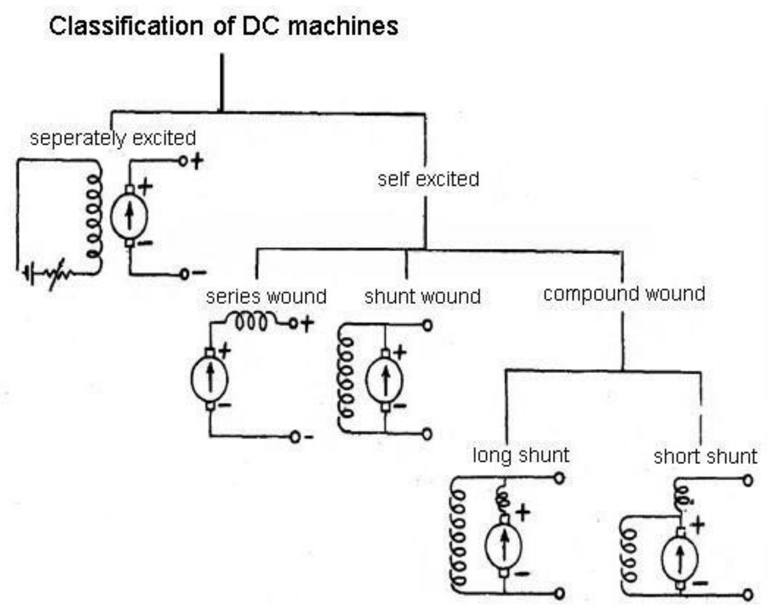
Now, for simplex wave wound generator
no. of parallel paths = A = 2

∴. Eg= $\frac{P\text{Ø}N\ Z}{120}$ volts

and, for simplex lap wound generator
no. of parallel paths = A = no. of poles = P

∴. Eg= $\frac{P\text{Ø}N}{60} \quad \frac{Z}{P}$ volts

From the above emf equation, we can calculate the net generated emf across a DC generator. Also, the same equation can be used to calculate the back emf generated in a dc motor.

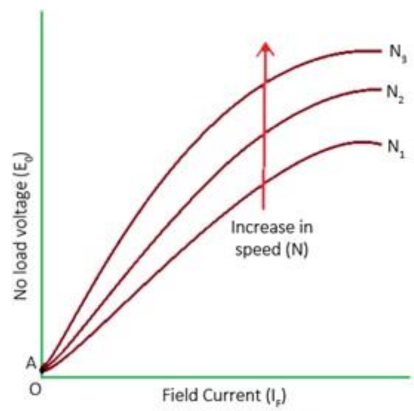



**Characteristics of DC Generators**

Generally, following three characteristics of DC generators are taken into considerations: (i) Open Circuit Characteristic (O.C.C.), (ii) Internal or Total Characteristic and (iii) External Characteristic. These characteristics of DC generators are explained below.

Open Circuit Characteristic (O.C.C.) (E0/If)

Open circuit characteristic is also known as magnetic characteristic or no-load saturation characteristic. This characteristic shows the relation between generated emf at no load (E0) and the field current (If) at the given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by operating the generator at no load and keeping speed constant. Field current is varied and the corresponding terminal voltage is recorded.



Open Circuit Characteristic (O.C.C.)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

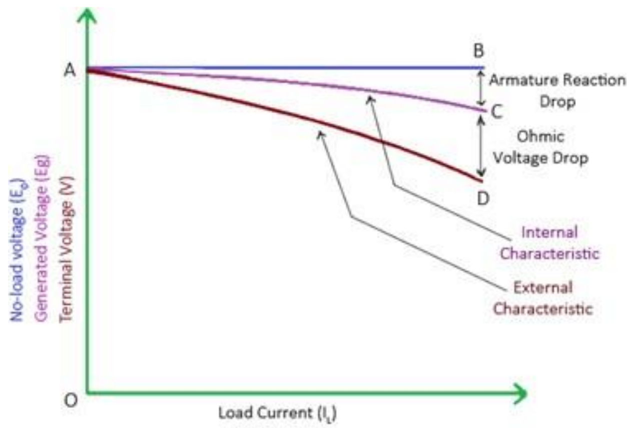
Internal Or Total Characteristic (E/Ia)

The internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (Ia). The on-load generated emf Eg is always less than E0 due to armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E0. Therefore, internal characteristic curve lies below O.C.C. curve.

External Characteristic (V/IL)

The external characteristic curve shows the relation between the terminal voltage (V) and load current (IL). The terminal voltage V is less than generated emf Eg due to voltage drop in the armature circuit. Therefore the external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose.

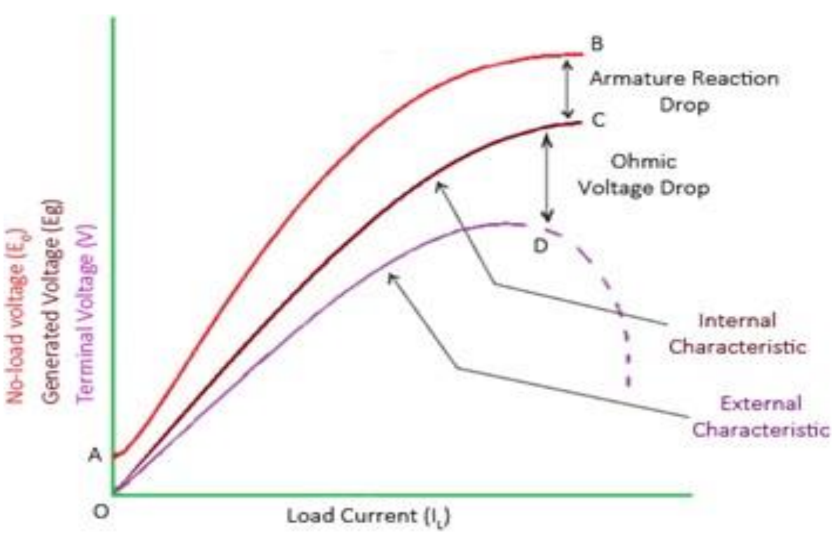
Characteristics Of Separately Excited DC Generator




Characteristics of separately excited DC generator

If there is no armature reaction and armature voltage drop, voltage will remain constant for any load current. Thus the straight line AB in above figure represents the no-load voltage vs. load current IL. Due to demagnetizing effect of armature reaction the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current IL i.e. internal characteristic. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Characteristics Of DC Series Generator




Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because, in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current. The curve OC and OD represents internal and external characteristic respectively.

# UNIT - IV

# Electrical Technology – SEEA1102
# UNIT IV- DC MOTOR

# IV. DC MOTOR

Construction, Principles of operation of DC MOTORS - Types – Back EMF – Torque Equation - Torque - Speed Characteristics of Series and Shunt Motors -Speed Control and Applications.

## 4.1 Working Principle of A DC Motor

A motor is an electrical machine which converts electrical energy into mechanical energy. The principle of working of a DC motor is that "whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force". The direction of this force is given by Fleming's left hand rule and it's magnitude is given by F = BIL. Where, B = magnetic flux density, I = current and L = length of the conductor within the magnetic field.

Fleming's left hand rule: If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other AND direction of magnetic field is represented by the first finger, direction of the current is represented by second finger then the thumb represents the direction of the force experienced by the current carrying conductor.

## 4.2 Back EMF

According to fundamental laws of nature, no energy conversion is possible until there is something to oppose the conversion. In case of generators this opposition is provided by magnetic drag, but in case of dc motors there is back emf.

When the armature of the motor is rotating, the conductors are also cutting the magnetic flux lines and hence according to the Faraday's law of electromagnetic induction, an emf induces in the armature conductors. The direction of this induced emf is such that it opposes the armature current (Ia). The circuit diagram below illustrates the direction of the back emf and armature current. Magnitude of Back emf can be given by the emf equation of DC generator.

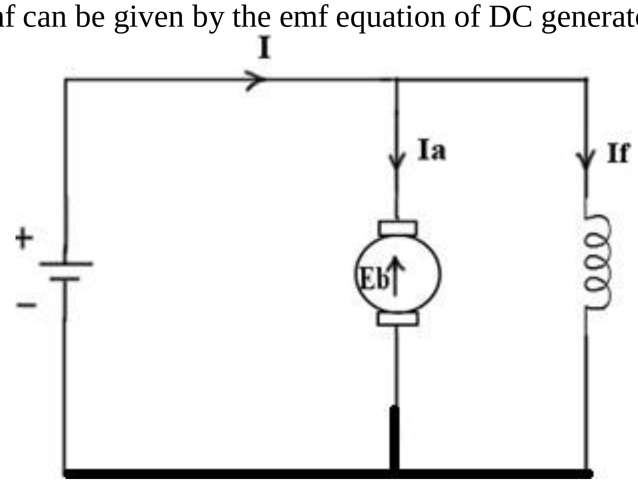


**Fig.4.1 DC motor**

## 4.3 Significance of Back Emf

Magnitude of back emf is directly proportional to speed of the motor. Consider the load on a dc motor is suddenly reduced. In this case, required torque will be small as compared to the current torque. Speed of the motor will start increasing due to the excess torque. Hence, being proportional to the speed, magnitude of the back emf will also increase. With increasing back emf armature current will start decreasing. Torque being proportional to the armature current, it will also decrease until it becomes sufficient for the load. Thus, speed of the motor will regulate.
On the other hand, if a dc motor is suddenly loaded, the load will cause decrease in the speed. Due to decrease in speed, back emf will also decrease allowing more armature current. Increased armature current will increase the torque to satisfy the load requirement. Hence, presence of the back emf makes a dc motor 'self-regulating'.

## 4.4 Types Of A DC Motor:

1. DC Shunt Motor
2. DC Seires Motor
3. DC Compound Motor

## 4.5 Characteristics of DC Motors

Generally, three characteristic curves are considered for DC motors which are, (i) Torque vs. armature current (Ta - Ia), (ii) Speed vs. armature current and (iii) Speed vs. torque. These are explained below for each type of DC motor. These characteristics are determined by keeping following two relations in mind.
$T_a \propto \Phi . I_a$ and $N \propto E_b/\Phi$

### 4.5.1 Characteristics of DC Series motors

**Torque Vs. Armature Current (Ta-Ia)**

This characteristic is also known as electrical characteristic. We know that torque is directly proportional to armature current and flux, $T_a \propto \Phi . I_a$. In DC series motors, field winding is connected in series with armature. Thus, before magnetic saturation of the field, flux Φ is directly proportional to Ia. Therefore, before magnetic saturation $T_a \propto I_a^2$. At light loads, Ia as well as Φ is small and hence the torque increases as the square of

the armature current. Therefore, the Ta-Ia curve is parabola for smaller values of Ia. After magnetic saturation of the field winding, flux Φ is independent of armature current Ia. Therefore, the torque varies proportional to Ia only, $T \propto I_a$.Therefore, after magnetic saturation, Ta-Ia curve becomes straight line. The shaft torque (Tsh) is less than armature torque (Ta) due to stray losses. In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required

**Speed Vs. Armature Current (N-Ia)**

We know the relation, N α Eb/Φ
For small load current (and hence for small armature current) change in back emf Eb is small and it may be neglected. Thus, for small currents speed is inversely proportional to Φ. As we know, flux is directly proportional to Ia, speed is also inversely proportional to Ia.
When armature current is very small the speed becomes dangerously high. That is why a series motor should never be started without some mechanical load.
But, at heavy loads, armature current Ia is large. And hence speed is low which results in decreased back emf Eb. Due to decreased Eb, more armature current is allowed.

**Speed Vs. Torque (N-Ta)**

This characteristic is also called as mechanical characteristic. From the above two characteristics of DC series motor, it can be found that when speed is high, torque is low and vice versa.

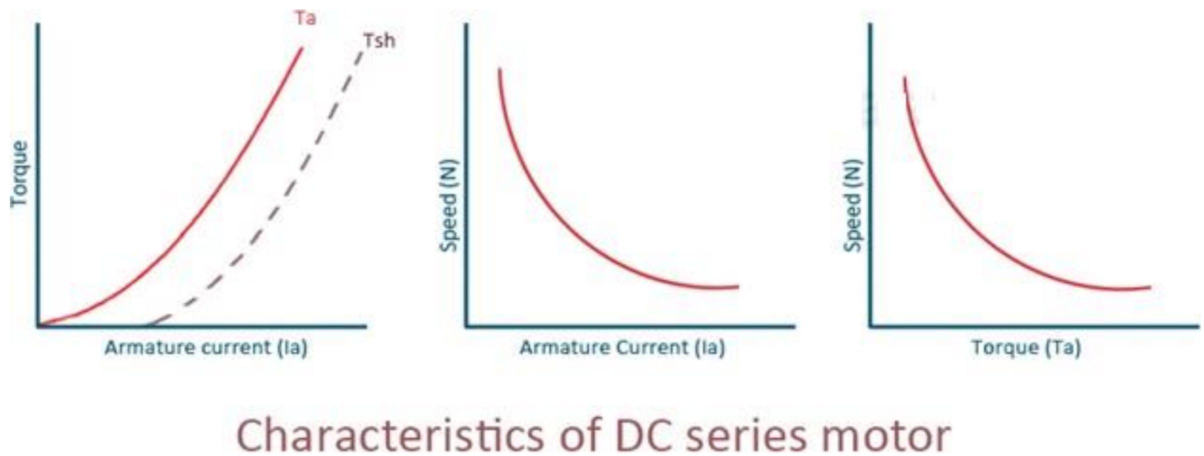



**Fig. 4.2 Characteristics of DC series motor**

**4.5.2 Characteristics of DC Shunt Motors**

**Torque Vs. Armature Current (Ta-Ia)**
In case of DC shunt motors we can assume the field flux Φ to be constant. Though at heavy loads, Φ decreases in a small amount due to increased armature reaction. But as we are neglecting the change in the flux Φ, we can say that torque is proportional to armature current. Hence the Ta-Ia characteristic for a dc shunt motor will be a straight

line through origin. Since, heavy starting load needs heavy starting current, shunt motor should never be started on a heavy load.

**Speed Vs. Armature Current (N-Ia)**

As flux Φ is assumed constant, we can say N α Eb. But, back emf is also almost constant, the speed remains constant. But practically, Φ as well as Eb decreases with increase in load. But, the Eb decreases slightly more than Φ, and hence the speed decreases slightly. Generally, the speed decreases by 5 to 15% of full load speed only. And hence, a shunt motor can be assumed as a constant speed motor.

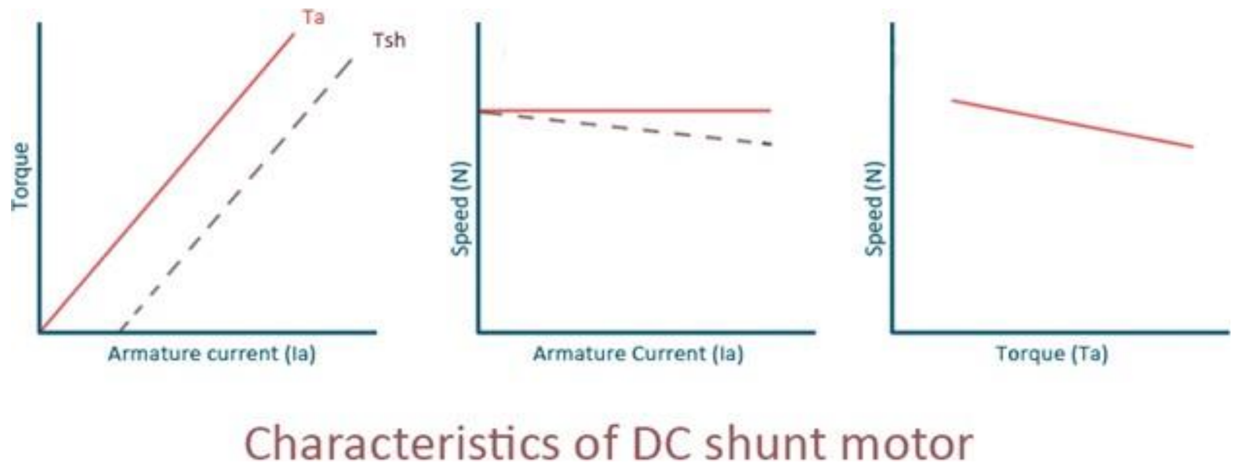



**Fig.4.3 Characteristics of DC Shunt motor**

### 4.5.3 Characteristics Of DC Compound Motor

DC compound motors have both series as well as shunt windings. In a compound motor series and shunt windings are connected such that series flux is in direction with shunt flux then the motor is said to be cumulatively compounded. And if series flux is opposite direction as that of the shunt flux, then the motor is said to be differentially compounded. Characteristics of both these types are explained below.

**(a) Cumulative compound motor**

Cumulative compound motors are used where series characteristics are required but the load is likely to be removed completely. Series winding takes care of the heavy load, whereas the shunt winding prevents the motor from running at dangerously high speed when the load is suddenly removed. These motors are generally employed a flywheel, where sudden and temporary loads are applied like in rolling mills.

**(b) Differential compound motor**

Since in differential field motors, series flux opposes shunt flux, the total flux decreases with increase in load. Due to this, the speed remains almost constant or even it may increase slightly with increase in load. Differential compound motors are not commonly use, but they find limited applications in experimental and research work

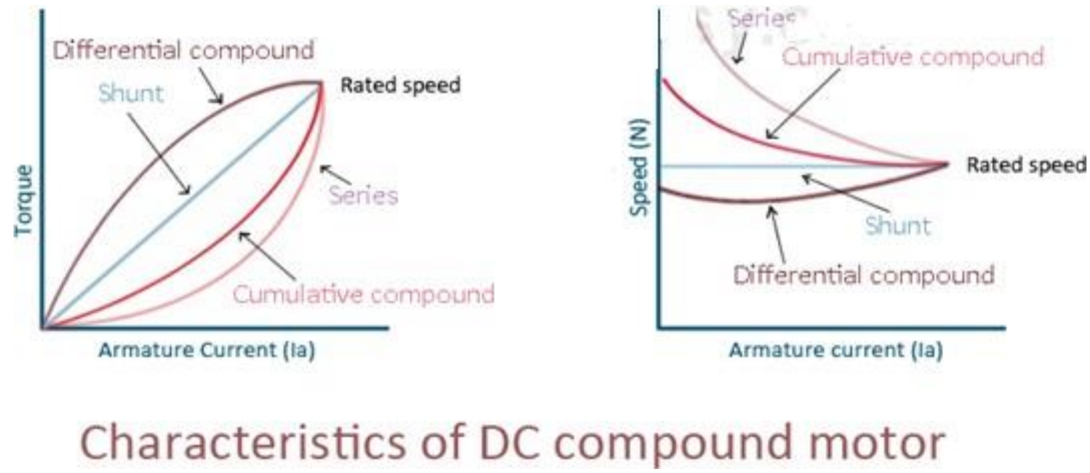



**Fig.4.4 Characteristics of DC Compound motor**

## 4.6 Speed Control Methods of DC Motor

### 4.6.1Speed Control of Shunt Motor

#### Flux Control Method

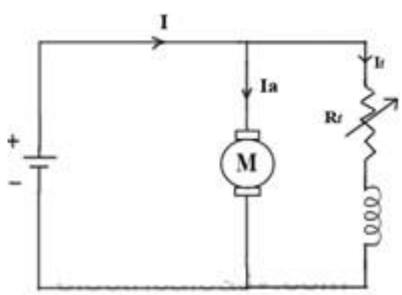



**Fig.4.5 Flux control**

It is seen that speed of the motor is inversely proportional to flux. Thus by decreasing flux speed can be increased and vice versa.

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with field winding will increase the speed, as it will decrease the flux. Field current is relatively small and hence I2R loss is small, hence this method is quiet efficient. Though speed can be increased by reducing flux with this method, it puts a limit to maximum speed as weakening of flux beyond the limit will adversely affect the commutation.

**Armature Control Method**

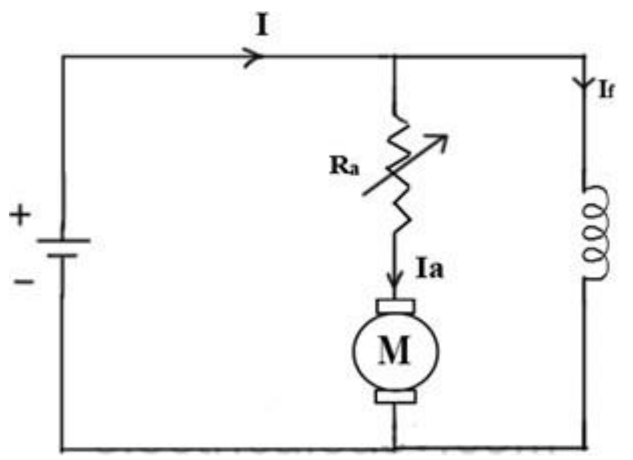



**Fig. 4.6 Armature control**

Speed of the motor is directly proportional to the back emf Eb and Eb = V- IaRa. That is when supply voltage V and armature resistance Ra are kept constant, speed is directly proportional to armature current Ia. Thus if we add resistance in series with armature, Ia decreases and hence speed decreases.

Greater the resistance in series with armature, greater the decrease in speed.

**Voltage Control Method**

A) **Multiple voltage control:** In this method the, shunt filed is connected to a fixed exciting voltage, and armature is supplied with different voltages. Voltage across armature is changed with the help of a suitable switchgear. The speed is approximately proportional to the voltage across the armature.

**B) Ward-Leonard System:**

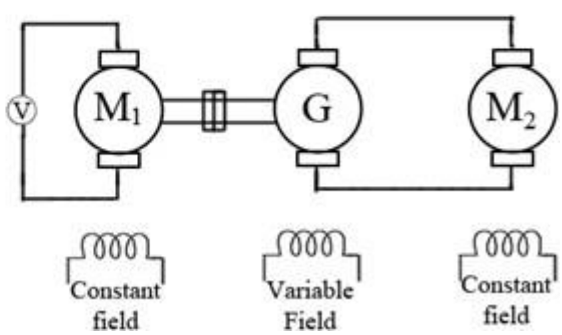


**Fig.4.7 Ward- Leonard System**

This system is used where very sensitive speed control of motor is required (e.g electric excavators, elevators etc.) The arrangement of this system is as required in the figure beside.

M2 is the motor whose speed control is required.
M1 may be any AC motor or DC motor with constant speed. G is the generator directly coupled to M1.
In this method the output from the generator G is fed to the armature of the motor

M2 whose speed is to be controlled. The output voltage of the generator G can be varied from zero to its maximum value, and hence the armature voltage of the motor M2 is varied very smoothly. Hence very smooth speed control of motor can be obtained by this method.

## QUESTIONS

### PART A

1. Why a series motor should not be started on no load?
2. Give the equation for the shaft torque and armature torque of a DC motor.
3. What is back emf or counter voltage?
4. Why does the speed of the motor dip upon loading?
5. State the methods of speed control of a DC shunt motor.
6. 14. A 250V dc machine has an armature resistance of 0.25Ω. If the full load armature current is 40A, find the induced emf when the machine acts as a motor.

### PART B

1. Explain the construction of DC machine.
2. Explain the working principle of DC motor.
3. Explain the characteristic of series DC motor.
4. Explain the characteristic of shunt DC motor.
5. Explain the characteristic of compound DC motor.
6. Explain various speed control methods of DC motor.
7. Derive an expression for the torque developed in a dc machine.

8. A 400V DC shunt motor takes 5A on no load. The armature resistance is 0.25Ω and the field resistance is 180 Ω. Calculate the efficiency of the machine as a generator when it delivers a load current of 40A.

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# UNIT - V

# Electrical Technology – SEEA1102
## UNIT V- TRANSFORMERS AND SPECIAL MACHINES

## V. TRANSFORMERS AND SPECIAL MACHINES

Constructional Details and Principle of operation of Single Phase Transformer - EMF Equation –Auto Transformer – Special Machines : Stepper Motor – Permanent stepper motor – Variable Reluctance stepper motor – Servomotor – AC servomotor – DC servomotor – Stepper motor selection and control : An Industrial case study.

### 5.1 Electrical Transformer - Basic Construction, Working and Types

Electrical transformer is a static electrical machine which transforms electrical power from one circuit to another circuit, without changing the frequency. Transformer can increase or decrease the voltage with corresponding decrease or increase in current. Working Principle of Transformer

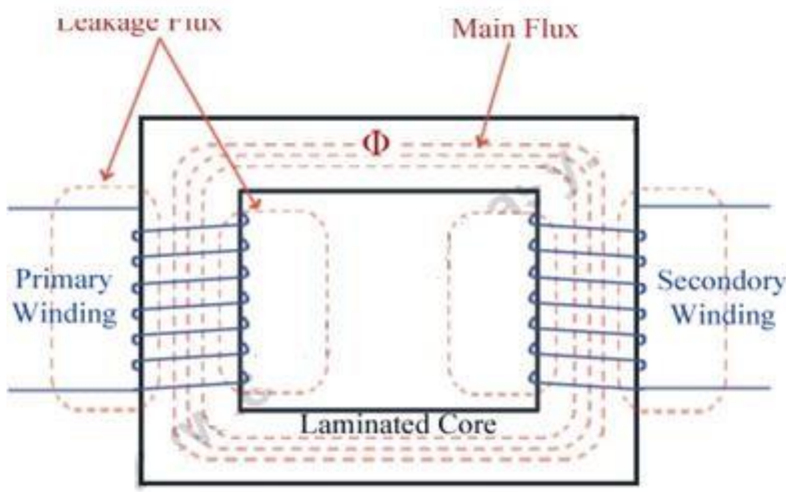



**Fig.5.1 Transformer**

The basic principle behind working of a transformer is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure at right shows the simplest form of a transformer. Basically a transformer consists of two inductive coils; primary winding and secondary winding. The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit.

## 5.2 Basic Construction of Transformer

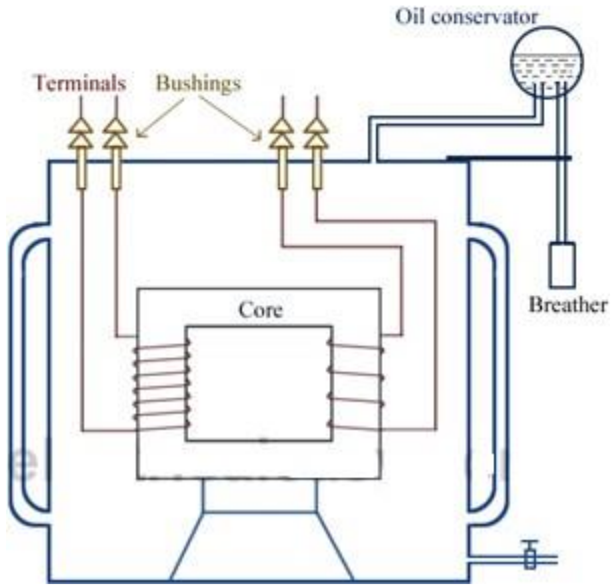



**Fig.5.2 Construction of transformer**

Basically a transformer consists of two inductive windings and a laminated steel core. The coils are insulated from each other as well as from the steel core. A transformer may also consist of a container for winding and core assembly (called as tank), suitable bushings to take out the terminals, oil conservator to provide oil in the transformer tank for cooling purposes etc. The figure at left illustrates the basic construction of a transformer.


**Fig. 5.3 Lamination**

In all types of transformers, core is constructed by assembling (stacking) laminated sheets of steel, with minimum air-gap between them (to achieve continuous magnetic path). The steel used is having high silicon content and sometimes heat treated, to provide high permeability and low hysteresis loss. Laminated sheets of steel are used to reduce eddy current loss. The sheets are cut in the shape as E,I and L. To avoid high reluctance at joints, laminations are stacked by alternating the sides of joint. That is, if joints of first sheet assembly are at front face, the joints of following assemble are kept at back face.

## 5.3 Types of Transformers

Transformers can be classified on different basis, like types of construction, types of cooling etc.

(A) **On the basis of construction**, transformers can be classified into two types as;
(i) Core type transformer and
(ii) Shell type transformer, which are described below.

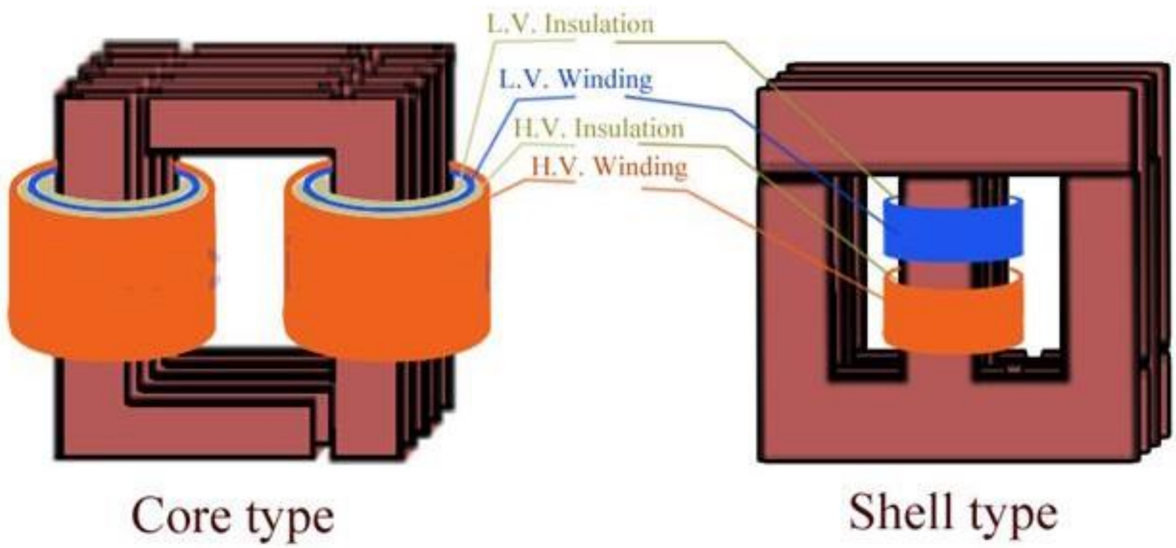



**Fig.5.4 core and shell type**

**1) Core Type Transformer**
In core type transformer, windings are cylindrical former wound, mounted on the core limbs as shown in the figure above. The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.

**2) Shell Type Transformer**
The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form (as shown in above fig), or it may have a distributed form.

**(B) On the basis of their purpose**
Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.
Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

(C) **On the basis of type of supply** Single phase transformer
Three phase transformer

**(D) On the basis of their use**

Power transformer: Used in transmission network, high rating
Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.
Instrument transformer: Used in relay and protection purpose in different instruments in industries
Current transformer (CT)
Potential transformer (PT)

(E) **On the basis of cooling employed** Oil-filled self cooled type
Oil-filled water cooled type Air blast type (air cooled)

## 5.4 Ideal Transformer and its Characteristics

An ideal transformer is an imaginary transformer which has
- no copper losses (no winding resistance)
- no iron loss in core
- no leakage flux

In other words, an ideal transformer gives output power exactly equal to the input power. The efficiency of an idea transformer is 100%. Actually, it is impossible to have such a transformer in practice, but ideal transformer model makes problems easier.

### 5.4.1 Characteristics of Ideal Transformer

**Zero winding resistance:**

It is assumed that, resistance of primary as well as secondary winding of an ideal transformer is zero. That is, both the coils are purely inductive in nature.
Infinite permeability of the core: Higher the permeability, lesser the mmf required for flux establishment. That means, if permeability is high, less magnetizing current is required to magnetize the transformer core.

**No leakage flux:**

Leakage flux is a part of magnetic flux which does not get linked with secondary winding. In an ideal transformer, it is assumed that entire amount of flux get linked with secondary winding (that is, no leakage flux).

**100% efficiency:**

An ideal transformer does not have any losses like hysteresis loss, eddy current loss etc. So, the output power of an ideal transformer is exactly equal to the input power. Hence, 100% efficiency.

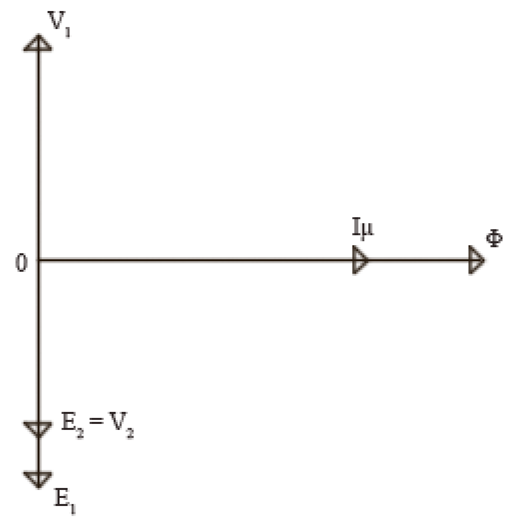



**Fig.5.5 Ideal transformer characteristics**

Now, if an alternating voltage V1 is applied to the primary winding of an ideal transformer, counter emf E1 will be induced in the primary winding. As windings are purely inductive, this induced emf E1 will be exactly equal to the apply voltage but in 180 degree phase opposition. Current drawn from the source produces required magnetic flux. Due to primary winding being

purely inductive, this current lags 90° behind induced emf E1. This current is called magnetizing current of the transformer Iμ. This magnetizing current Iμ produces alternating magnetic flux Φ. This flux Φ gets linked with the secondary winding and emf E2 gets induced by mutual induction. (Read Faraday's law of electromagnetic induction.) This mutually induced emf E2 is in phase with E2. If closed circuit is provided at secondary winding, E2 causes current I2 to flow in the circuit.

For an ideal transformer, E1I1 = E2I2.

EMF Equation Of A Transformer And Voltage Transformation Ratio

In a transformer, source of alternating current is applied to the primary winding. Due to this, the current in the primary winding (called as magnetizing current) produces alternating flux in the core of transformer. This alternating flux gets linked with the secondary winding, and because of the phenomenon of mutual induction an emf gets induced in the secondary winding. Magnitude of this induced emf can be found by using the following EMF equation of the transformer.

## 5.5 EMF Equation of the Transformer

Let,

N1 = Number of turns in primary winding N2 = Number of turns in secondary winding

Φm = Maximum flux in the core (in Wb) = (Bm x A) f = frequency of the AC supply (in Hz)

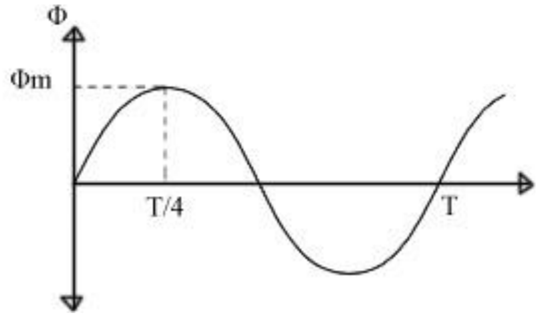



**Fig.5.6 waveform**

As, shown in the fig., the flux rises sinusoidally to its maximum value Φm from 0. It reaches to the maximum value in one quarter of the cycle i.e in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).

Therefore,

average rate of change of flux = Φm /(T/4) =

Φm/(1/4f) Therefore,

average rate of change of flux = 4f Φm............... (Wb/s).

Now,

Induced emf per turn = rate of change of flux per turn

Therefore, average emf per turn = 4f Φm..............(Volts).

Now, we know, Form factor = RMS value / average value

Therefore, RMS value of emf per turn = Form factor X average emf

per turn. As, the flux Φ varies sinusoidally, form factor of a sine wave

is 1.11 Therefore, RMS value of emf per turn = 1.11 x 4f Φm = 4.44f

Φm.

RMS value of induced emf in whole primary winding (E1) = RMS value of emf per turn X Number of turns in primary winding

E1 = 4.44f N1 Φm........................................eq 1

Similarly, RMS induced emf in secondary winding (E2) can be

given as E2 = 4.44f N2 Φm .........................eq 2

from the above equations 1 and 2,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\,\Phi m$$

This is called the emf equation of transformer, which shows, emf / number of turns is same for both primary and secondary winding.

For an ideal transformer on no load, $E1 = V1$ and $E2 = V2$ . where, $V1$ = supply voltage of primary winding

$V2$ = terminal voltage of secondary winding

Voltage Transformation Ratio (K) As derived above,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = K$$

Where, K = constant

This constant K is known as voltage transformation ratio.

If $N2 > N1$, i.e. $K > 1$, then the transformer is called step-up transformer.

If $N2 < N1$, i.e. $K < 1$, then the transformer is called step-down transformer.

## 5.6 Auto Transformer

An auto transformer is an electrical transformer having only one winding. The winding has at least three terminals which is explained in the construction details below.

Some of the advantages of auto-transformer are that,
they are smaller in size,
cheap in cost,
low leakage
reactance, increased
kVA rating, low
exciting current etc.

An example of application of auto transformer is, using an US electrical equipment rated for 115 V supply (they use 115 V as standard) with higher Indian voltages. Another example could be in starting method of three phase induction motors.

### 5.6.1 Construction Of Auto Transformer

An auto transformer consists of a single copper wire, which is common in both primary as well as secondary circuit. The copper wire is wound a laminated silicon steel core, with at least three tappings taken out. Secondary and primary circuit share the same neutral point of the winding. The construction is well explained in the diagram. Variable turns ratio at secondary can be obtained by the tappings of the winding (as shown in the figure), or by providing a smooth sliding brush over the winding. Primary terminals are fixed.

Thus, in an auto transformer, you may say, primary and secondary windings are connected magnetically as well as electrically.

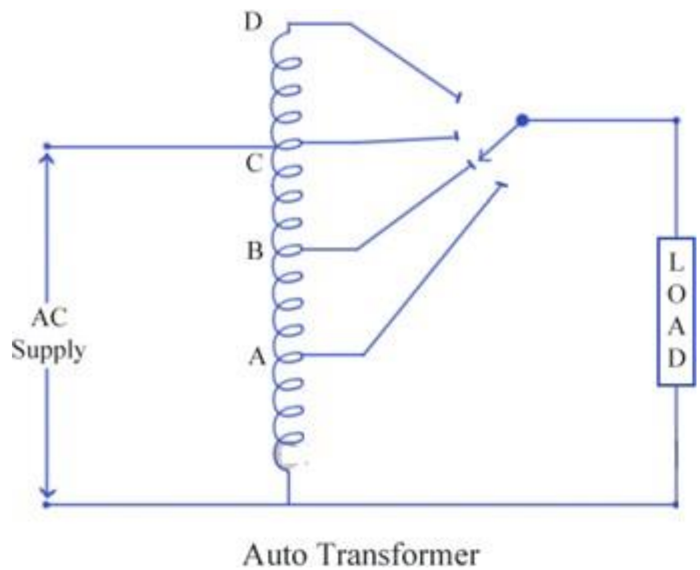


**Fig. 5.7 Auto Transformer**

### 5.6.2 Working of Auto Transformer

As I have described just above, an auto transformer has only one winding which is shared by both primary and secondary circuit, where number of turns shared by secondary are variable. EMF induced in the winding is proportional to the number of turns. Therefore, the secondary voltage can be varied by just varying secondary number of turns.
As winding is common in both circuits, most of the energy is transferred by means of electrical conduction and a small part is transferred through induction.

The considerable disadvantages of an auto transformer are,
Any undesirable condition at primary will affect the equipment at secondary (as windings are not electrically isolated),
Due to low impedance of auto transformer, secondary short circuit currents are very high,
Harmonics generated in the connected equipment will be passed to the supply.

## 5.7 Stepper Motor Theory of Operation

Stepper motors provide a means for precise positioning and speed control without the use of feedback sensors. The basic operation of a stepper motor allows the shaft to move a precise number of degrees each time a pulse of electricity is sent to the motor. Since the shaft of the motor moves only the number of degrees that it was designed for when each pulse is delivered, you can control the pulses that are sent and control the positioning and speed. The rotor of the motor produces torque from the interaction between the magnetic field in the stator and rotor. The strength of the magnetic fields is proportional to the amount of current sent to the stator and the number of turns in the windings.

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. You learned previously that like poles of a magnet repel and unlike poles attract. Figure 1 shows a typical cross-sectional view of the rotor and stator of a stepper motor. From this diagram you can see that the stator (stationary winding) has eight poles, and the rotor has six poles (three complete magnets). The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives. The number of degrees the rotor will turn when a pulse of electricity is delivered to the motor can be calculated by dividing the number of degrees in one revolution of the shaft (360°) by the number of poles (north and south) in the rotor. In this stepper motor 360° is divided by 24 to get 15°.

When no power is applied to the motor, the residual magnetism in the rotor magnets will cause the rotor to detent or align one set of its magnetic poles with the magnetic poles of one of the stator magnets. This means that the rotor will have 24 possible detent positions. When the rotor is in a detent position, it will have enough magnetic force to keep the shaft from moving to the next position. This is what makes the rotor feel like it is clicking from one position to the next as you rotate the rotor by hand with no power applied.

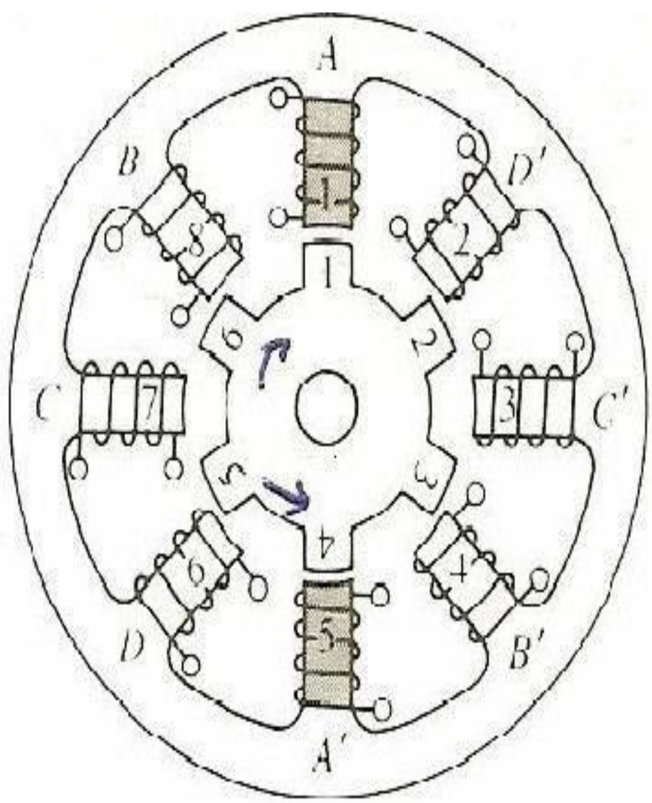



**Fig. 5.8 Position of the six-pole rotor and eight-pole stator of a typical stepper motor.**

When power is applied, it is directed to only one of the stator pairs of windings, which will cause that winding pair to become a magnet. One of the coils for the pair will become the North Pole, and the other will become the South Pole. When this occurs, the stator coil that is the North Pole will attract the closest rotor tooth that has the opposite polarity, and the stator coil that is the South Pole will attract the closest rotor tooth that has the opposite polarity. When current is flowing through these poles, the rotor will now have a much stronger attraction to the stator winding, and the increased torque is called holding torque.By changing the current flow to the next stator winding, the magnetic field will be changed 45°. The rotor will only move 15° before its magnetic fields will again align with the change in the stator field. The magnetic field in the stator is continually changed as the rotor moves through the 24 steps to move a total of 360°. Figure 2 shows the position of the rotor changing as the current supplied to the stator changes.

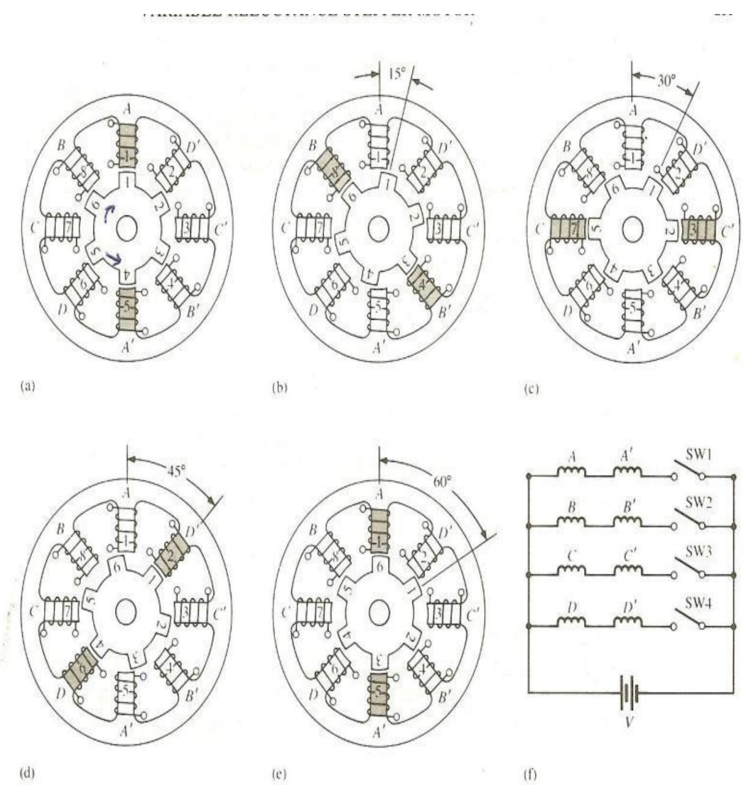



**Fig. 5.9 Stepper motor rotor**

Movement of the stepper motor rotor as current is pulsed to the stator. (a) Current is applied to the A and A’ windings, so the A winding is north, (b) Current is applied to B and B’ windings, so the B winding is north, (c) Current is applied to the C and C’ windings, so the C winding is north, (d) Current is applied to the D and D’ windings so the D winding is north. (e) Current is applied to the A and A’ windings, so the A’ winding is north.

In Fig. 2a you can see that when current is applied to the A and A’ stator windings, they will become a magnet with the top part of the winding being the North Pole, and the bottom part of the winding being the South Pole. You should notice that this will cause the rotor to move a small amount so that one of its south poles is aligned with the north stator pole (at A), and the opposite end of the rotor pole, which is the north pole, will align with the south pole of the stator (at A’). A line is placed on the south-pole piece so that you can follow its movement as current is moved from one stator winding to the next. In Fig. 2b current has been turned off to the A and A” windings, and current is now applied to the stator windings shown at the B and B’ sides of the motor. When this occurs, the stator winding at the B’ position will have the polarity for the south pole of the stator magnet, and the winding at the B position will have the north-pole polarity. In this condition, the next rotor pole that will be able to align with the stator magnets is the next pole in the clockwise position to the previous pole. This means that the rotor will only need to rotate 15° in the clockwise position for this set of poles to align itself so that it attracts the stator poles.

In Fig. 2c you can see that the C and C’ stator windings are again energized, but this time the C winding is the north pole of the magnetic field and the C’ winding is the south pole. This change in magnetic field will cause the rotor to again move 15° in the clockwise position until its poles will align with the C and C’ stator poles. You should notice that the original rotor pole that was labeled 1 now moved three steps in the clockwise position.

In Fig.2d you can see that the D and D’ stator windings are energized, the winding at D position is the north pole. This change in polarity will cause the rotor to move another 15° in the clockwise direction. You should notice that the rotor has moved four steps of 15° each, which means the rotor has moved a total of 60° from its original position. This can be verified by the position of the rotor pole that has the line on it, which is now pointing at the stator winding that is located in the 2 o'clock position.

In Fig.2e you can see that the A and A’ stator windings are energized, the winding at A position is the south pole. This change in polarity will cause the rotor to move another 15° in the clockwise direction. You should notice that the rotor has moved four steps of 15° each, which means the rotor has moved a total of 75° from its original position. Thus the sequence of energizing ABCDA will move the rotor in the clockwise direction. It can be easily verified that for the counter clockwise direction the sequence should be ADCBA.

### Stepper Motor Switching Sequence

The stepper motor can be operated in three different stepping modes, namely, full-step, half-step, and micro-step.

#### Full-Step

The stepper motor uses a four-step switching sequence, which is called a full-step switching sequence which is already described above.

#### Half-Step

Another switching sequence for the stepper motor is called an eight-step or half-step sequence. The switching diagram for the half-step sequence is shown in Fig. 3. The main feature of this switching sequence is that you can double the resolution of the stepper motor by causing the rotor to move half the distance it does when the full-step switching sequence is used. This means that a 200-step motor, which has a resolution of 1.8°, will have a resolution of 400 steps and 0.9°. The half-step switching sequence requires a special stepper motor controller, but it can be used with a standard hybrid motor. The way the controller gets the motor to reach the half-step is to energize both phases at the same time with equal current.

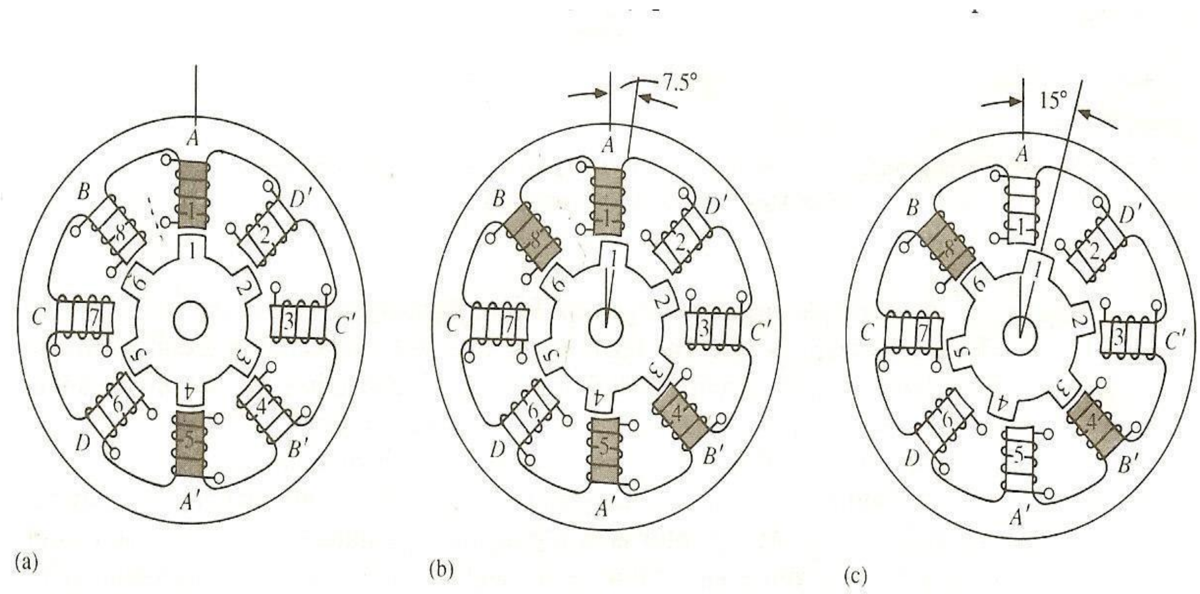



**Fig. 5.10 The switching sequence for the eight-step input (half-step mode).**

In this sequence the first step has SW1 is on, and SW2,SW3 and SW4 are off. The sequence for the first step is the same as the full-step sequence. The second step has SW1 and SW2 are on and all of the remaining switches are off. This configuration of switches causes the rotor to move an additional half- step because it is acted upon by two equal magnetic forces and the rotor turns to the equilibrium position which is half a step angle. The third step has SW2 is on, and SW1, SW4 and SW3 are off, which is the same as step 2 of the full-step sequence. The sequence continues for eight steps and then repeats. The main difference between this sequence and the full-step sequence is that the energizing sequence for half step is A AB B BC C CD D DA.

**Micro Step Mode**

The full-step and half-step motors tend to be slightly jerky in their operation as the motor moves from step to step. The amount of resolution is also limited by the number of physical poles that the rotor can have. The amount of resolution (number of steps) can be in- creased by manipulating the current that the controller sends to the motor during each step. The current can be adjusted so that it looks similar to a sine wave. Figure 4 shows the waveform for the current to each phase. From this diagram you can see that the current sent to each of the four sets of windings is timed so that there is always a phase difference with each other.

The fact that the current to each individual phase increases and decreases like a sine wave and that is always out of time with the other phase will allow the rotor to reach hundreds of intermediate steps. In fact it is possible for the controller to reach as many as 500 micro steps for a full-step sequence, which will provide 100,000 steps for each revolution.

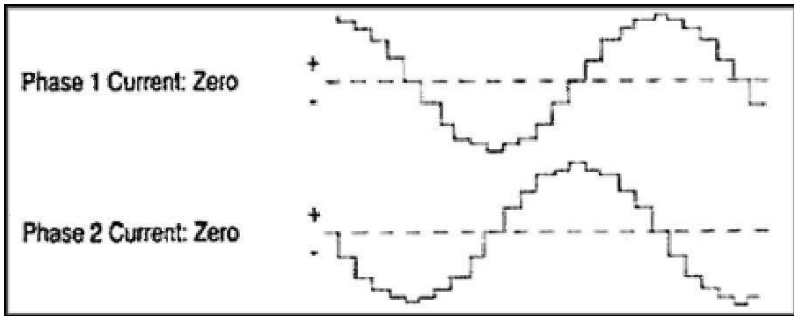



**Fig. 5. 11 Phase-current diagram for a stepper motor controller in micro step mode.**

### 5.8 Types of Stepper Motors

A stepper, or stepping motor converts electronic pulses into proportionate mechanical movement. Each revolution of the stepper motor's shaft is made up of a series of discrete individual steps. A step is defined as the angular rotation produced by the output shaft each time the motor receives a step pulse. These types of motors are very popular in digital control circuits, such as robotics, because they are ideally suited for receiving digital pulses for step control. Each step causes the shaft to rotate a certain number of degrees. A step angle represents the rotation of the output shaft caused by each step, measured in degrees. Figure 5 illustrates a simple application for a stepper motor. Each time the controller receives an input signal, the paper is driven a certain incremental distance. In addition to the paper drive mechanism in a printer, stepper motors are also popular in machine tools, process control systems, tape and disk drive systems, and programmable controllers.

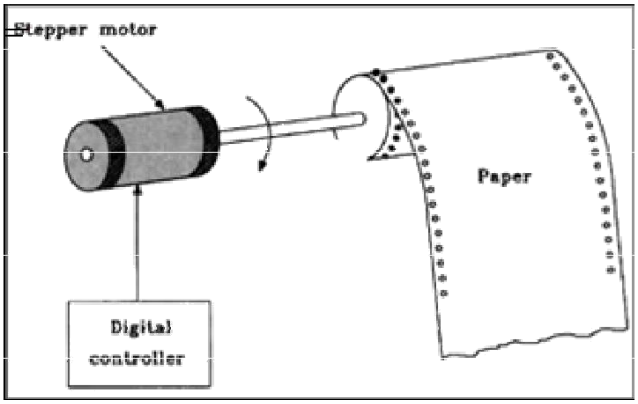



**Fig.5.12. Paper drive mechanism using stepper machine**

The most popular types of stepper motors are permanent-magnet (PM) and variable reluctance (VR).

### 5.8.1 Permanent-magnet (PM) Stepper Motors

The permanent-magnet stepper motor operates on the reaction between a permanent- magnet rotor and an electromagnetic field. Figure 6 shows a basic two-pole PM stepper motor. The rotor shown in Figure 6(a) has a permanent magnet mounted at each end. The stator is illustrated in Figure 6(b). Both the stator and rotor are shown as having teeth. The teeth on the rotor surface and the stator pole faces are offset so that there will be only a limited number of rotor teeth aligning themselves with an energized stator pole. The number of teeth on the rotor and stator determine the step angle that will occur each time the polarity of the winding is reversed. Greater the number of teeth, smaller the step angle.

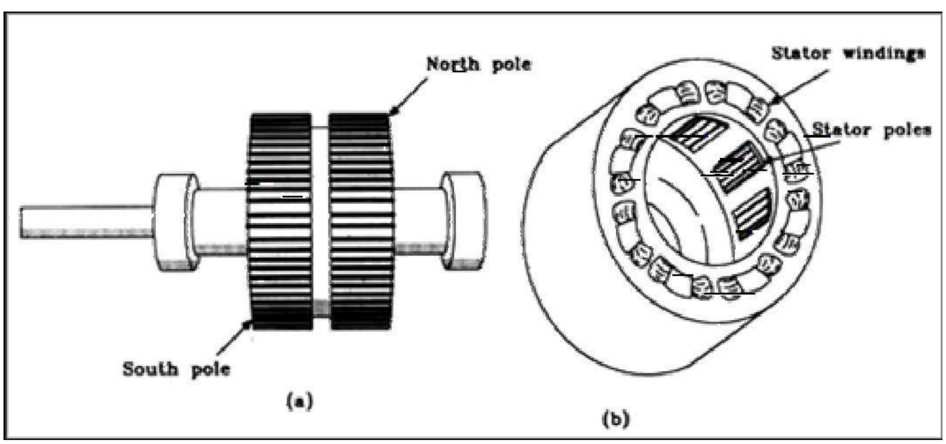



**Fig.5.13 Components of a PM stepper motor: (a) Rotor; (b) stator**

When a PM stepper motor has a steady DC signal applied to one stator winding, the rotor will overcome the residual torque and line up with that stator field. The holding torque is defined as the amount of torque required to move the rotor one full step with the stator energized. An important characteristic of the PM stepper motor is that it can maintain the holding torque indefinitely when the rotor is stopped. When no power is applied to the windings, a small magnetic force is developed between the permanent magnet and the stator. This magnetic force is called a residual, or detent torque. The detent torque can be noticed by turning a stepper motor by hand and is generally about one-tenth of the holding torque.

Figure 7(a) shows a permanent magnet stepper motor with four stator windings. By giving pulses the stator coils in a desired sequence, it is possible to control the speed and direction of the motor. Figure 7(b) shows the timing diagram for the pulses required to rotate the PM stepper motor illustrated in Figure 7(a). This sequence of positive and negative pulses causes the motor shaft to rotate counterclockwise in 90° steps. The waveforms of Figure 7(c) illustrate how the pulses can be overlapped and the motor made to rotate counterclockwise at 45° intervals.

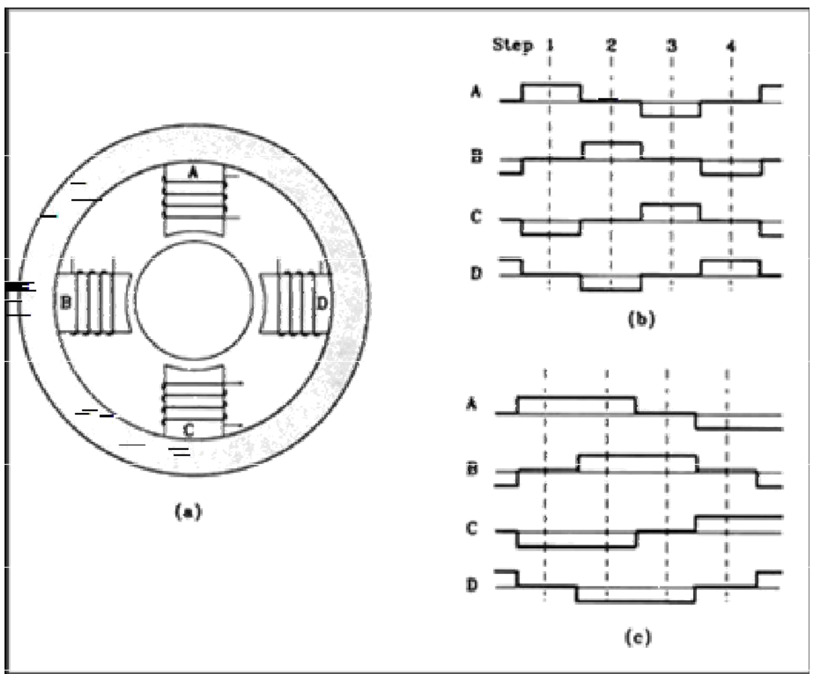



**Fig.5.14 (a) PM stepper motor; (b) 90 step; (c) 45 step.**

A more recent development in PM stepper motor technology is the thin-disk rotor. This type of stepper motor dissipates much less power in losses such as heat than the cylindrical rotor and as a result, it is considerably more efficient. Efficiency is a primary concern in industrial circuits such as robotics, because a highly efficient motor will run cooler and produce more torque or speed for its size. Thin-disk rotor PM stepper motors are also capable of producing almost double the steps per second of a conventional PM stepper motor. Figure 8 shows the basic construction of a thin-disk rotor PM motor. The rotor is constructed of a special type of cobalt-steel, and the stator poles are offset by one-half a rotor segment.

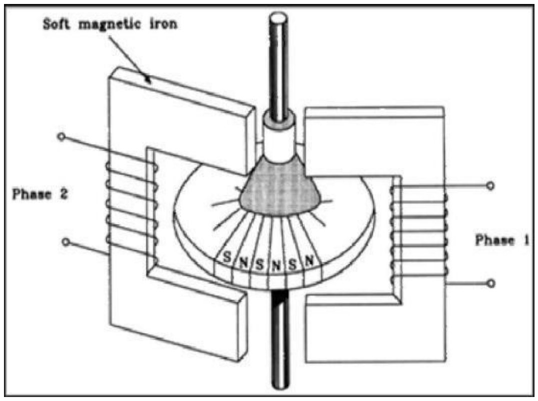
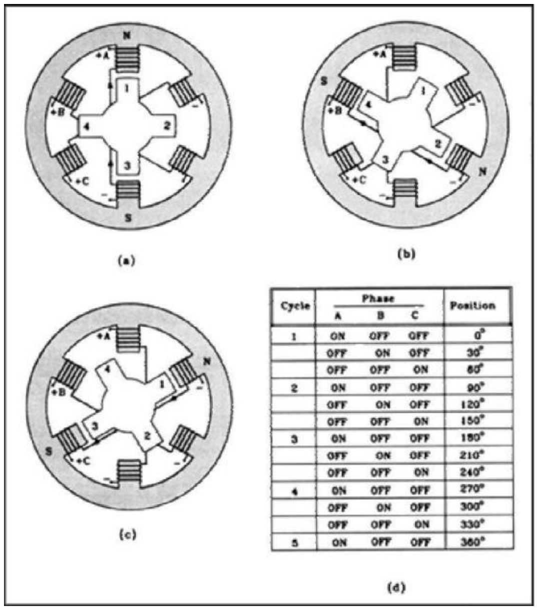



**Fig.5.14 Thin-disk rotor PM stepper motor.**

### 5.8.2 Variable-reluctance (VR) Stepper Motors

The variable-reluctance (VR) stepper motor differs from the PM stepper in that it has no permanent-magnet rotor and no residual torque to hold the rotor at one position when turned off. When the stator coils are energized, the rotor teeth will align with the energized stator poles. This type of motor operates on the principle of minimizing the reluctance along the path of the applied magnetic field. By alternating the windings that are energized in the stator, the stator field changes, and the rotor is moved to a new position.

The stator of a variable-reluctance stepper motor has a magnetic core constructed with a stack of steel laminations. The rotor is made of unmagnified soft steel with teeth and slots. Figure 9 shows a basic variable-reluctance stepper motor. In this circuit, the rotor is shown with fewer teeth than the stator. This ensures that only one set of stator and rotor teeth will align at any given instant. The stator coils are energized in groups referred to as phases. In Figure 9, the stator has six teeth and the rotor has four teeth. According to Eq. (1), the rotor will turn 30° each time a pulse is applied. Figure 9 (a) shows the position of the rotor when phase A is energized. As long as phase A is energized, the rotor will be held stationary. When phase A is switched off and phase B is energized, the rotor will turn 30° until two poles of the rotor are aligned under the north and south poles established by phase B. The effect of turning off phase B and energizing phase C is shown in Figure 9 (c). In this circuit, the rotor has again moved 30° and is now aligned under the north and south poles created by phase C. After the rot or has been displaced by 60° from its starting point, the step sequence has completed one cycle. Figure 9 (d) shows the switching sequence to complete a full 360° of rotation for a variable-reluctance motor with six stator poles and four rotor poles. By repeating this pattern, the motor will rotate in a clockwise direction. The direction of the motor is changed by reversing the pattern of turning ON and OFF each phase.




| Cycle | Phase A | Phase B | Phase C | Position |
|---|---|---|---|---|
| 1 | ON | OFF | OFF | 0° |
| | OFF | ON | OFF | 30° |
| | OFF | OFF | ON | 60° |
| 2 | ON | OFF | OFF | 90° |
| | OFF | ON | OFF | 120° |
| | OFF | OFF | ON | 150° |
| 3 | ON | OFF | OFF | 180° |
| | OFF | ON | OFF | 210° |
| | OFF | OFF | ON | 240° |
| 4 | ON | OFF | OFF | 270° |
| | OFF | ON | OFF | 300° |
| | OFF | OFF | ON | 330° |
| 5 | ON | OFF | OFF | 360° |

**Fig.5.15 Variable-reluctance stepper motor and switching sequence.**

The VR stepper motors mentioned up to this point are all single-stack motors. That is, all the phases are arranged in a single stack, or plane. The disadvantage of this design for a stepper motor is that the steps are generally quite large (above 15°). Multistack stepper motors can produce smaller step sizes because the motor is divided along its axial length into magnetically isolated sections, or stacks. Each of these sections is excited by a separate winding, or phase. In this type of motor, each stack corresponds to a phase, and the stator and rotor have the same tooth pitch.

### 5.8.3 Stepper Motor Applications

Stepper motors are used in a wide variety of applications in industry, including computer peripherals, business machines, motion control, and robotics, which are included in process control and machine tool applications.

## 5.9 Servo Motor | Servo Mechanism | Theory and Working Principle

This is nothing but a simple electrical motor, controlled with the help of servomechanism. If the motor as controlled device, associated with servomechanism is DC motor, then it is commonly known **DC Servo Motor**. If the controlled motor is operated by AC, it is called AC Servo Motor.

### Servo Motor Theory

There are some special types of application of electrical motor where rotation of the motor is required for just a certain angle not continuously for long period of time. For these applications some special types of motor are required with some special arrangement which makes the motor to rotate a certain angle for a given electrical input (signal). For this purpose **servo motor** comes into picture. This is normally a simple DC motor which is controlled for specific angular rotation with help of additional servomechanism (a typical closed loop feedback control system). Now day's servo system has huge industrial applications. Servo motor applications are also commonly seen in remote controlled toy cars for controlling direction of motion and it is also very commonly used as the motor which moves the tray of a CD or DVD player. Beside these there are other hundreds of servo motor applications we see in our daily life. The main reason behind using a servo is that it provides angular precision, i.e. it will only rotate as much we want and then stop and wait for next signal to take further action. This is unlike a normal electrical motor which starts rotating as and when power is applied to it and the rotation continues until we switch off the power. We cannot control the rotational progress of electrical motor; but we can only control the speed of rotation and can turn it ON and OFF.

Now we come to the specific answer of the question "**what is servo motor**?" **Servo motor** is a special type of motor which is automatically operated up to certain limit for a given command with help of error-sensing feedback to correct the performance.

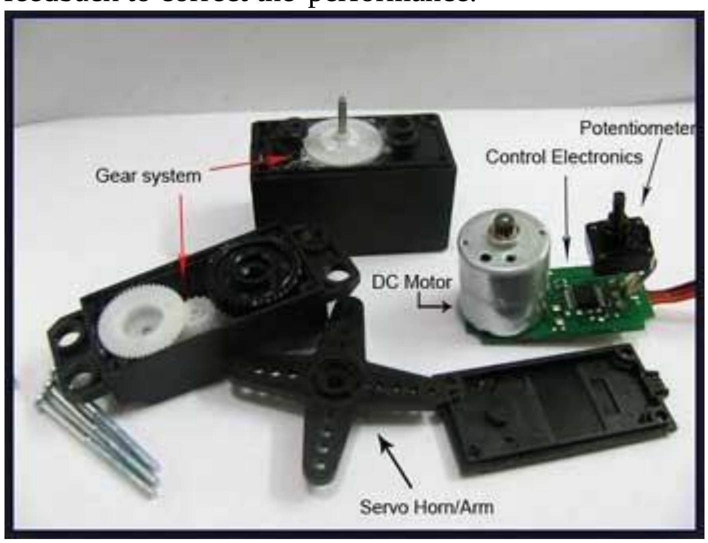



**Fig. 5.16 Servo Motor**

**Servo Motor Working Principle**

A servo system mainly consists of three basic components - a controlled device, a output sensor, a feedback system. This is an automatic closed loop control system. Here instead of controlling a device by applying variable input signal, the device is controlled by a feedback signal generated by comparing output signal and reference input signal. When reference input signal or command signal is applied to the system, it is compared with output reference signal of the system produced by output sensor, and a third signal produced by feedback system. This third signal acts as input signal of controlled device. This input signal to the device presents as long as there is a logical difference between reference input signal and output signal of the system. After the device achieves its desired output, there will be no longer logical difference between reference input signal and reference output signal of the system. Then, third signal produced by comparing theses above said signals will not remain enough to operate the device further and to produce further output of the system until the next reference input signal or command signal is applied to the system. Hence the primary task of a servomechanism is to maintain the output of a system at the desired value in the presence of disturbances.

**Working Principle of Servo Motor**

A servo motor is basically a DC motor(in some special cases it is AC motor) along with some other special purpose components that make a DC motor a servo. In a servo unit, you will find a small DC motor, a potentiometer, gear arrangement and an intelligent circuitry. The intelligent circuitry along with the potentiometer makes the servo to rotate according to our wishes.

As we know, a small DC motor will rotate with high speed but the torque generated by its rotation will not be enough to move even a light load. This is where the gear system inside a servomechanism comes into picture. The gear mechanism will take high input speed of the motor (fast) and at the output, we will get a output speed which is slower than original input speed but more practical and widely applicable.

Say at initial position of servo motor shaft, the position of the potentiometer knob is such that there is no electrical signal generated at the output port of the potentiometer . This output port of the potentiometer is connected with one of the input terminals of the error detector amplifier. Now an electrical signal is given to another input terminal of the error detector amplifier. Now difference between these two signals, one comes from potentiometer and another comes from external source, will be amplified in the error detector amplifier and feeds the DC motor. This amplified error signal acts as the input power of the dc motor and the motor starts rotating in desired direction. As the motor shaft progresses the potentiometer knob also rotates as it is coupled with motor shaft with help of gear arrangement. As the position of the potentiometer knob changes there will be an electrical signal produced at the potentiometer port. As the angular position of the potentiometer knob progresses the output or feedback signal increases. After desired angular position of motor shaft the potentiometer knob is reaches at such position the electrical signal generated in the potentiometer becomes same as of external electrical signal given to amplifier. At this condition, there will be no output signal from the amplifier to the motor input as there is no difference between external applied signal and the signal generated at potentiometer . As the input signal to the motor is nil at that position, the motor stops rotating. This is how a simple conceptual servo motor works.

Servo Motor Control

For understanding **servo motor control** let us consider an example of servomotor that we have given a signal to rotate by an angle of 45° and then stop and wait for further instruction.

The shaft of the DC motor is coupled with another shaft called output shaft, with help of gear

assembly. This gear assembly is used to step down the high rpm of the motor's shaft to low rpm at output shaft of the servo system.

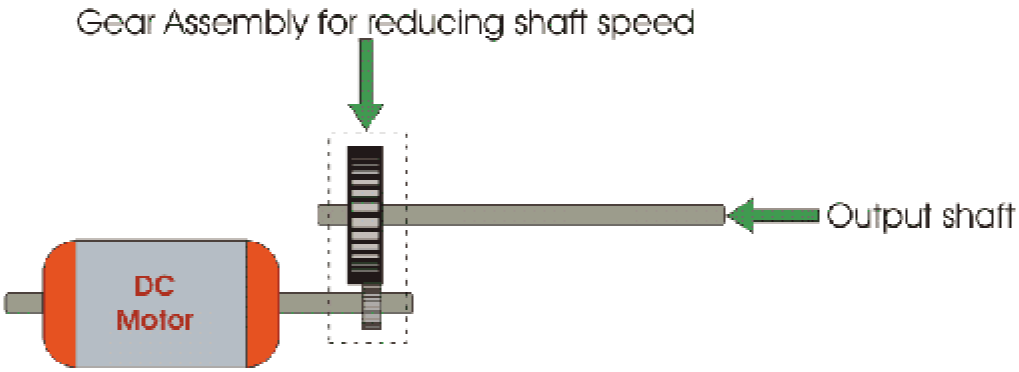



**Fig. 5.17**

The voltage adjusting knob of a potentiometer is so arranged with the output shaft by means of another gear assembly, that during rotation of the shaft, the knob also rotates and creates an varying electrical potential according to the principle of potentiometer . This signal i.e. electrical potential is increased with angular movement of potentiometer knob along with the system shaft from 0° to 45°. This electrical potential or voltage is taken to the error detector feedback amplifier along with the input reference commends i.e. input signal voltage.

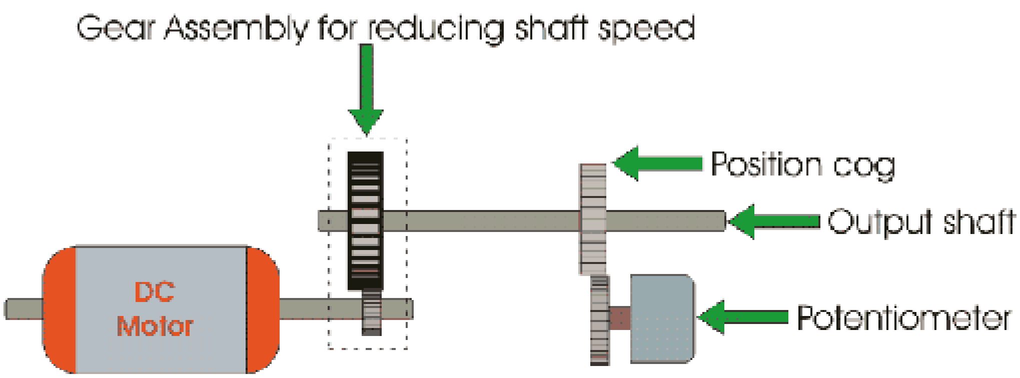



**Fig. 5.18**

As the angle of rotation of the shaft increases from 0° to 45° the voltage from potentiometer increases. At 45° this voltage reaches to a value which is equal to the given input command voltage to the system. As at this position of the shaft, there is no difference between the signal voltage coming from the potentiometer and reference input voltage (command signal) to the system, the output voltage of the amplifier becomes zero.

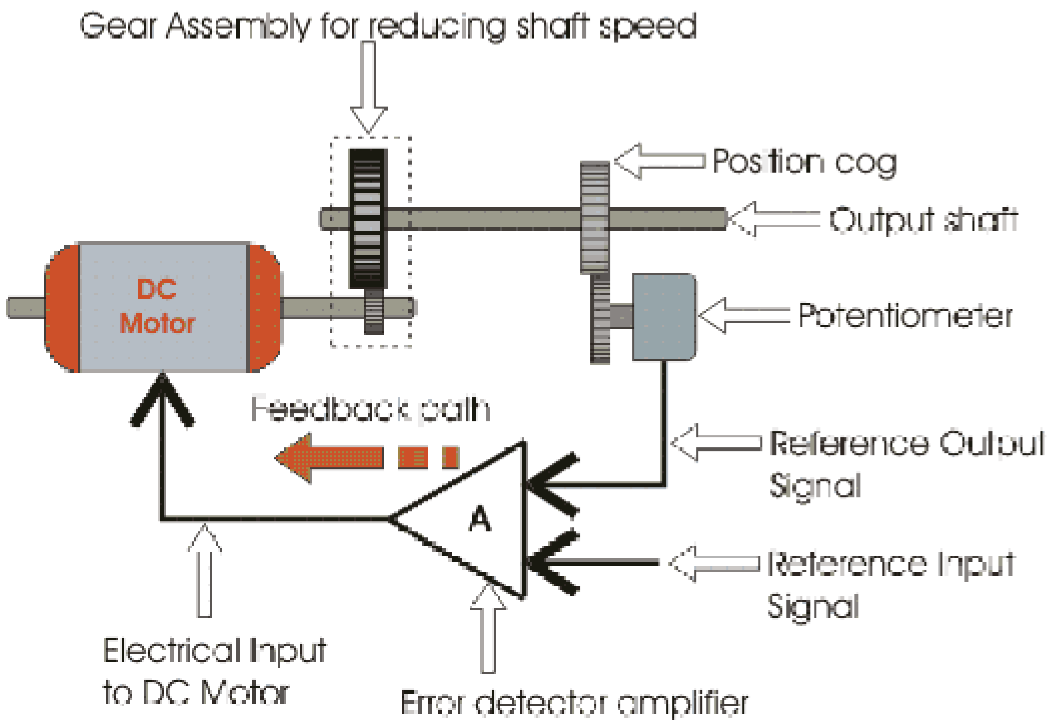


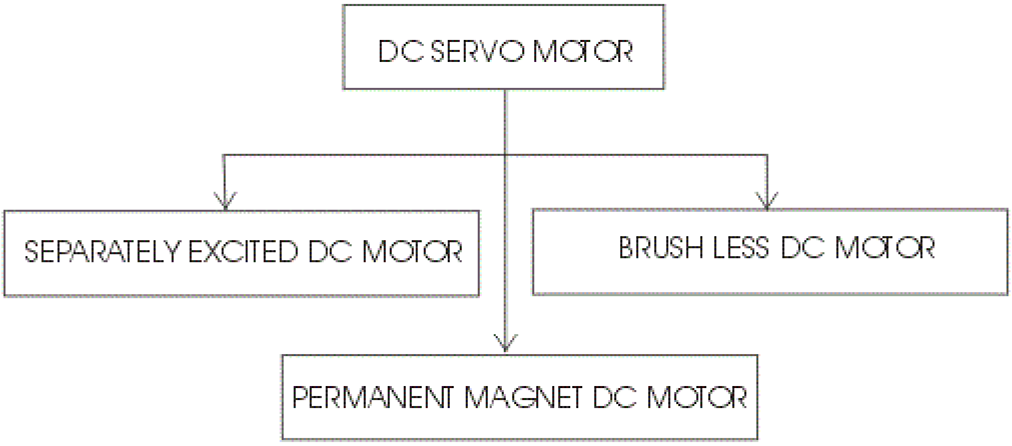

**Fig.5.19**

As per the picture given above the output electrical voltage signal of the amplifier, acts as input voltage of the DC motor. Hence the motor will stop rotating after the shaft rotates by 45°. The motor will be at this rest position until another command is given to the system for further movement of the shaft in desired direction. From this example we can understand the most basic **servo motor theory** and how **servo motor control** is achieved.

## 5.10 DC Servo Motors | Theory of DC Servo Motor

As we know that any electrical motor can be utilized as servo motor if it is controlled by servomechanism. Likewise, if we control a DC motor by means of servomechanism, it would be referred as **DC servo motor**. There are different types of DC motor, such shunt wound DC motor, series DC motor, Separately excited DC motor, permanent magnet DC motor, Brushless

DC motor etc. Among all mainly separately excited DC motor, permanent magnet motor and




brush less DC motor are used as servo.

**Fig.5.20**

### 5.10.1 Separately Excited DC Servo motor

**DC Servo Motor Theory**

The motors which are utilized as DC servo motors, generally have separate DC source for field winding and armature winding. The control can be archived either by controlling the field current or armature current. Field control has some specific advantages over armature control and on the other hand armature control has also some specific advantages over field control. Which type of control should be applied to the DC servo motor, is being decided depending upon its specific applications. Let's discus DC servo motor working principle for field control and armature control one by one.

**a) Field Controlled DC Servo Motor Theory**

The figure below illustrates the schematic diagram for a field controlled DC servo motor. In this arrangement the field of DC motor is excited be the amplified error signal and armature winding is energized by a constant current source .

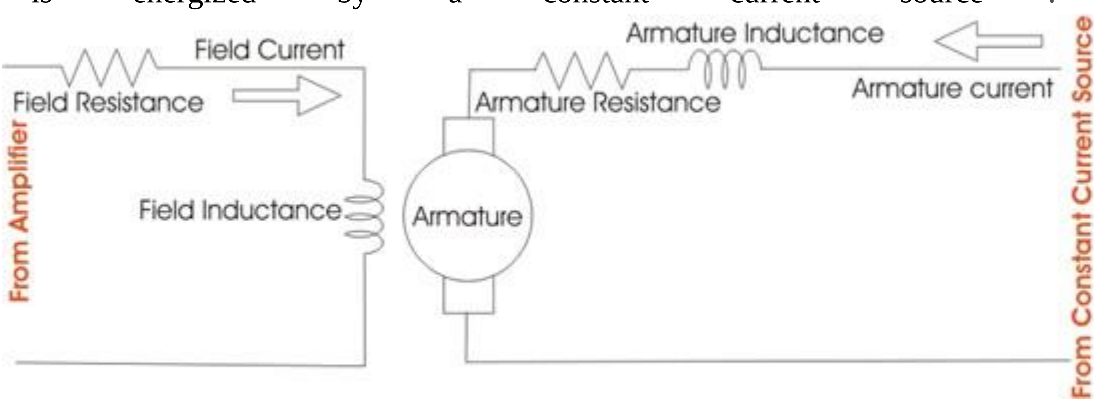



**Fig.5.21 Field controller DC servo motor**

The field is controlled below the knee point of magnetizing saturation curve. At that portion of the curve the mmf linearly varies with excitation current. That means torque developed in the DC motor is directly proportional to the field current below the knee point of magnetizing saturation curve.

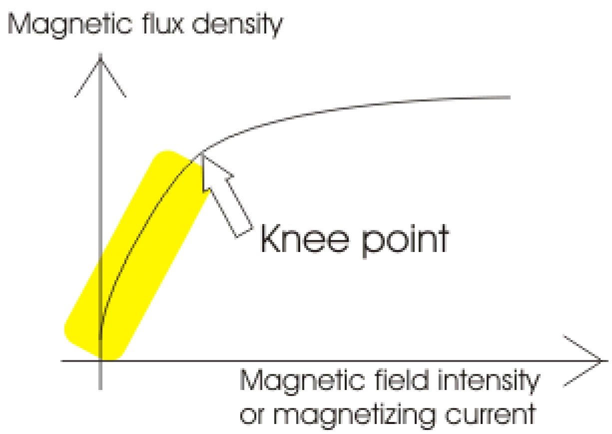



**Fig. 5.22**

From general torque equation of DC motor it is found that, torque $T \propto \varphi I_a$. Where, $\varphi$ is field flux and $I_a$ is armature current. But in field controlled DC servo motor, the armature is excited by constant current source , hence $I_a$ is constant here. Hence, $T \propto \varphi$

As field of this DC servo motor is excited by amplified error signal, the torque of the motor i.e. rotation of the motor can be controlled by amplified error signal. If the constant armature current is large enough then, every little change in field current causes corresponding change in torque on the motor shaft.

The direction of rotation can be changed by changing polarity of the field.
The direction of rotation can also be altered by using split field DC motor, where the field winding is divided into two parts, one half of the winding is wound in clockwise direction and other half in wound in anticlockwise direction. The amplified error signal is fed to the junction point of these two halves of the field as shown below. The magnetic field of both halves of the field winding opposes each other. During operation of the motor, magnetic field strength of one half dominates other depending upon the value of amplified error signal fed between these halves. Due to this, the DC servo motor rotates in a particular direction according to the amplified error signal voltage.
The main disadvantage of field control **DC servo motors**, is that the dynamic response to the error is slower because of longer time constant of inductive field circuit. The field is an electromagnet so it is basically a highly inductive circuit hence due to sudden change in error signal voltage, the current through the field will reach to its steady state value after certain period depending upon the time constant of the field circuit. That is why field control DC servo motor arrangement is mainly used in small servo motor applications.

The main advantage of using field control scheme is that, as the motor is controlled by field -

the controlling power requirement is much lower than rated power of the motor.

**b) Armature Controlled DC Servo Motor Theory**

The figure below shows the schematic diagram for an armature controlled DC servo motor. Here the armature is energized by amplified error signal and field is excited by a constant current source

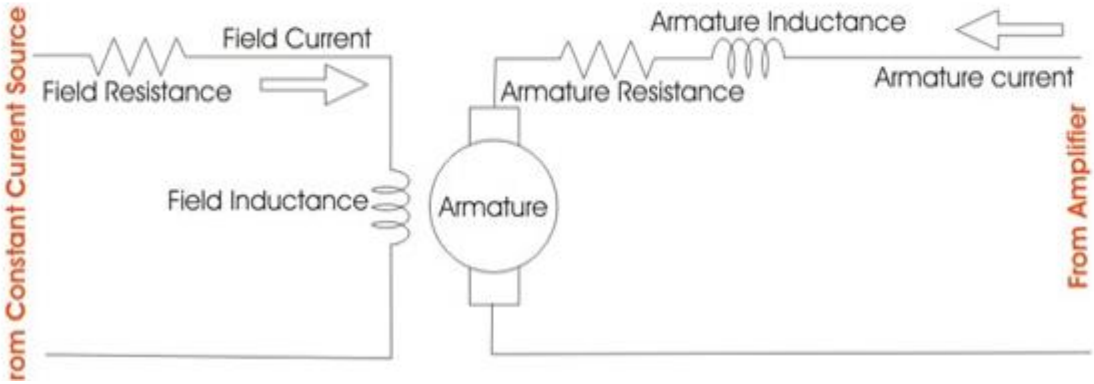



**Fig.5.23 Armature controller DC Servo motor**

The field is operated at well beyond the knee point of magnetizing saturation curve. In this portion of the curve, for huge change in magnetizing current, there is very small change in mmf in the motor field. This makes the servo motor is less sensitive to change in field current. Actually for armature controlled DC servo motor, we do not want that, the motor should response to any change of field current.

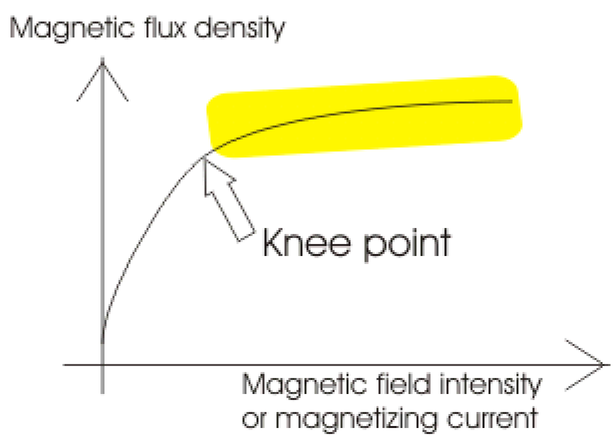



**Fig. 5.24**

Again, at saturation the field flux is maximum. As we said earlier, the general torque equation of DC motor is, torque $T \propto \varphi I_a$. Now if $\varphi$ is large enough, for every little change in armature current $I_a$ there will be a prominent changer in motor torque. That means servo motor becomes much sensitive to the armature current.

As the armature of DC motor is less inductive and more resistive, time constant of armature winding is small enough. This causes quick change of armature current due to sudden change in armature voltage. That is why dynamic response of armature controlled DC servo motor is much faster than that of field controlled DC servo motor. The direction of rotation of the motor can easily be changed by reversing the polarity of the error signal.

## PART A

1. Why a transformer is rated in KVA?
2. A single phase 3000/220V, 50Hz, core type transformer has a square cross section of 0.2 m side. If the maximum flux density in the core is 1.0T. Calculate the number of turns in HV and LV winding.
3. The maximum flux density in the core of a 110/220V, 1 phase transformer is 0.6Wb/m2. If the emf per turn is 6V, find the area of the core.
4. List the types of stepper motor
5. Draw the torque/speed characteristics of PM synchronous motor.
6. Draw the phasor diagram of PM synchronous motor.
7. Give the expression for the reluctance torque.
8. What is step angle and resolution of stepper motor?
9. Write the expression for 3-phase e.m.f. of a permanent magnet synchronous motor.
10. What is two-phase servomotor?
11. Bring out the differences between A.C.and D.C. servomotors.
12. Mention applications of stepper motors.
13. Explain the principle of operation of permanent magnet synchronous motor.

## PART B

1. Derive the emf equation of a transformer.
2. Explain the construction and working principle of transformer.
3. Explain the construction and working principle of permanent magnet stepper motor
4. Explain the construction and working Principle of
    i. DC servomotor
    ii. AC servomotor

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