DC MACHINES AND ALTERNATORS

Introduction:

- A machine which transfer (converts) energy either from mechanical to electrical form or from electrical to mechanical form, this process is called **electromechanical energy conversion**.
- Electrical machine which converts mechanical energy into an electrical energy is called an **electric generator**. Electrical machine which converts electrical energy into mechanical energy is called an **electric motor.**

Basics of Electromagnetism:

Magnet and magnetism:

A substance that attracts pieces of iron and steel is called a magnet and property of the material is called magnetism.

Magnets are classified into 3 types, they are. i) Permanent magnet ii) Temporary magnet iii) Electromagnet.

i) Permanent magnet:

A magnet that retains its magnetic properties in the absence of an inducing field or current.

ii) Temporary magnet:

A magnet that create its own magnetic field while in the presence of a stronger magnet.

iii) Electromagnet:

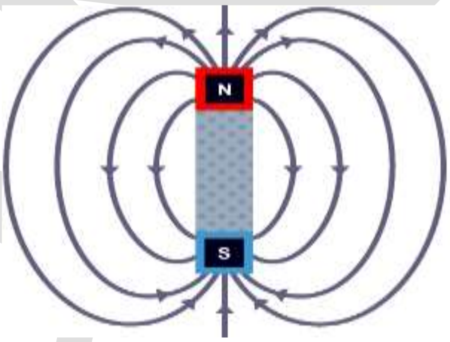
Electromagnet is a type of magnet in which the magnetic field is produced by an electric current.

Magnetic field:

The magnetic field is the area around a magnet in which there exists a magnetic force.

Magnetic flux:

Magnetic flux is the number of magnetic lines of forces discharge from a magnetic material. It is represented by ϕ and its unit is Weber (Wb).



Magnetic flux density:

The magnetic flux density is the flux per unit area at right angle (90^0) to the flux. It is represented by **B** and its unit is Wb/m2 or Tesla.

$$B = \frac{\phi}{A}$$

Permeability:

It is defined as the ability in which the magnetic material forces the magnetic flux through a given medium. It is represented by a letter μ and its unit is Henries per meter. (H/m)

$$\mu = \mu_0 \mu_r$$

Where μ_0 is the permeability of free space or air and

μr is the relative permeability of the medium with respect to air,

$\mu o = 4\pi \times 10^{-7}$ H/m

Magnetic permeability is the opposite of magnetic reluctance.

Reluctance:

It is the property of a material which opposes the establishment of magnetic flux in it.

It is represented by S and its unit is AT/Wb

$$S = MMF / \phi \; ; \; S = l / \mu A \; ;$$

Magneto motive force MMF:

In an electric circuit an electromotive force is required to produce current flow. In magnetic circuits magneto motive force is required for the flow of flux. It is found that a product of number of turns in the winding and the current flowing in. It is a measure of how much excitation is applied. This product is called magneto motive force.

The force which causes the magnetic flux in a magnetic circuit is called magneto motive force. The unit of MMF is Ampere Turns.

$$MMF = NI$$

Coulomb's law of magnetic force:

When two isolated poles are placed nearer to each other, they experience a force.

First law:

Like poles repel each other while unlike poles attract each other.

Second law:

The force between two magnetic poles is directly proportional to the product of their pole strength and inversely proportional to the square of the distance between their centers.

$$F \alpha \; m_1 \; m_2 / d^2$$

Where m_1 & m_2 represents the magnetic field strength of the two poles and d represents the distance between the two poles.

Magnetic effects of electric current:

When an electric current flows through a conductor, magnetic field is set up all along the length of the conductor. The magnetic effects of electric current are:

i. The greater the current flow to the conductor, the stronger is the magnetic field and vice versa.

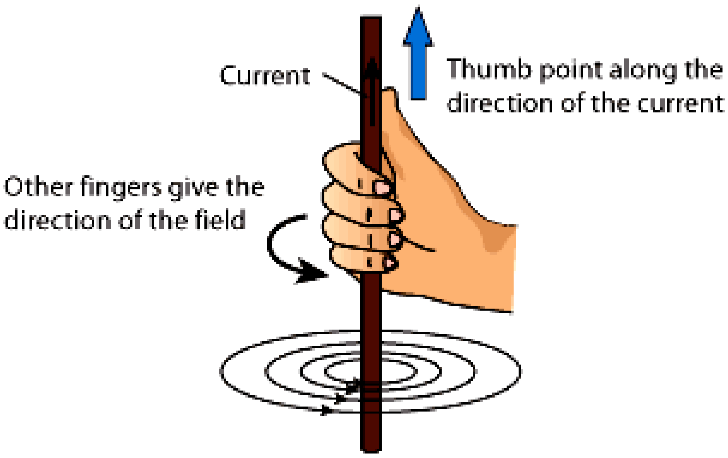
ii. The magnetic field near the conductor is stronger and weaker away from the conductor.

iii. Magnetic lines of force around the conductor will be either clockwise or anticlockwise, depending upon the direction of current. Right Hand Thumb Rule is used to determine the direction of magnetic field around the conductor.

iv. The shape of the magnetic field depends upon the shape of the conductor.

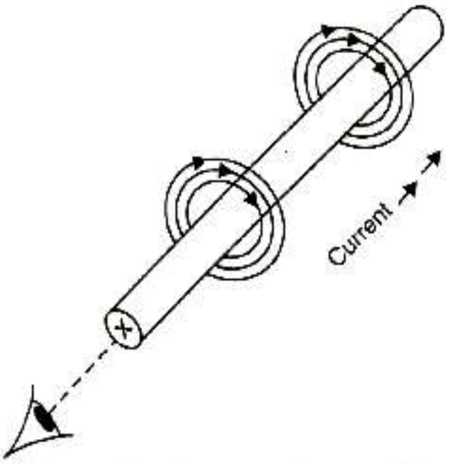
Right Hand Thumb Rule:

Hold the conductor in the right hand with the thumb pointing in the direction of current as shown in the below figure. Then the fingers will point the direction of the magnetic field around the conductor.

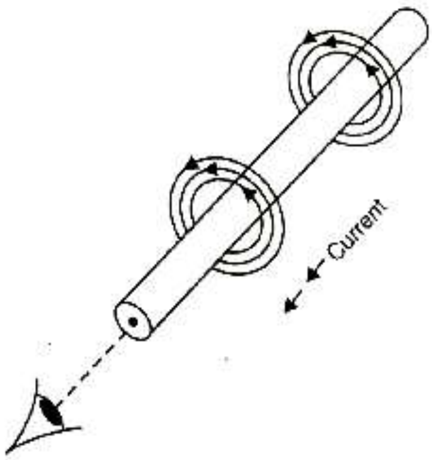


Cross and Dot notation:

Cross and Dot notation can be used to indicate the direction of current flow. In the below figure (i), current flowing away from observer is indicated by cross. The cross is based on the tail of an arrow moving away from the observer. Below Figure (ii) also shows that current flowing towards an observer and is indicated by a dot. The dot is based on the point of an arrow moving towards the observer.



(*i*) Current Flowing away from an Observer

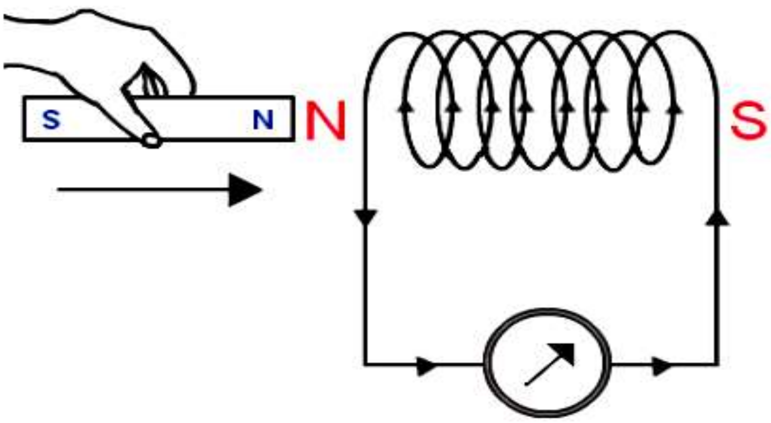


(*ii*) Current Flowing toward an Observer

Faraday's laws of electromagnetic induction

DC generator works on the principle of Faraday's law of electromagnetic induction.

Faraday's experiment:



Consider a coil C of several turns connected to a central zero galvanometer as shown in the above figure. If a permanent magnet is moved towards the coil it will be observed that the galvanometer shows deflection in one direction. If the magnet is moved away from coil, the galvanometer again shows deflection but in opposite direction. Deflection of galvanometer indicates there is a current flow through the coil. For the current to flow, there must be an EMF in the coil. Hence it is concluded that when magnetic flux linking a conductor or coil changes an EMF is induced in it.

Faraday's laws of electromagnetic induction:

First law :

Whenever the magnetic flux linking a conductor or coil changes, an EMF is induced in it.

Second law:

The magnitude of the EMF induced in a conductor or coil is directly proportional to the rate of change of flux linkage. Here the minus sign of the RHS represents the Lenz's law.

Induced EMF $e \propto d\phi/dt$

$e = - N\, d\phi/dt$

Faradays law states that whenever a conductor cuts the magnetic flux or magnetic flux cuts the conductor, an EMF is induced in the conductor.
Therefore the essential components of a generator are
i. Magnetic field.
ii. Conductor or a group of conductors
iii. Motion of conductor with respect to magnetic field.(prime mover)

For the generation of induced EMF there should be a relative motion between the conductor and the magnetic field. i.e. either the magnetic field should be moved while conductor is being stationary or the conductor is made to move in a stationary magnetic field.
When the magnetic flux linking a conductor or coil changes, an EMF is induced in the conductor. This can be done in two ways.

1) Dynamically induced EMF:

If the conductor is moved in a stationary magnetic field then the EMF induced is called dynamically induced EMF. Example: DC generator.

2) Statically induced EMF:

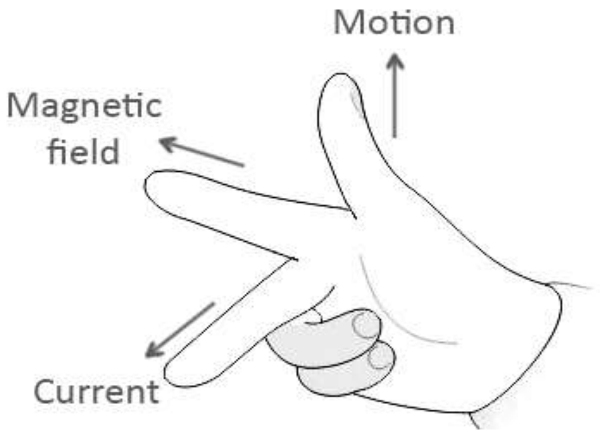
If the conductor is stationary and the magnetic field is moving or changing then the induced EMF is called statically induced EMF. Example: Transformer and ac generator (alternator).
Statically induced EMF can be classified into two types, they are

a) **Self-induced EMF:** The phenomenon in which a changing current in a coil, induced an EMF itself is called self-induced EMF.
b) **Mutually induced EMF:** The EMF induced in one coil by the influence of the other coil is called mutually induced EMF.

Direction of induced EMF and current:

The direction of induced EMF and current can be determined by one of the following two methods 1.Lenz's law 2.Fleming's right hand rule.

1. **Lenz's law:**
The induced current will set up magnetic flux that opposes the increase in flux through the coil.
2. **Fleming's right hand rule:**
This law is used to find the direction of the induced EMF of DC generator. Hold the fore finger, middle finger and thumb of the right hand mutually perpendicular to one another. If the fore finger points in the direction of magnetic field, thumb in the direction of motion of conductor then the middle finger will point the direction of induced current.



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UNIT 1

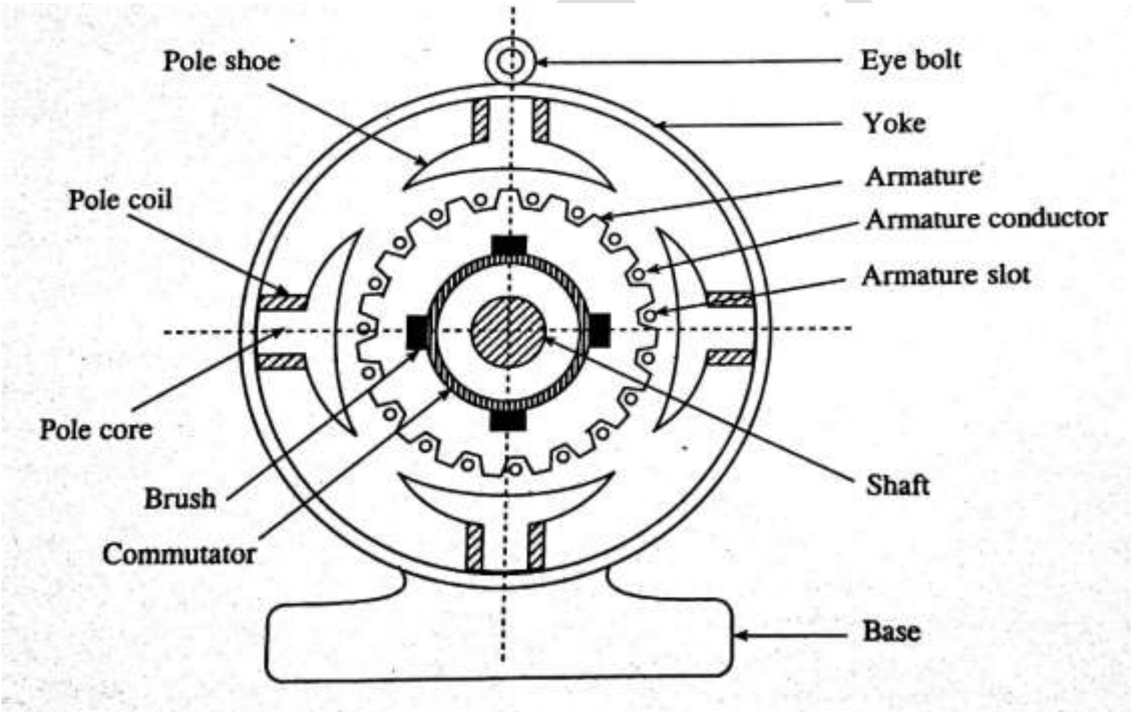
DC GENERATORS CONSTRUCTION AND WORKING

DC GENERATORS:

DC generator is an electrical machine which converts mechanical energy into direct current (DC) electricity.

- Energy conversion is based on the principle of Faraday's Law of electromagnetic induction.
- Whenever a rotating conductor cut's the stationary magnetic flux, an EMF will be induced, this induced EMF causes a current to flow through a conductor circuit.

CONSTRUCTION:



DC machine consists of following parts:

1) Stator.
2) Armature (Rotor).
3) Commutator.
4) Brushes and Bearings.
5) Shaft.
6) End plates.

1) **STATOR:**

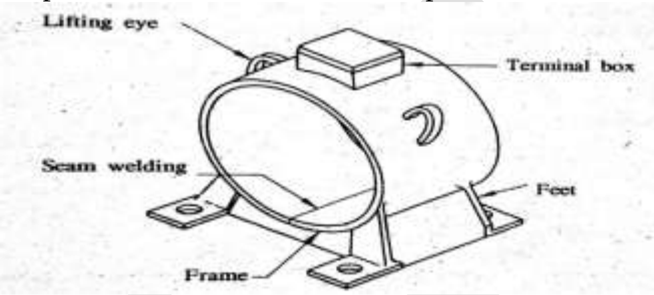
- Stator is the stationary part of a DC generator (machine).
- Stator is a magnetic field system. Function of this part is to create a uniform magnetic field. This magnetic field system consists of yoke and pole.

YOKE:

- The outermost layer of a DC generator (machine) is called yoke (Magnetic frame).
- Yoke is made-up of cast iron (small machines) **or** cast steel (large machines).

Functions:

- It provides mechanical support for poles and field windings.
- To provide magnetic path for the field flux.
- The insulating material gets protected from harmful atmospheric elements like dust, moisture, gas.

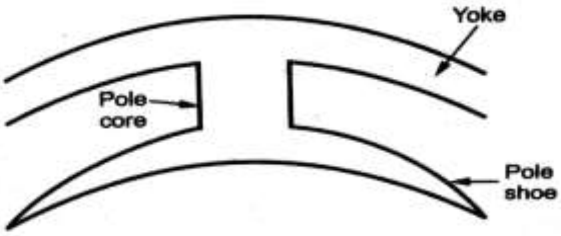


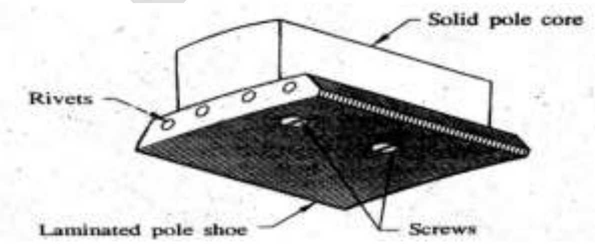
POLE: Pole is a north or south magnetic field of force that is generated by a permanent magnet or current passing through a coil of wire.

- Each pole is divided into two parts, they are.
  - ➢ Pole core.
  - ➢ Pole shoe.

POLE CORE: Pole core provides base for the windings. Pole core is made-up of cast steel **or** cast iron.

POLE SHOE: Pole shoe gives support to the field coils and distributes the flux in the air gap. Pole shoe made-up of silicon steel lamination.



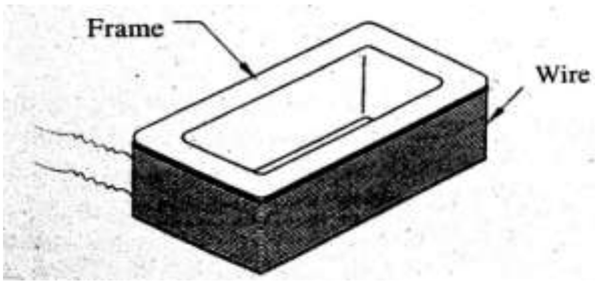


❖ Function of field poles are

- To provide low reluctance magnetic path to the field flux.
- To support field windings.
- To distribute the field flux uniformly around the armature.

POLE COILS (FIELD WINDING):

Field windings are made-up of copper conductors insulated by impregnated paper or varnish or double cotton covering. The main function of the field coils is to produce the field flux when DC supply is given to them.



2) **ARMATURE (ROTOR):**

Armature core is a rotating part of a DC generator. Armature consists of two main parts, they are

i. Armature core.

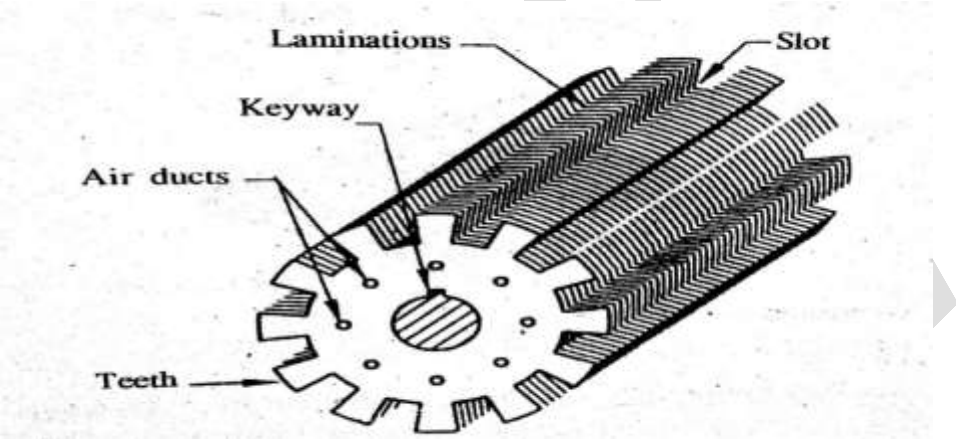
ii. Armature windings.

i. Armature core:

- Armature core is made-up of silicon steel.
- Armature core is in cylindrical shape mounted on the shaft. It consists of slots on its outer periphery (surface) & each slot contains armature conductors with varnish insulator. (in between core and windings).

Functions:

- It provides house for armature windings in the slots.
- Armature core lamination (varnish insulation) reduces eddy current losses.



ii. **Armature winding (Conductors):**

Armature winding is the inter connection of armature conductors placed in the armature core slot. It's made-up of Enamelled copper wire.

Functions:

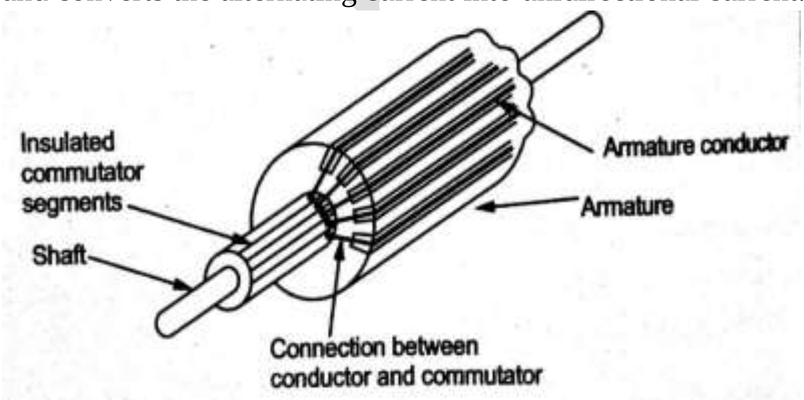
- Generates EMF in the armature winding with the help of field fluxes.
- It carries induced current to outside.

3) **COMMUTATOR:**

- A commutator is a rotary electrical switch & that periodically reverses the current direction between the rotor & the external circuit.
- Commutator is made-up of Hard-drawn (Thick wire having high tensile strength) copper wire.

Functions:

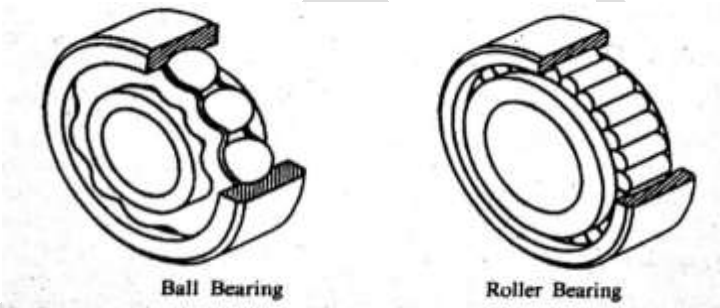
- It provides the electrical connection between the rotating armature coils and the stationary external circuit.
- The function of commutator is to easier collection of current from the armature conductor. It rectifies and converts the alternating current into unidirectional current.



4) **BRUSHES AND BEARINGS:**

- Brushes are made-up of copper or carbon or alloy of copper & carbon.
- The main function of the brushes is to collect the current from the commutator and supply it to the external load circuit. It provides electrical connection between the rotating commutator and stationary external load circuit.

- Bearings are made up of cast steel. Ball bearings are used in small machines and Roller bearings (Roller bearings having lubricant oil for quicker operation) are used in large machines. Bearings are connected in both the ends of the machine for the easy movement of rotor.



5) **SHAFT:**

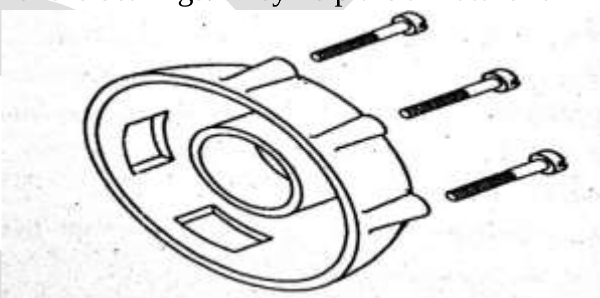
Shaft is made-up of mild steel (high strength steel) with a maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine.

Functions:

- It supports the armature, armature windings and commutator.
- Helps the armature to rotate.

6) **END PLATES:**

End plate provides a house for the bearings. They help the armature for frictionless rotation.



MATERIALS USED IN CONSTRUCTION OF DC GENERATOR:

- Cast iron **or** cast steel is used for designing the outer frame **or** Yoke and pole core of DC generator.
- High enamelled (magnetic) copper wire is used for designing the armature winding.
- Cast iron **or** cast steel **or** silicon steel is used for construction of armature core.
- High strength (Hard drawn) copper wire is used for construction of commutator.
- Carbon is used for designing the brushes of generator.

PROPERTIES OF MATERIALS USED FOR DC MACHINE (GENERATOR):

✓ **CAST IRON:**
- Hard and low strength.
- Low in ductility (flexibility).

✓ **CAST STEEL:**
- High strength.
- High corrosion resistance.

✓ **COPPER:**
- Good conductor of electricity.
- High melting point.
- Good resistance to corrosion.

✓ **CARBON:**
- High thermal conductivity.
- Poor electric conductivity.
- Very good lubricant.

Or

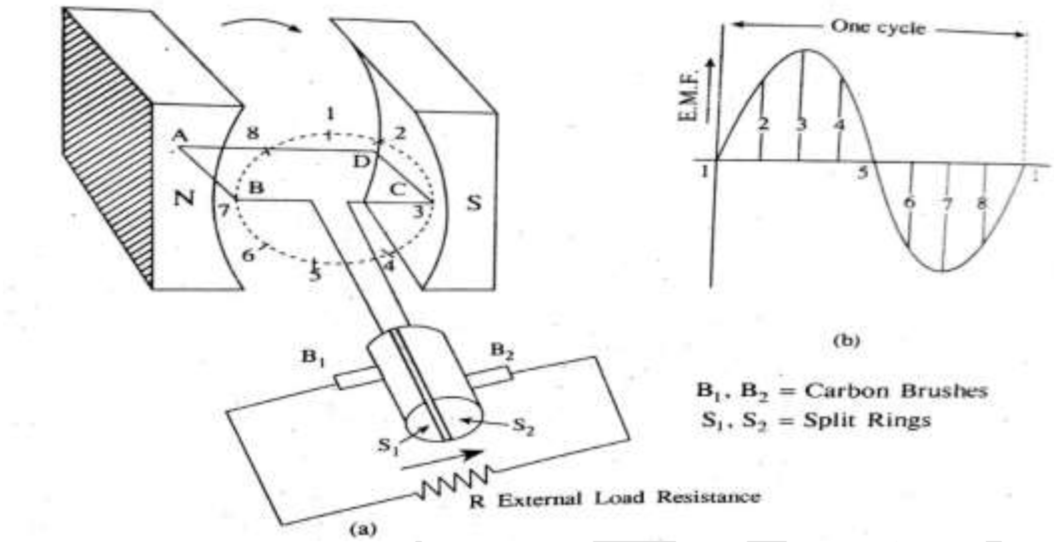
- Resistivity (resisting power) of the material used for the winding is low. So voltage drop and copper losses is less.
- Resistance temperature co-efficient is low. So that change in the temperature as small effect on resistance value.
- The material have high magnetic permeability (material to support the formation of a magnetic field). So that weak current can produce large flux.
- The resistance of the material used for the yoke and core is high. So that eddy current (current induced in a conductor by a varying magnetic field) losses are low.

SLOT INSULATION MATERIALS AND THEIR PROPERTIES:

The back portions of the coils insulated with varnish and cotton tape is connected in between winding and slot core.

Properties:
- High insulating resistance.
- High dielectric (medium or substance that transmits electric force without conduction) strength.
- Providing mechanical strength.
- High melting point.
- No attraction for moisture.

WORKING PRINCIPLE OF DC GENERATOR
Or
EMF INDUCED IN A SIMPLE LOOP GENERATOR and its DIRECTION



Principle of operation:

DC Generator works on the principle of Faraday's law of electromagnetic induction (Dynamically induced EMF). Whenever field flux is cut by the armature conductor an EMF is induced, which cause a current to flow if the conductor circuit is closed.

WORKING:

- Consider single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in fig (a) & alternating induced EMF in different position as shown in fig (b).
- The coil rotates, the flux linking the coil sides AB and CD changes continuously. The EMF induced in these coil sides also changes, but it produces alternating EMF.

Position 1:

When the coil is in the position No1 as shown in the fig (a), the EMF induced is zero because coil sides (AB&CD) are cutting no flux but are moving parallel to the field lines.

Position 2:

The coil is coming to position No2, the coil sides are moving at an angle to the flux and a low EMF is generated as indicated by point 2 in fig (b).

Position 3:

The coil is moving to position No3, the coil sides (AB&CD) are at perpendicular to the flux and are cutting the flux at a maximum rate. The generated EMF is maximum as indicated by point 3 in fig (b).

Position 4:

The coil is moving to position No4, the generated EMF is less because the coil sides are cutting the flux at an angle. It indicated at point 4 in fig (b).

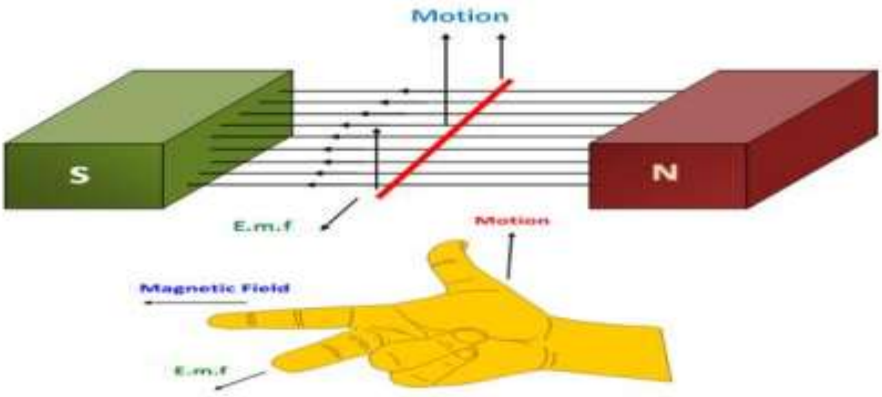
Position 5:

The coil is moving to position No5, no magnetic fluxes are cut by conductor (flux lines are parallel to conductor) and hence induced EMF is zero. It indicated at point 5 in fig (b).

- The coil sides move under a pole of opposite polarity and hence the direction of generated EMF is reversed. The maximum EMF in this direction will occur when the loop is at position 7 is shown in fig (b).
- EMF induced in the armature conductors of a DC generator is alternating, which is rectified by the split-ring known as commutator and then the carbon brushes collected the current from the commutator and supply to the external load circuit.

DIRECTION OF INDUCED EMF:

Direction of induced EMF is defined by Flaming's right-hand rule, which states that to hold **First** three fingers of right hand mutually perpendicular to each other, Fore finger indicates the direction of magnetic field, Thumb indicates the direction of Motion of the conductors, then Middle finger indicates the direction of induced EMF.



INDUCED EMF IN THE DC GENERATOR:

Let,

Z= Total number of armature conductors.
P= Numbers of poles.
N= Speed of the armature in rpm.
A= Number of parallel paths in the armature.
Ø = Flux produced per pole in Weber's.

The flux cut by the conductor in one revolution = ØP = dØ

The Time taken by the conductor to completing one revolution is = $\frac{60}{N}$ seconds=dt

EMF induced in one conductor = $\frac{d\text{Ø}}{dt} = \frac{\text{Ø}P}{60/N} = \frac{\text{Ø}PN}{60}$ …………volts

EMF induced per parallel path = (EMF induced per conductor × Number of conductor Per parallel path)

$$E_g = \frac{\text{Ø}PN}{60} \times \frac{Z}{A}$$

$$\boxed{\mathbf{E_g} = \frac{\textbf{ØPNZ}}{\mathbf{60}A} \text{………………volts}}$$

For lap winding: A=P

$$\mathbf{E_g} = \frac{\textbf{ØNZ}}{\mathbf{60}}$$

For wave winding: A=2

$$\mathbf{E_g} = \frac{\textbf{ØPNZ}}{\mathbf{120}}$$

TYPES OF DC GENERATORS:

Generators are classified according to the method of their field excitation.
The process of generating a magnetic field by means of an electric current is called excitation.

Or

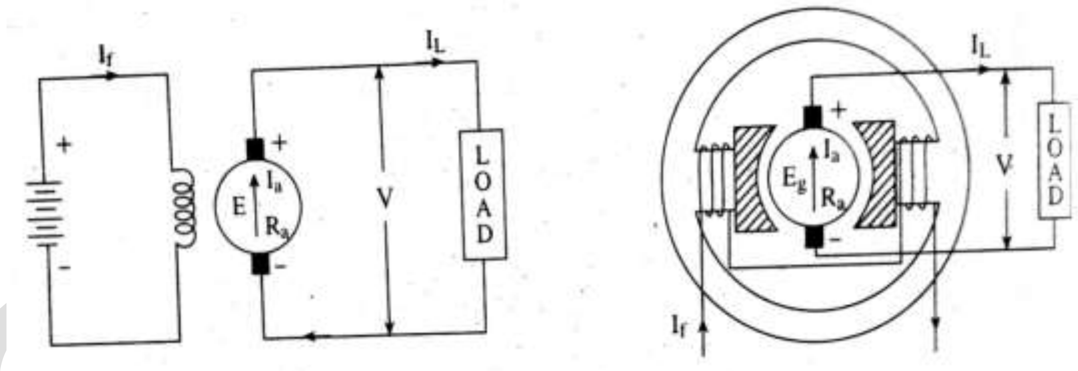
The system that provides current to the field winding to produce (generate) magnetic field is known as excitation.

Generator can be mainly classified in to the following types.

1. SEPARATELY EXCITED DC GENERATOR.
2. SELF EXCITED DC GENERATOR.
    A. SERIES WOUND DC GENERATOR.
    B. SHUNT WOUND DC GENERATOR.
    C. COMPOUND WOUND DC GENERATOR.
        a) CUMULATIVE LONG SHUNT COMPOUND WOUND DC GENERATOR.
        b) DIFFERENTIAL LONG SHUNT COMPOUND WOUND DC GENERATOR.
        c) CUMULATIVE SHORT SHUNT COMPOUND WOUND DC GENERATOR.
        d) DIFFERENTIAL SHORT SHUNT COMPOUND WOUND DC GENERATOR.

1. SEPARATELY EXCITED DC GENERATOR:

Dc generator field windings are energised from external source of DC current is called separately excited DC Generator.



The field current (I_f) of this machine is supplied by another generator (source) is called exciter or Battery.

This type of DC generators are generally more expensive than self-excited DC generator, because of their requirement of separate excitation source.

Relations:

Armature current = $I_a = I_L$………..Amps

Terminal voltage = $V=E_g-I_aR_a$-brush drop ......Volts

Power developed = $P=E_gI_a$………..Watts

Power delivered to load=$P_{out}=VI_L$

Applications:

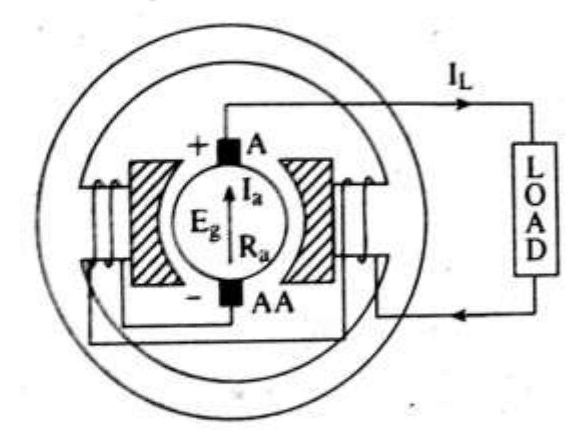
- Used for testing purpose in the laboratories, because of their ability of giving wide range of voltage output.
- Used as supply source of DC motors (Motor speed are to be controlled for various applications).

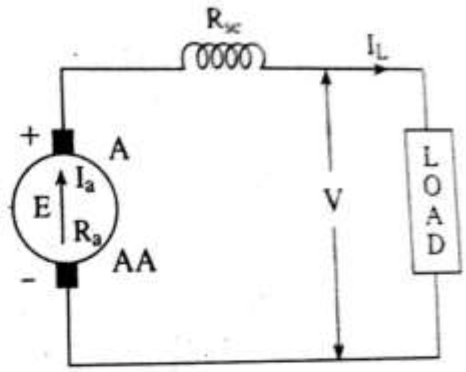
2. **SELF EXCITED DC GENERATOR:**

- Dc generator field windings are energised by the current produced by the generators itself is called self-excited DC Generator.
- In a self-excited generator field coils are connected in series with the armature coils (series wound generator) or parallel with armature coils (shunt wound generator) or partly in series and partly in parallel with armature coils (compound wound generator).

a. **SERIES WOUND DC GENERATOR.**

The field winding of a DC generator is connected in series with the armature windings is called series wound DC generator.





Whole current flows through the field coils as well as the load.

Series field winding carries the full load current, they are made-up of large cross-sectional area and having low resistance (nearly 0.5Ω).

RELATIONS:

Armature current = $I_a = I_{se} = I_L = I$…………Amps

Terminal voltage = $V = E_g - I_a(R_a + R_{se})$-brush drop.......Volts

Power developed = $P = E_g I_a$………………Watts

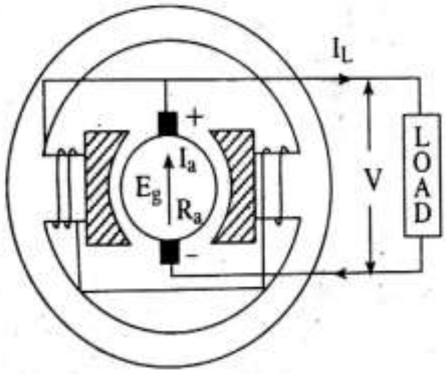
Power delivered to load=$P_{out} = VI_L$

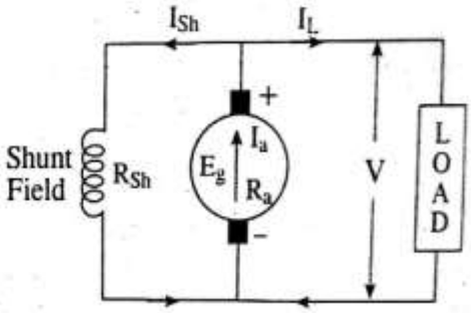
Applications:

- Used as boosters for adding voltage to the transmission lines & to compensate for the line drop.
- Used in arc welding.
- Used in arc lighting.
- Used in series incandescent lighting.
- Used for supplying field excitation DC current to locomotives (rail engine).

b. <u>SHUNT WOUND DC GENERATOR:</u>

- The field windings of DC generator is connected in parallel with the armature windings is called shunt wound DC generator.
- Total generated current is divided into field winding current and load current. ($I_a = I_{sh} + I_L$)





- In shunt wound DC generators the voltage in the field winding is same as the voltage across the terminal.
- The armature current (I_a) splits in to Ish & I_L. $I_a = I_{sh} + I_L$

<u>Relations:</u>

Armature current = $I_a = I_{sh} + I_L$…………Amps

Terminal voltage = $V = E_g$-IaRa-brush drop ....Volts

Power developed = $P = E_g I_a$……………….Watts

Power delivered to load=$P_{out} = VI_L$

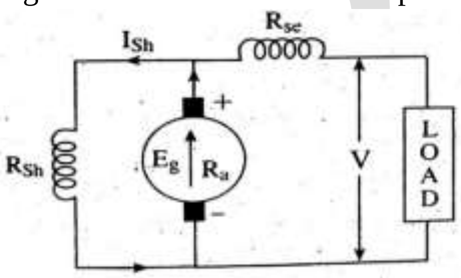
<u>Applications:</u>

- Used for small power supply.
- Used for constant terminal voltage requirement.
- Lighting purpose.
- Charging batteries.
- To provide DC excitation to the AC generator.

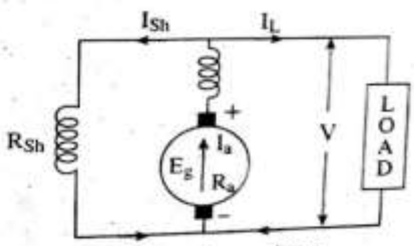
c. <u>COMPOUND WOUND DC GENERATOR:</u>

Both shunt & series field windings are wound on the same pole is called compound wound DC generator.

One winding is in series and the other in parallel with the armature.



Short shunt



Long shunt

Compound wound dc generators are classified in to two types, they are

i. Short shunt compound wound DC generator.

ii. Long shunt compound wound DC generator.

The shunt field winding is connected in parallel with the armature winding is called **short shunt compound wound DC generator.**

The shunt field winding is connected in parallel with the both the armature & series field winding combination is called **long shunt compound wound DC generator.**

SHORT SHUNT COMPOUND DC GENERATOR:

Relations:

Series field current = $I_{se}=I_L$…………...Amps

Shunt field current = I_{sh}= $(V+I_LRse)$ / R_{sh} = $(E_g-I_aR_a)$ / R_{sh}……Amps

Armature current = I_a =$I_{sh}+I_L$…………………Amps

Terminal voltage = $V=E_g$-IaRa-I_LR_{se}-Brush drop...............Volts

Power developed = $P=E_gI_a$……………………Watts

Power delivered to load=$P_{out}=VI_L$

LONG SHUNT COMPOUND DC GENERATOR:

Relations:

Shunt field current = I_{sh}= V/ R_{sh}………………Amps

Armature current = I_a =I_{se}=Ish+I_L…………………Amps

Terminal voltage = $V=E_g$-IaRa-$I_{se}R_{se}$-Brush drop...............Volts

Power developed = $P=E_gI_a$……………………Watts

Power delivered to load=$P_{out}=VI_L$

CUMULATIVE (COMMUTATIVELY) AND DIFFERENTIALCOMPOUND GENERATOR:

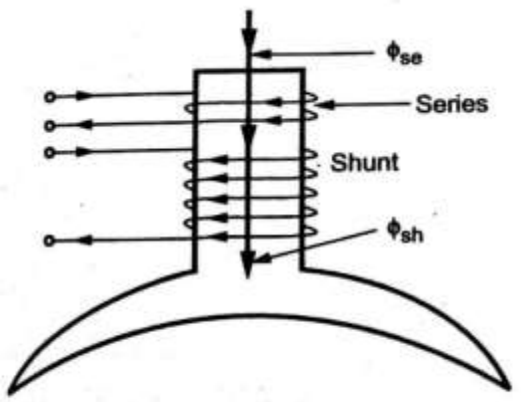
- Depending on the direction of winding on the pole, compound wound DC generator classified in to two types, they are (1) Cumulative compound wound DC generator. (2) Differential compound wound DC generator.
- The DC generator series field fluxes assists (help) the shunt field fluxes is called cumulative compound wound DC generator.

  $\Phi_T = \Phi_{sh} + \Phi_{se}$

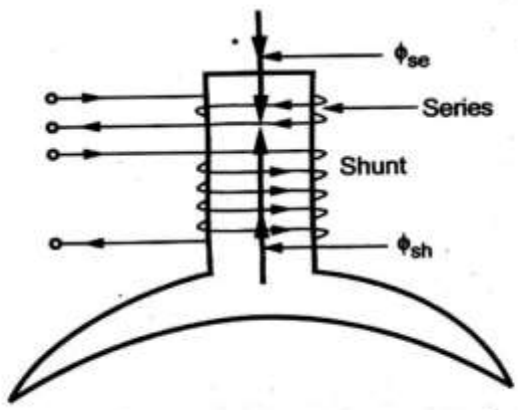
  Where, Φ_{sh} = flux produced by shunt field winding.

  Φ_{se} = flux produced by series field winding.
- The DC generator series field fluxes opposes the shunt field fluxes is called differential compound wound DC generator.

  $\Phi_T = \Phi_{sh} - \Phi_{se}$



Cumulative compound generator



Differential Compund generator

Applications:

- Compound generators are used to supply power for offices, hostels & lodges.
- Used in arc welding. (provide constant current)
- Compound generators are used to compensate the voltage drop in feeders.
- Compound generators are used to power supply in DC welding.
- Compound wound generators are generally used for lighting & power supply purpose.
- Cumulative compound wound generators are used for driving a motor.

ARMATURE WINDINGS:

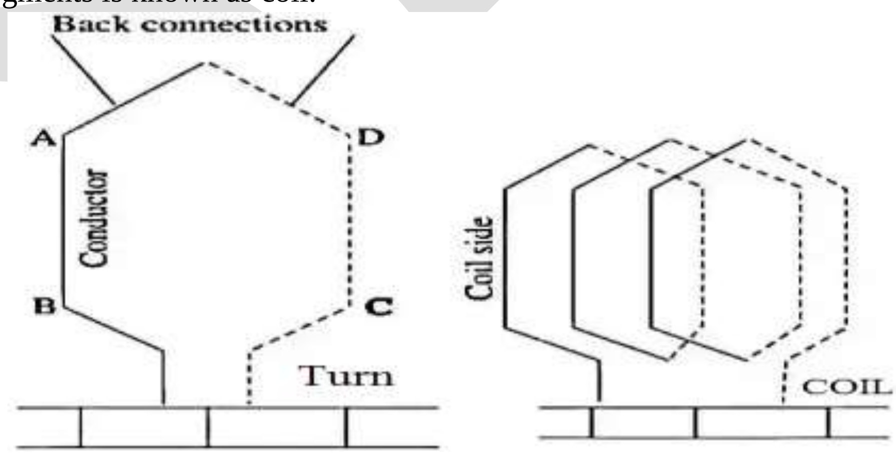
- Armature winding is an arrangement of conductors to develop desired (required) EMF by relative motion with in a magnetic field.
- Conductor or group of conductors are distributed in different ways in slots all over the periphery of the armature winding.
- The conductors may be connected in series and parallel combinations, depending upon the current and voltage rating of the machine. i. conductors connected in series to raise voltage ratings.
  ii. Conductors connected in parallel to raise current ratings.
- Armature windings are classified in to two types, they are
  a) RING TYPE WINDINGS. (not used in modern DC machines)
  b) DRUM TYPE WINDINGS.

TERMS USED IN ARMATURE WINDINGS:

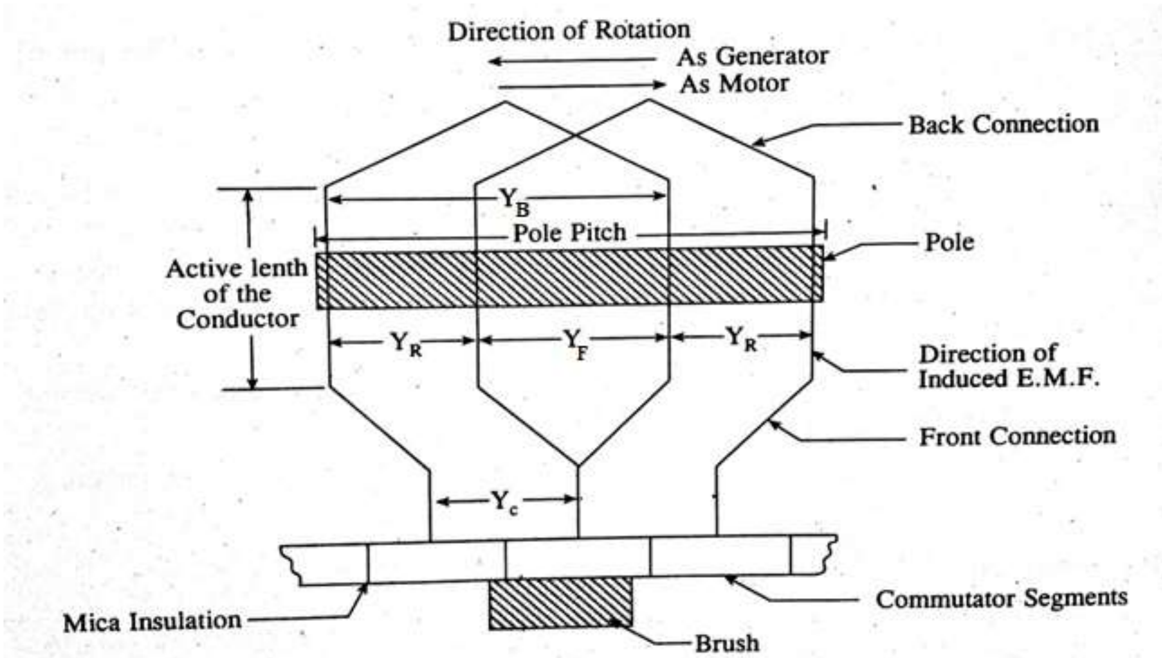
1) **CONDUCTOR:**
   Each individual length of wire lying (placed) with in the magnetic field is called conductor.

   Or

   Conductor is a wire or a part of wire carrying current.
   Denoted in "Z".it may be made of one or two or more parallel strands.
   Z = 2 × Number of turns
2) **TURN:**
   The two conductors placed in a magnetic field and are connected in series is known as turn.
   1turn = 2 conductors
3) **COIL:**
   One or more turns are connected in series and the two ends of it are connected to adjacent (series) commutator segments is known as coil.



4) **COIL GROUP:**
   A coil group is a group of one or more single coils.
5) **WINDING:**
   Number of coils arranged in coil groups (series) is called windings.



6) **<u>INDUCTOR:</u>**
One of the wires making up the coil side is called the inductor and a voltage is induced in the inductor.

7) **<u>FRONT END CONNECTOR:</u>**
A wire that connects the two ends of a coil to a commutator segment, is called front end connector.

Or

A wire that is used to connect end of a coil at the front to the commutator segments is called a front-end connector.

8) **<u>BACK END CONNECTOR:</u>**
A wire that is used to connect one coil side to the other coil side at the back is called back-end connector.

Or

A wire that connects an inductor on one side of the coil to an inductor on the other side of the coil is called the back-end connector.

9) **<u>POLE PITCH (Y_P):</u>**
The peripheral distance between centre of two adjacent poles. Expressed in terms of number of slots or conductors.

Or

It is defined as the number of conductors per pole.
Pole pitch (Y_P or PP) = S/P = Z/P
One pole pitch = 180^o electrical = Full pitch.

10) **<u>FRONT PITCH(Y_F):</u>**
It is defined as the distance in terms of number of armature conductors between the second conductor of one coil and the first conductor of next coil which are connected to the same commutator segment on the commutator end.

11) **<u>BACK PITCH(Y_B):</u>**
It is defined as the distance in terms of number of armature conductors between the last and the first conductors of the coil.

12) **<u>RESULTANT PITCH(Y_R):</u>**
It is the distance between the beginning of one coil and the beginning of the next coil connection.
LAP WINDING: $Y_R = Y_B - Y_F$
WAVE WINDING: $Y_R = Y_B + Y_F$

13) COMMUTATOR PITCH(Y_C):

It is defined as the distance measured in terms of commutator segments between the segments to which the two ends of a coil are connected.

14) AVERAGE PITCH(Y_A):

It is the average of back pitch and front pitch of winding.

$$Y_A = (Y_B + Y_F) / 2$$

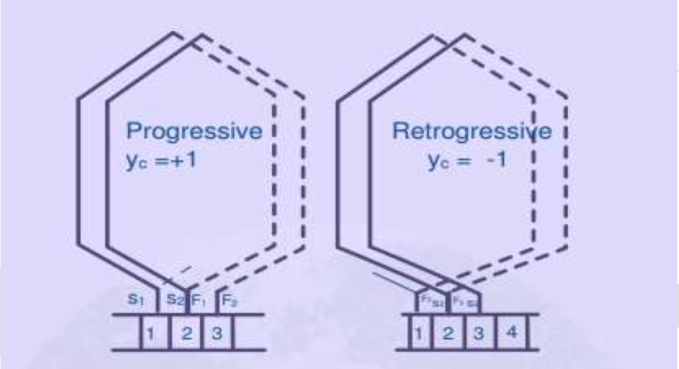
15) COIL SPAN (COIL PITCH):

Coil span is defined as the peripheral (outer) distance between two sides of a coil.
Measured in terms of the number of slots.
If the coil span is equal to the pole pitch, then the armature winding is said to be Full-pitched.

Coil span = Y_P = full pitch = $\frac{S}{P} = \frac{Z}{P}$

Types of Armature windings:

I. Single layer windings and double layer windings.
II. Lap windings and wave windings.
III. Progressive winding and retrogressive winding.



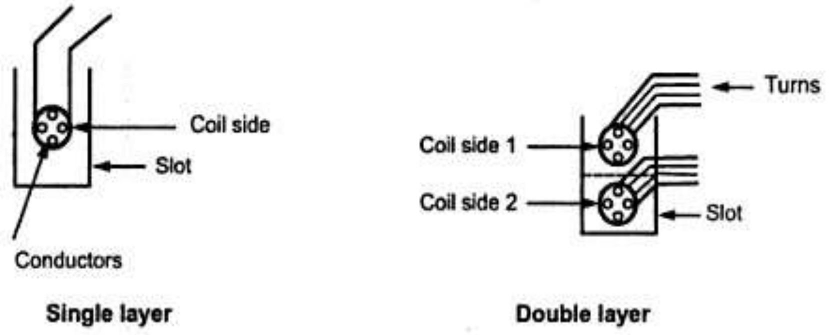
IV. Simplex winding and multiplex winding.
V. Full pitch and fractional pitch winding.

According to the end connections the armature windings are classified in to two types

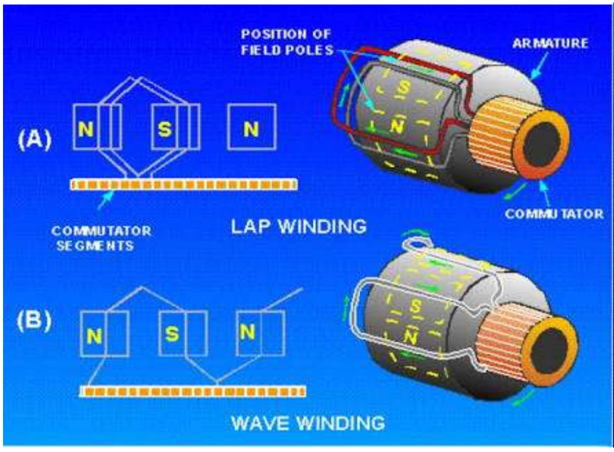
- Open coil windings: Used in AC machines.
- Closed coil windings: Used in DC machines.

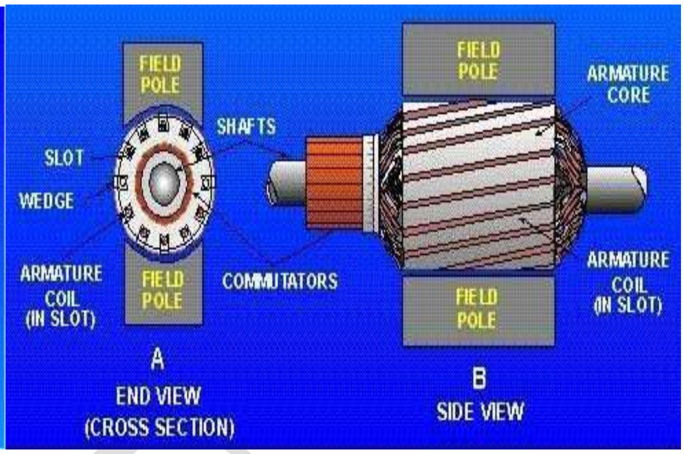
I. Single layer and double layer windings:

One coil side per slot of the armature is called single layer winding.
Two coil side per slot of the armature is called double layer winding.



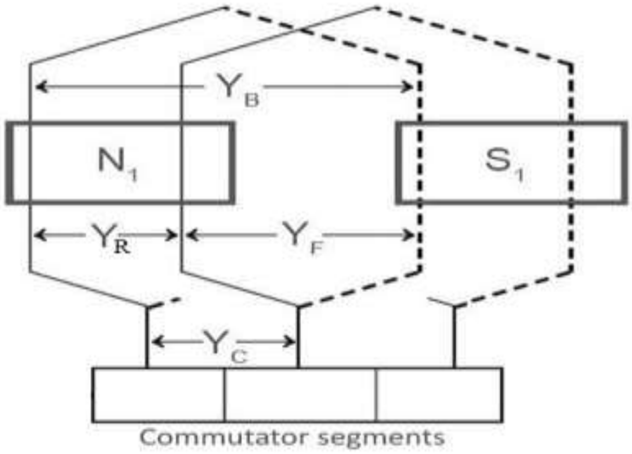
II. Lap windings and wave windings:





Lap windings:

- In Lap windings, if the connection is started from conductor in slot 1, then the connection is overlap each other, as winding proceeds till the starting point reach again.
- Armature winding in lap fashion is shown in the below figure and over lapping of coils also seen in the below figure.
- In this type of connection total number of conductors gets divided into “P” number of parallel paths.
- A=P, where A= Number of parallel paths.
  P = Number of poles.



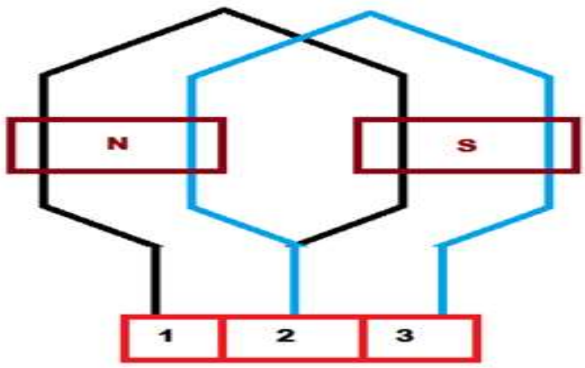
Lap Winding

- Lap windings are divided into two types.

1. Simplex Lap Winding
2. Duplex Lap Winding

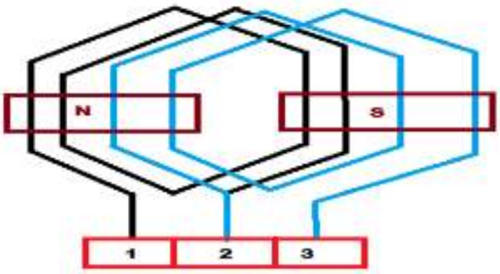
1. SIMPLEX LAP WINDING

A winding in which the number of parallel paths between the brushes is equal to the number of poles is called **simplex lap winding**.



Simplex lap winding

2. **DUPLEX LAP WINDING**
   A winding in which the number of parallel paths between the brushes is twice the number of poles is called **duplex lap winding**.



Duplex lap winding

Rules for LAP winding:

- The back & front pitches are odd and are of opposite signs. They differ numerically by 2.

$Y_B = Y_F + 2$ for progressive winding

$Y_B = Y_F - 2$ for retrogressive winding

$Y_B = Y_F \pm 2$

$Y_B = Y_F \pm 2m$ (m=Multiplicity of the winding)

  Y_B should be either lesser than or greater than Y_F by 2m, where 'm' is multiplicity of the windings.
  Y_B is greater than Y_F, the winding progresses from left to right is called progressive winding.
  Y_B is lesser than Y_F, then the winding will progress from right to left is called Retrogressive winding.
- Both Y_B and Y_F should be nearly equal to a pole pitch.
- The number of commutator segments must be odd.
- The average pitch $Y_A = (Y_B+Y_F) / 2$, it should be equal to pole pitch $Y_P = Z / P$.
- The number of coils must be odd.
- The resultant pitch (Y_R) is always even ($Y_R = Y_B – Y_F = 2m$).
- Commutator pitch $Y_C = \pm m$. (m=1 for simplex winding and m=2 for multiplex winding). (+ for progressive winding and – for retrogressive winding)
- Number of parallel paths = m * Number of poles =mP= Number of brushes.
  For simplex winding, parallel path = P.
  For duplex winding, parallel path = 2P.
- For progressive winding: $Y_B = \frac{Z}{P} + 1$, $Y_F = \frac{Z}{P} – 1$
- For retrogressive winding: $Y_B = \frac{Z}{P} - 1$, $Y_F = \frac{Z}{P} + 1$

APPLICATIONS:

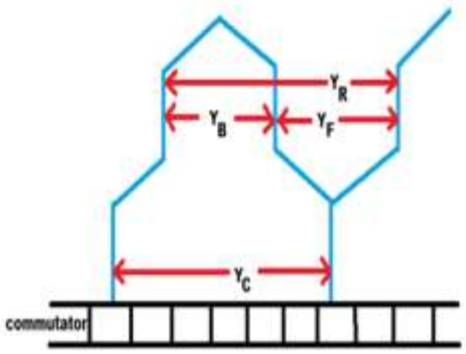
a) Lap winding is used in low voltage and high current machines. (50KW TO 500KW).
b) The large number of parallel paths (A=P) indicate high current capacity of machine, hence lap winding is preferred for high current rating generators.

DISADVANTAGES OF LAP WINDING:

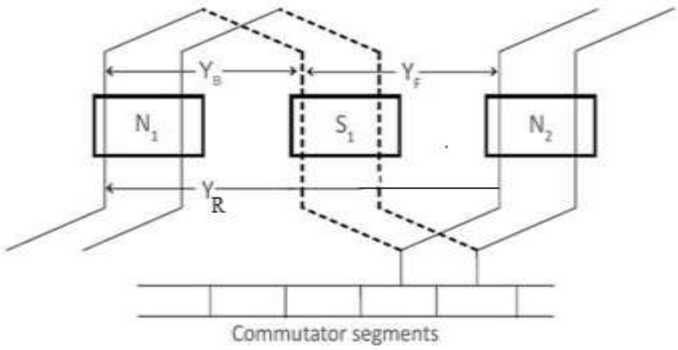
1. It gives less EMF compared to wave winding. This winding requires more number of conductors for giving the same EMF, it results high winding cost.
2. It has less efficient utilization of space in the armature slots.

WAVE WINDING (SERIES WINDING):

- In wave winding connection, windings always travel in forward manner to avoiding over lapping and it travels like a progressive wave hence it is called as wave winding.
- Armature winding in wave fashion is shown in the below figure and in this case, coil starting from slot 1 or N pole and forward to S pole it continuously repeats and finally coil returns to where it was started.
- In this type of connection total number of conductors always equal to two number of parallel paths. A = 2



wave winding



Wave winding

Rules for wave winding:

- Both back pitch (Y_B) and front pitch (Y_F) are odd and are of same sign.
- Both back pitch (Y_B) and front pitch (Y_F) are nearly equal to the pole pitch and may be equal or differ by 2 (±2). + Sign for progressive winding and – sign for retrogressive winding.
- Resultant pitch, $Y_R = Y_B + Y_F$.
- Average pitch (Y_A) must be an integer number (Because it may close itself).

$$Y_A = (Z \pm 2) / P = (Y_b + Y_f) / 2$$

- The number of armature parallel paths = 2.
- Commutator pitch is given by,

$$Y_C = Y_A = \frac{\text{Number of commutator segments} \pm 1}{\text{Number of pair of poles}}$$

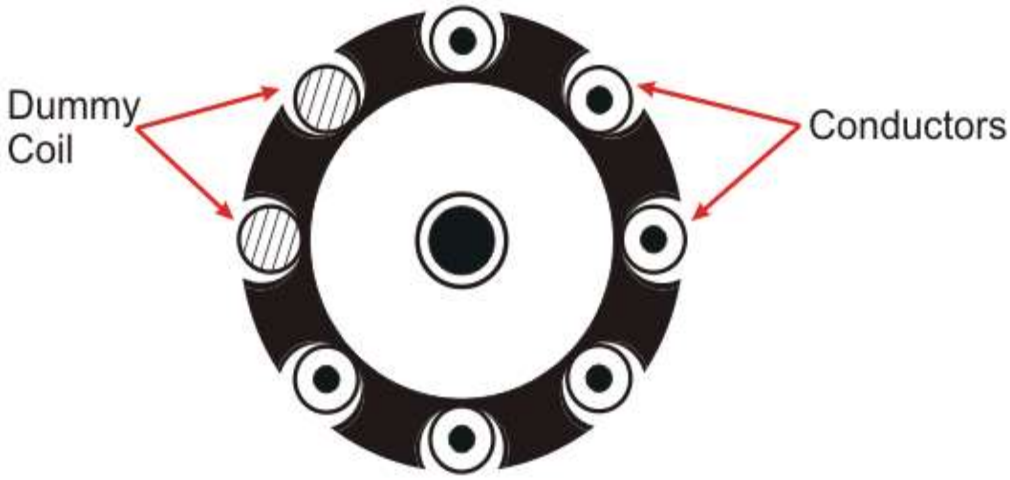
- Number of coils = $\frac{Z}{2} = \frac{PYA \pm 2}{2}$

APPLICATIONS:

- Wave winding is used in high voltage and low current machines. (less than 50KW)
- The small number of parallel paths (A=2) indicate low current capacity of machine, hence lap winding is preferred for low current rating generators.

DUMMY COIL:

- The coil ends are not connected to the commutator bars are called dummy coils.
- Sometimes the armature slots are more than the required number of conductors. In that case coils (Dummy coils) are placed in that empty slots.
- This coil is placed in the slots to give the mechanical balance to the Machin but they are not electrically connected to the rest of the winding.



Example:

Let us consider that the wave winding of 26 slots and 4 poles.

$Z = 26 \times 2 = 52$

Simplex wave winding

$Y_A = (Z \pm 2) / P$

$= (52 \pm 2) / 4$

$= 25/2$ or $27/2$

But the Y_A must be an integer therefore the winding is not possible with 52 conductors. However if the number of coils are 25

$Y_A = (Z \pm 2) / P$

$= (50 \pm 2) / 4$

$= 12$ or 13

It means that one coil (26 – 25 = 1) is inactive, it is called as dummy coil.

(Dummy coils are not necessary in Lap winding, because the lap winding is designed for any number of conductors)

DIFFERENCE BETWEEN LAP WINDING AND WAVE WINDING:

Sl. No.	Lap Winding	Wave Winding
1	The number of parallel paths in lap winding is equal to the number of poles.	The number of parallel paths is always equal to 2
2	The number of carbon brush in lap winding is equal to the number of poles.	The number of carbon brushes requirement in wave winding is two, due to two parallel paths.
3	Lap winding are used for low voltage and high current rating machines.	Wave connected winding is required for high voltage and low current rating machines.
4	Thus, emf generated in lap winding is independent of number of poles. EMF = (ØZN /60).	In wave winding, the number of parallel path = 2, therefore emf generated = (ØZPN /60×2). Thus, the emf generated depends on the number of poles.
5	The conductor current in each parallel path is (I/A).	The conductor current in each parallel path is (I/2) in wave winding.
6	Lap coils movement is forward and backward alternatively.	Wave coils movement is forward only.
7	The commutator pitch for lap winding is always 1.	The commutator pitch for wave winding is almost equal to 2 pole pitch i.e. 360 electrical degree.
8	It is more costly.	It is comparatively cheap.

UNIT-1

1) **A 6 pole wave connected DC generator has 52 slots and each slot has 20 conductors. Find the speed of the generator. The induced emf is 240 v and the flux per pole is 5 m Wb.**

Given:

P=6, A=2, Slots=52, conductors/slot = 20, N=?, E_g=240 V, $\phi=5\times10^{-3}$ Wb.

$E_g=\frac{\phi PNZ}{60A}$

$N=\frac{Eg60A}{\phi PZ}$

Z= Number of slots × Number of conductors/slot.

Z=52 × 20

Z=1040

$N=\frac{Eg60A}{\phi PZ}=\frac{240\times60\times2}{5\times10^{-3}\times6\times1040}$

N=923 rpm

2) **A 4 pole DC shunt generator with wave connected armature has 32 slots with 16 conductors per slot. The flux per pole is 25 m Wb. If the armature is driven at 1000 rpm calculate emf induced.**

Given:

P=4, A=2, Slots=32, conductors/slot=16, $\phi=25\times10^{-3}$, N=1000 rpm, E_g=?.

$E_g=\frac{\phi PNZ}{60A}$

Z= Number of slots × Number of conductors/slot.

Z=32×16

Z=512

$E_g=\frac{\phi PNZ}{60A}=\frac{25\times10^{-3}\times4\times1000\times512}{60\times2}$

E_g=426.67 volts.

3) **A 4-pole generator has an induced emf of 262 V when driven at 400 rpm. The armature is lap wound and has 652 conductors. Calculate the flux density in the air gap.**

Given:

P=4, E_g=262 V, N=400 rpm, A=P=4, Z=652, ϕ=?.

$E_g=\frac{\phi PNZ}{60A}$

$\phi=\frac{Eg60A}{PNZ}=\frac{262\times60\times4}{4\times400\times652}$

ϕ = 0.0598 Weber = 59.8 m Wb.

4) Find the power output of a DC armature having 1152 lap connected conductors carrying 120 A and rotating at 250 rpm in a 12 pole field, the flux per pole being 0.075 Wb.

<u>Given:</u>

P_a=?, A=P=12, Z=1152, I_a=120 A, N=250 rpm, P=12, ϕ=0.075 Wb.

$P_a = E_g I_a$

$E_g = \frac{\phi PNZ}{60A} = \frac{0.075 \times 12 \times 250 \times 1152}{60 \times 12}$

E_g = 360 V.

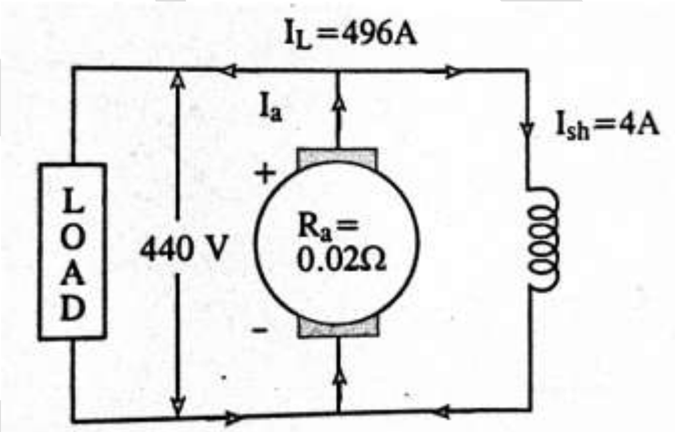
$P_a = E_g I_a$ = 360×120

P_a = 43200 = 43.2 KW.

5) A shunt generator delivers 496 A at 440 volts. The resistance of the shunt field and armature is 110 Ω and 0.02 Ω respectively. Calculate the generated emf.

<u>Given:</u>

I_L=496 A, V=440 volts, R_{sh}=110 Ω, R_a=0.02 Ω, E_g=?.



$E_g = V + I_a R_a$

$I_a = I_{sh} + I_L$

$I_a = \frac{V}{Rsh} + I_L = \frac{440}{110} + 496$

I_a=500 A.

$E_g = V + I_a R_a$ = 440+(500×0.02)

E_g=450 volts.

6) **A 4-pole, 1500 rpm DC generator has a lap wound armature, having 32 slots and 8 conductors per slot. If the flux per pole is 0.04 webs, calculate the emf induced in the armature. What would be the emf induced, if the winding is wave connected.**

Given: P=4, N=1500 rpm, A=P=4, Slots=32, Conductors/slot=8, ϕ=0.04 Wb
E_g=?, E_g=? if the winding is wave connected, A=2.

For lap winding: **A=P=4**

$$E_g = \frac{\phi PNZ}{60A}$$

Z = Number of slots × Number of conductors/slot = 32×8

Z = 256

$$E_g = \frac{\phi PNZ}{60A} = \frac{0.04 \times 4 \times 1500 \times 256}{60 \times 4}$$

E_g = 256 volts.

For wave winding: **A=2**

$$E_g = \frac{\phi PNZ}{60A} = \frac{0.04 \times 4 \times 1500 \times 256}{60 \times 2}$$

E_g = 512 volts.

7) **A 4 pole wave connected generator has a useful flux of 0.02 weber per pole. If the induced EMF is 288 V at 1200 rpm. Find the number of conductors in the armature. If each slot contains 10 conductors. Find the number of slots on the armature.**

Given:

P=4, A=2, ϕ=0.02 weber per pole, E_g=288 V, N=1200 rpm, Z=?, Conductor/slot = 10, Number of slots=?.

$$E_g = \frac{\phi PNZ}{60A}$$

$$Z = \frac{Eg60A}{\phi PN} = \frac{288 \times 60 \times 2}{0.02 \times 4 \times 1200}$$

Z = 360

Z = Number of slots × Number of conductors/slot

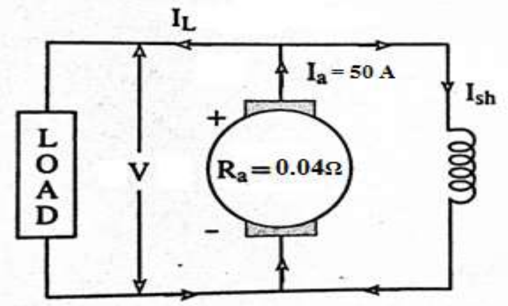
$$\text{Number of slots} = \frac{Z}{\text{Number of conductors/slot}} = \frac{360}{10}$$

Number of slots = 36

8) **A 4 pole lap wound DC shunt generator has a useful flux/pole of 0.07 wb. The armature winding consists of 220 turns, each of 0.04 Ω resistance. Calculate the terminal voltage when running at 900 rpm, if armature current is 50A.**

Given:

P=4, A=P=4, ϕ=0.07 Wb, Number of turns = 220, R_a=0.04, V=?, N=900 rpm, I_a=50 A.



$E_g = \frac{\phi PNZ}{60A}$

Z = 2 × Number of turns = 2 × 220

Z = 440

$E_g = \frac{\phi PNZ}{60A} = \frac{0.07 \times 4 \times 900 \times 440}{60 \times 4}$

$\mathbf{E_g = 462}$ **volts.**

$V = E_g - I_a R_a = 462 - (50 \times 0.04)$

V = 460 volts.

9) **An 8-pole DC shunt generator with 778 wave connected armature conductors and running at 500 rpm supplies a load of 12.5 Ω resistance at terminal voltage of 250 V. The armature resistance is 0.24 Ω and the field resistance is 250 Ω. Find the armature current, the induced emf and the flux per pole.**

Given:

P=8, Z=778, A=2, N=500 rpm, R_L=12.5 Ω, V=250 volt, R_a=0.24 Ω, R_{sh}=250 Ω, I_a=?, E_g=?, ϕ=?.

i) $I_a = I_{sh} + I_L = \frac{V}{Rsh} + \frac{V}{RL} = \frac{250}{250} + \frac{250}{12.5}$

$\mathbf{I_a = 21}$ **A**

ii) $E_g = V + I_a R_a = 250 + (21 \times 0.24)$

$\mathbf{E_g = 255.04}$ **volts.**

iii) $E_g = \frac{\phi PNZ}{60A}$

$\phi = \frac{Eg60A}{PNZ} = \frac{255.04 \times 60 \times 2}{8 \times 500 \times 778}$

$\boldsymbol{\phi = 0.0098}$ **Weber = 9.83 m Wb.**

10) An 8-pole lap connected armature has 960 conductors, a flux of 40 m wb per pole and a speed of 400 rpm. Calculate the emf generated on open circuit. If the armature is wave connected, at what speed must it drive to generate 400 V.

<u>Given:</u>

P=8, A=P=8, Z=960, $\phi=40\times10^{-3}$ wb, N=400 rpm.

i. E_g=?

ii. N=?, A=2, E_g=400 V.

i. $E_g = \frac{\phi PNZ}{60A} = \frac{40\times10^{-3}\times8\times400\times960}{60\times8}$

E_g = 256 volts.

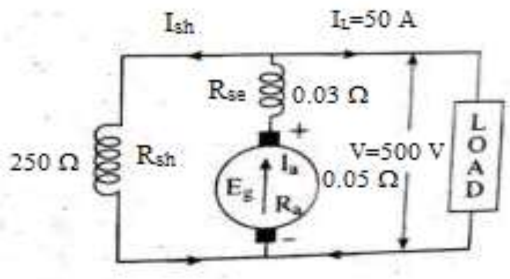
ii. $N = \frac{E_g 60A}{\phi PZ} = \frac{400\times60\times2}{40\times10^{-3}\times8\times960}$

N = 156.25 rpm.

11) A long shunt compound generator delivers a load current of 50 A at 500 V and has armature series and shunt field resistances of 0.05 Ω, 0.03 Ω and 250 Ω respectively, calculate generated emf and the armature current. Allow 1V per brush for brush contact.

<u>Given:</u>

I_L=50 A, V=500 V, R_a=0.05 Ω, R_{se}=0.03 Ω, R_{sh}=250 Ω, E_g=?, I_a=?, Voltage drop per brush=1 V.



Shunt field current = $I_{sh} = \frac{V}{Rsh} = \frac{500}{250}$ = 2 A.

Armature current = $I_a = I_L + I_{sh}$ = 50+2 = 52 A.

Voltage drop in series winding = I_aR_{se} = 52×0.03 = 1.56 volts.

Voltage drop in armature winding = I_aR_a = 52×0.05 = 2.6 volts.

Drop at brushes = 2×1 = 2 volts.

$E_g = V + I_aR_a + I_aR_{se}$ + brush drop

= 500+2.6+1.56+2

E_g = 506.16 volts

12) A dc generator generates an emf of 520 V. It has 2000 armature conductors, flux per pole of 0.013 Wb. Speed of 1200 rpm and armature winding has four parallel paths. Find the number of poles.

<u>Given:</u>

E_g=520 V, Z=2000, ϕ=0.013 Wb, N=1200 rpm, A=4, P=?

$E_g = \frac{\phi PNZ}{60A}$

$P = \frac{Eg60A}{\phi NZ} = \frac{520\times60\times4}{0.013\times1200\times2000}$

P = 4

13) The armature of a 6 pole DC generator has wave winding contains 660 conductor. Calculate the generated emf when flux/pole is 60 m Wb and the speed is 250 rpm.

At what speed the armature driven in order to generate an emf of 550 V, if the flux/pole is reduced to 58 m Wb.

<u>Given:</u>

P=6, A=2, Z=660, E_{g1}=?, $\phi_1=60\times10^{-3}$ Wb, N_1=250 rpm.

N_2=?, E_{g2}=550 V, $\phi_2=58\times10^{-3}$ Wb

$E_{g1} = \frac{\phi_1 P N_1 Z}{60A} = \frac{60\times10^{-3}\times6\times250\times660}{60\times2}$

E_{g1} = 495 volts.

$E_{g2} = \frac{\phi_2 P N_2 Z}{60A}$

$N_2 = \frac{E_{g2}60A}{\phi_2 PZ} = \frac{550\times60\times2}{58\times10^{-3}\times6\times660}$

N_2 = 287.35 rpm.

14) A 100 KW, 240 V, shunt generator has a field resistance of 55 Ω and armature resistance of 0.067 Ω. Find full load generated voltage.

<u>Given:</u>

P=100×10^3, V=240 V, R_{sh} = 55 Ω, R_a = 0.067 Ω, E_g = ?.

$I_L = \frac{100\times10^3}{240} = 416.6$ A

$I_{sh} = \frac{V}{R_{sh}} = \frac{240}{55} = 4.36$ A

$I_a = I_L + I_{sh}$ = 416.6+4.36 = 420.96 A

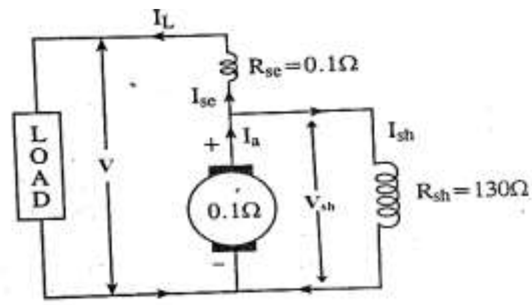
$E_g = V + I_aR_a$ = 240 + (420.96×0.067)

E_g = 268.20 volts.

15) A short shunt compound generator supplies a load current of 100 A at 250 V. The generator has the following winding resistances. R_{sh}=130Ω, R_a=0.1 Ω and R_{se} = 0.1 Ω., find emf generated if the brush drop is 1 V per brush.

<u>Given:</u>

I_L=100 A, V = 250 V, R_{sh} = 130 Ω, R_a = 0.1 Ω, R_{se} = 0.1 Ω, E_g = ?, brush drop = 1V.



I_L=I_{se}=100 A.

Voltage drop across series field winding = $I_{se}R_{se}$ = 100×0.1 = 10 volts.

Voltage across shunt field winding = V_{sh} = V + $I_{se}R_{se}$ = 250+10 = 260 V.

Shunt field current = $I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{260}{130}$ = 2 A

Armature current = I_a = I_L + I_{sh} = 100+2 = 102 A

E_g = V + I_aR_a + $I_{se}R_{se}$ + brush drop

= 250 + (102×0.1) + (100×0.1) + (2×1)

E_g = 272.2 volts

16) A 4 pole DC shunt generator delivers 20 A to a load of 10 Ω. If the armature resistance 0.5 Ω and the shunt field resistance is 50 Ω, calculate the induced emf and efficiency of the machine. Allow drop of 1 V per brush.

<u>Given:</u>

P = 4, I_L = 20 A, R_L = 10 Ω, R_a = 0.5 Ω, R_{sh} = 50 Ω, E_g = ?, η = ?.

Voltage drop=1 V.

E_g = V + I_aR_a + brush drop

V = I_LR_L = 20×10 = 200 volts

$I_a = I_L + I_{sh} = I_L + \frac{V}{R_{sh}} = 20 + \frac{200}{50} = 24$ A

E_g = V + I_aR_a + brush drop = 200 + (24×0.5) + (2×1) = 214 volts

Total power generated = P_G = E_g × I_a = 214 × 24 = 5136 watts

Total power delivered = P_D = V × I_L = 200 × 20 = 4000 watts

$\%\eta = \frac{P_D}{P_G} \times 100 = \frac{4000}{5136} \times 100 = 77.88$ %