MODULE I Principle and Construction of DC Generators

The electrical machines deals with the energy transfer either from mechanical to electrical form or from electrical to mechanical form, this process is called ELECTROMECHANICAL ENERGY CONVERSION.

- **An electrical machine which converts mechanical energy into electrical energy is called an ELECTRIC GENERATOR**
- **An electrical machine which converts electrical energy into the mechanical energy is called an ELECTRIC MOTOR.**

The conversion of Mechanical energy into Electrical energy in DC generator is based on the principle of electromagnetic Induction.

Faraday's law of electromagnetic induction

First law-

Faraday's first law of electromagnetic induction states that whenever the flux of magnetic field through the area bounded by a closed loop changes, an emf is produced in the loop.

Second law –

Faraday's second law of electromagnetic induction states that the magnitude of induced emf is directly proportional to the time rate of change in magnetic flux linked with the circuit.

The emf is given by

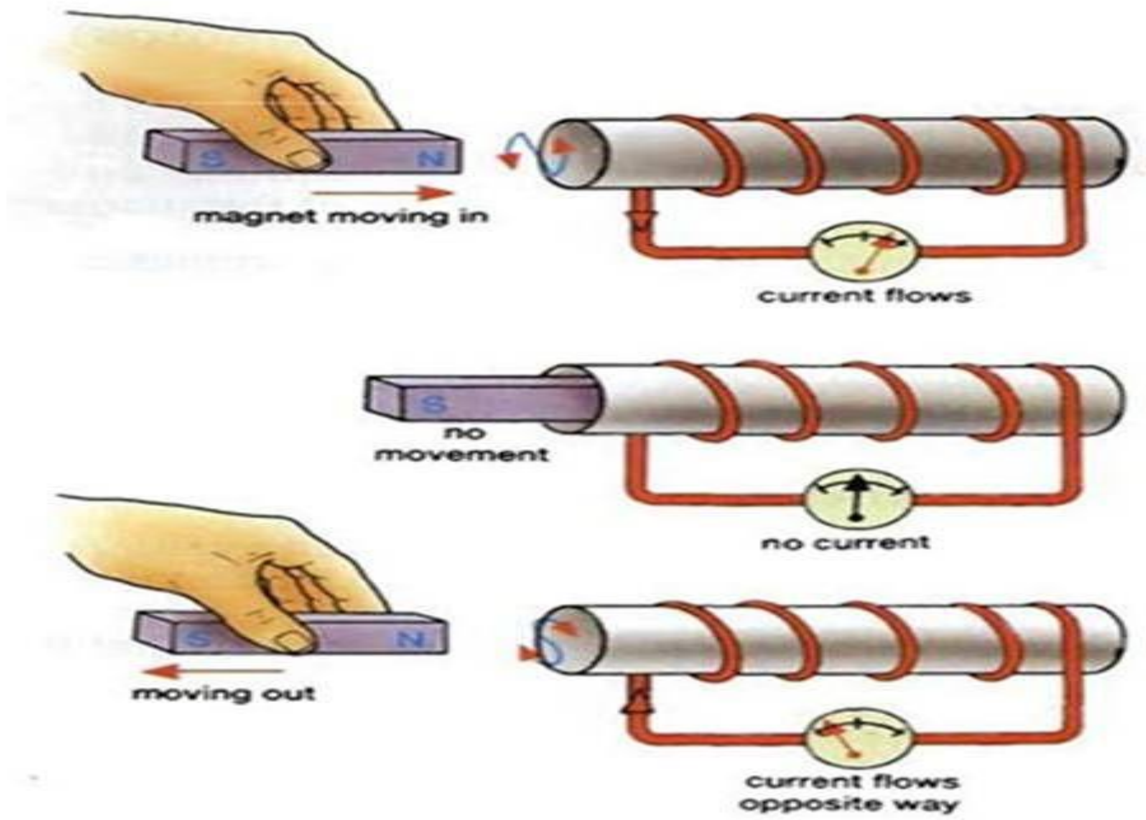
$$\varepsilon \propto \frac{d\Phi}{dt}$$

$$\varepsilon = -\frac{d\Phi}{dt}$$

Where, Φ is the flux of magnetic fields through the area.

Lenz's Law

"The induced currents in a conductor are in such a direction as to oppose the change in magnetic field that produces them.."



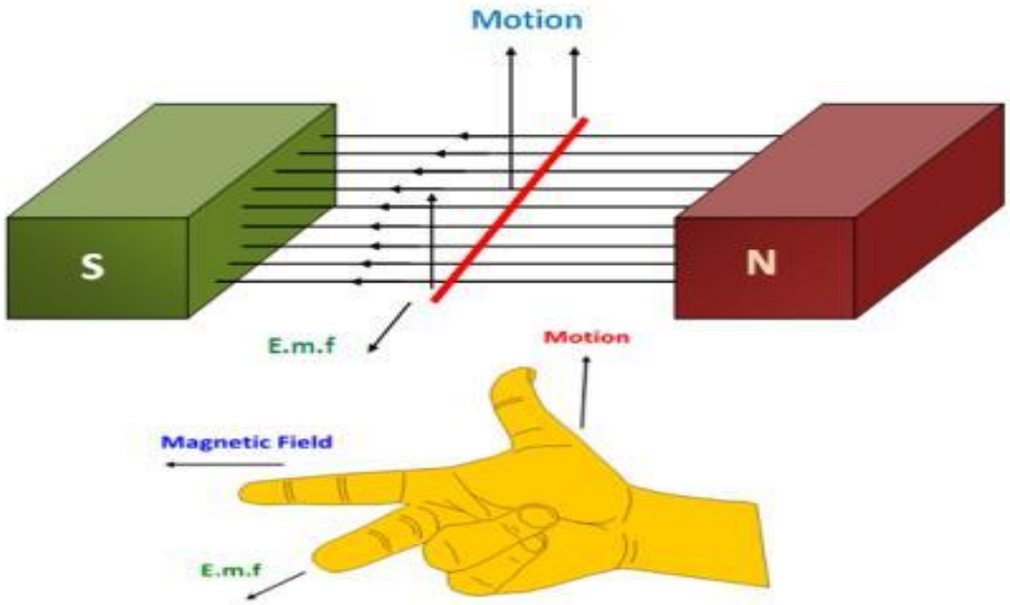
- ✓ **In a particular generator, the conductors are rotated to cut the magnetic flux, keeping flux stationary.**
- ✓ **To have a large voltage as the output, the number of conductors are connected together in a specific manner, to form a winding. This winding is called armature winding of a d.c. machine. The part on which this winding is kept is called armature of a d.c. machine.**
- ✓ **To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prime mover. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc.**
- ✓ **The necessary magnetic flux is produced by current carrying winding which is called field winding.**

- ✓ The direction of the induced e.m.f. can be obtained by using Fleming's right hand rule.
- ✓ The magnitude of induced emf = e = BLV sinØ= Em sinØ

So, a generating action requires the following basic components to exist.
1. The conductor or a coil
2. Flux
3. Relative motion between the conductor and the flux.

The basic constructional features of a DC generator and a DC Motor are same, and the same DC machine can work either as a DC generator or a DC motor.

Fleming's Right Hand Rule



- Fleming's right-hand rule (for generators) shows the direction of induced current when a conductor attached to a circuit moves in a magnetic field.
- It can be used to determine the direction of current in a generator's windings.

The right hand is held with the thumb, first finger and second finger mutually perpendicular to each other (at right angles).

- ➢ The thumb is pointed in the direction of the motion of the conductor relative to the magnetic field.

- The forefinger is pointed in the direction of the magnetic field. (north to south)
- Then the middle finger represents the direction of the induced or generated current within the conductor.

- The slip ring is a closed ring (continuous), whereas the split ring is divided into two parts or more. Slip ring is used in AC motors to provide a continuous transmitting of power and signal, whereas the split ring is used in DC motors to reverse the polarity of the current

Working of single loop DC generator with relevant wave forms.

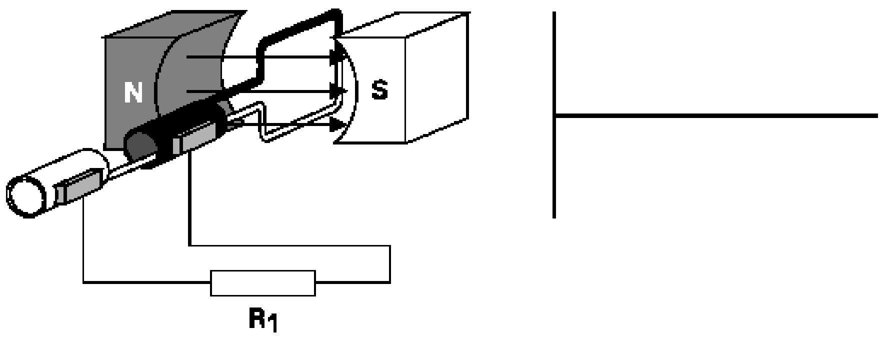
- ✓ It is a conductor placed between the magnet bars.
- ✓ These magnetic bars may be of permanent magnet or electro-magnet.
- ✓ The basic working of the simple loop generator is that when the two wires, conductors or coils are placed between the magnet bars and imagine the coil is rotating clockwise, the flux starts changing its value and as a result EMF is induced in it.

Construction

A Simple/Single Loop Generator basically consists of two conductors or coils, two magnet bars and two slip rings (which are insulated with each other and from central shaft) and a normal wire for connection as required. The rotating coil may be assumed as armature and the magnet bars field magnets.

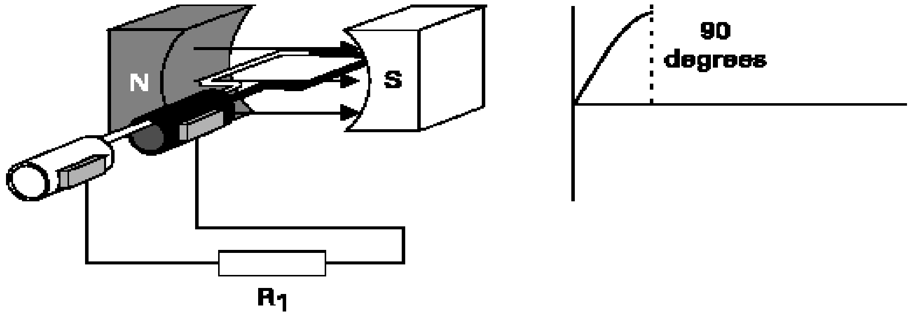
Basic generator operation

An armature rotates through the magnetic field. At an initial position of zero degrees, the armature conductors are moving parallel to the magnetic field and not cutting through any magnetic lines of flux. No voltage is induced.



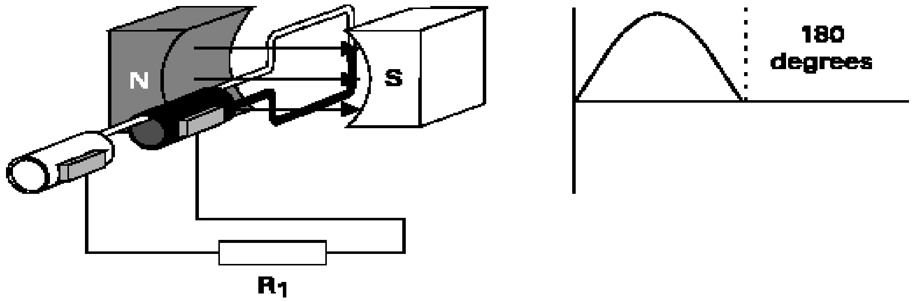
Generator operation from zero to 90 degrees

The armature rotates from zero to 90 degrees. The conductors cut through more and more lines of flux, building up to a maximum induced voltage in the positive direction.



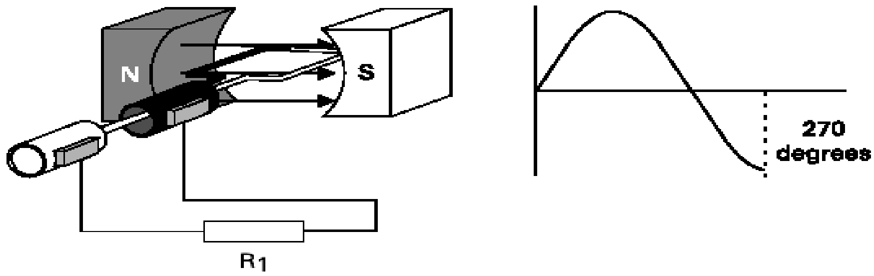
Generator operation from 90 to 180 degrees

The armature continues to rotate from 90 to 180 degrees, cutting less lines of flux. The induced voltage decreases from a maximum positive value to zero.



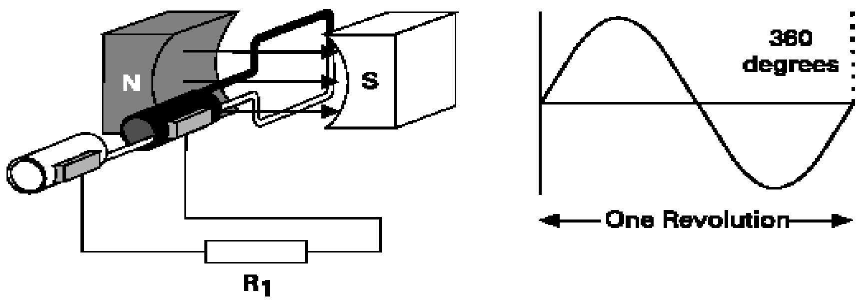
Generator operation from 180 to 270 degrees

The armature continues to rotate from 180 degrees to 270 degrees. The conductors cut more and more lines of flux, but in the opposite direction. Voltage is induced in the negative direction building up to a maximum at 270 degrees.



Generator operation from 270 to 360 degrees

The armature continues to rotate from 270 to 360 degrees. Induced voltage decreases from a maximum negative value to zero. This completes one cycle. The armature will continue to rotate at a constant speed. The cycle will continuously repeat as long as the armature rotates.



The following are the basic requirements to be satisfied for generation of E.M.F

1.A uniform Magnetic field

2.A System of conductors

3.Relative motion between the magnetic field and conductors

- **Magnetic field :- Permanent Magnet**

  (or)

  Electro Magnet (practical)

- **Conductor :-Copper (or) Aluminum bars placed in slots cut around the periphery of cylindrical rotor**
- **Relative motion:-**

  By Prime Mover

  Turbine

  I.C Engine (Internal combustion)

<u>Constructional Details Of DC Machine</u>

a) **Yoke:**

b) **Rotor:**

c) **Stator:**

d) **Field electromagnets:**

e) **Pole core and pole shoe:**

f) **Brushes:**

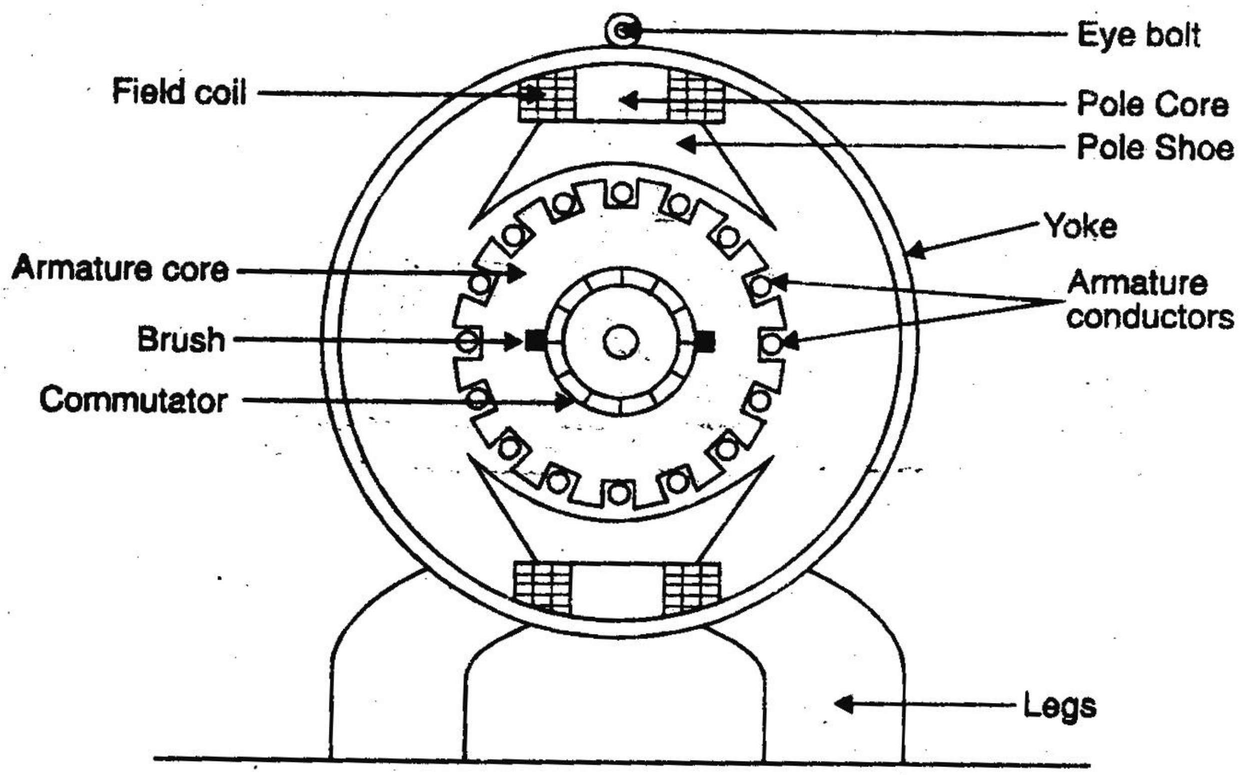
g) **Shaft:**

h) **Armature:**

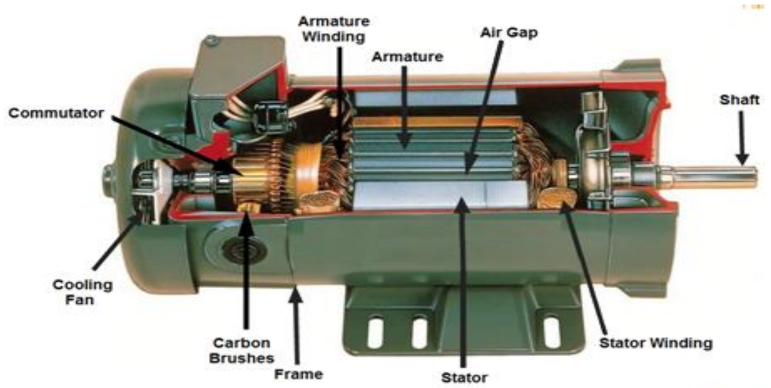
i) **Coil:**

j) **Commutator:**

k) **Bearings:**



Yoke

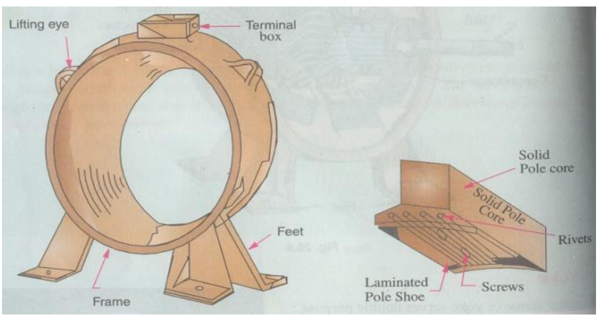


Yoke

- ❑ **Acts as frame of the machine**
- ❑ **Mechanical support**
- ❑ **low reluctance for magnetic flux**
- ❑ **High Permeability**

  -- For Small machines -- Cast iron—low cost

  -- For Large Machines -- Cast Steel (Rolled steel)



POLE CORES AND POLE SHOES

a) **Pole core (Pole body)**

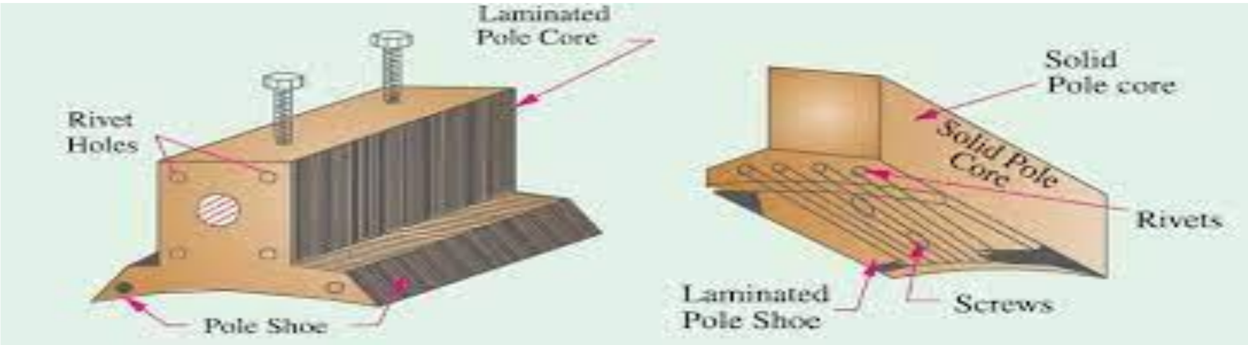
- **Carry the field coils**
- **Laminated to reduce heat losses**
- **Fitted to yoke through bolts**

b) Pole shoe:-

- **Acts as support to field poles and spreads out flux**

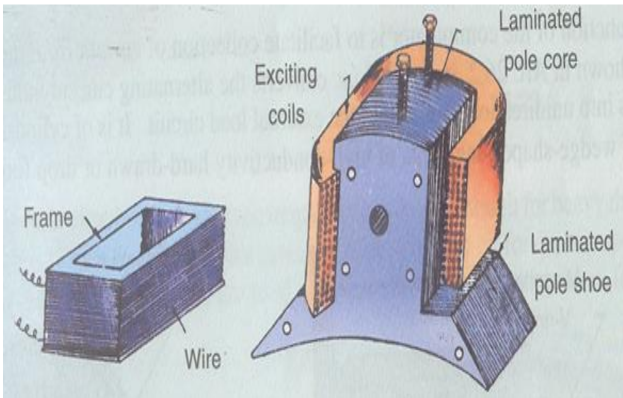
Pole core & Pole shoe are laminated of annealed steel

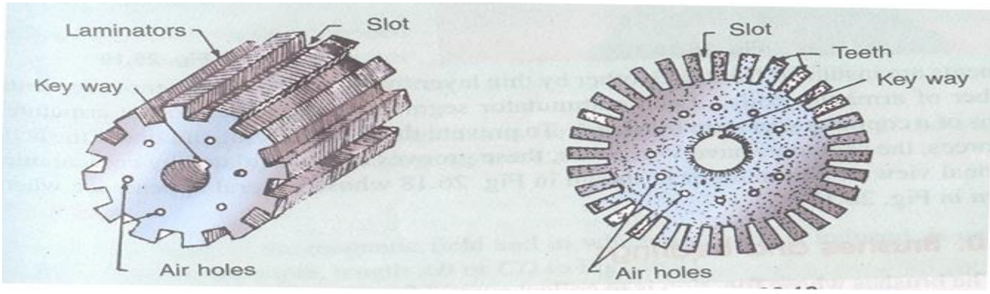
(Of thickness of 1mm to 0.25 mm)



Field winding (or) Pole coils

- **It produces uniform magnetic field within which the armature rotates.**
- **Field coils are mounted on the poles and carry the dc exciting current.**
- **The field coils are connected in such a way that adjacent poles have opposite polarity.**
- **The m.m.f. developed by the field coils produces a magnetic flux**
- **Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm.**
- **By reducing the length of air gap, we can reduce the size of field coils**





Armature core (Armature):-

- Armature core is the rotor of a dc 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 and Hysteresis loss
- 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,
- 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 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.
- Main flux cuts armature and hence E.M.F is induced.

COMMUTATOR

The action of commutator (called *commutation*) involves the change from a generated alternating current to a direct current.

Functions:

- To facilitate the collection of current from the armature conductors.
- To convert internally developed alternating emf to in directional (dc) emf
- To produce unidirectional torque in case of motor.
- 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:

- **Made of Carbon, graphite.**
- **Used to Collects current from commutation (in case of Generator)**

SHAFT AND BEARINGS:-

- **Shaft-- Mechanical link between prime over and armature**
- **Bearings– For free rotation**

EMF equation of DC generator.

Let-

P = Number of poles of the generator

ϕ = Flux produced by each pole (wb)

N = Speed of the armature (rpm)

Z = Total number of conductors in armature.

A = Number of parallel paths in which conductors are distributed

The emf (e) is given as

e = Rate of cutting the flux.

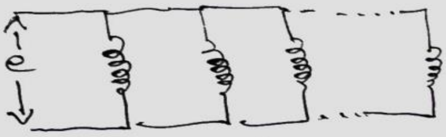
$$\boxed{e = \frac{d\phi}{dt}}$$ ... as per the faradays law of electromagnetic induction.

Total flux = Flux produced by each pole × Number of poles

Total $\phi = \phi \times P$

Time required for a conductor to complete one revolution $= \frac{60}{N}$

$$\therefore \quad e = \frac{\phi \times P}{60/N} = \frac{\phi P N}{60}$$



Z conductors are distributed in A parallel paths

Effectively $\frac{Z}{A}$ conductors need to be multiplied with emf induced in a conductor

$$\therefore \quad \boxed{e = \frac{\phi P N}{60} \times \frac{Z}{A}}$$

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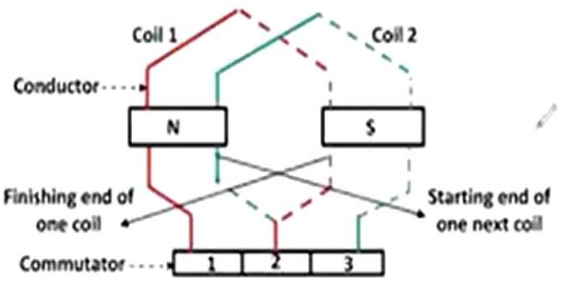
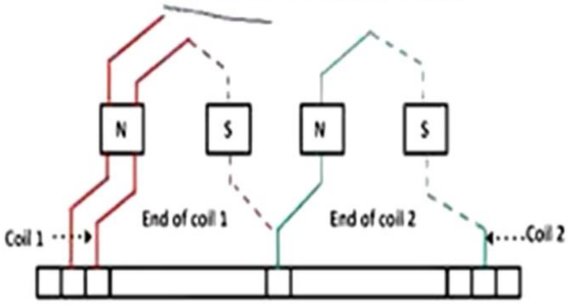
TYPES OF ARMATURE WINDINGS:

LAP WINDING



- The connection overlap each other as the winding proceeds.
- The numbers of the parallel path (A) are equal to the total of number poles (P). (A=P)
- The no. of brush set is equal to the no. of parallel paths.
- The e.m.f of lap winding is less.
- The lap winding used for high current, low voltage machines.

WAVE WINDING



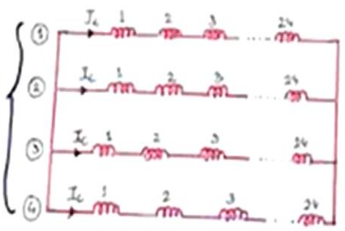
- The winding travels ahead without overlapping in a progressive manner.
- The number of parallel paths is equal to two. (A=2)
- The no. of brush set is equal to two.
- The e.m.f of wave winding is more.
- The applications of wave winding include low current and high voltage machines.

CONCEPT OF PARALLEL PATH

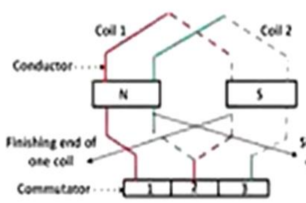
Let, Z = No. of conductors.
P = No. of poles
A = No. of parallel paths

Example : For Lap Winding
$Z = 96$, $P = 4$
$\therefore \boxed{A = P = 4}$
So, total no. of conductors in single path $= \frac{Z}{A}$
$\Rightarrow 96/4 = 24$

parallel paths (A=4)



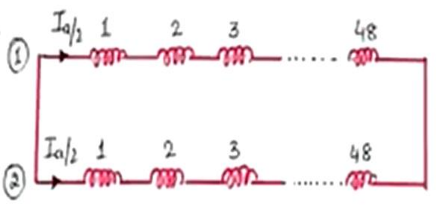
Total armature current, $\boxed{I_a = I_c \times A}$



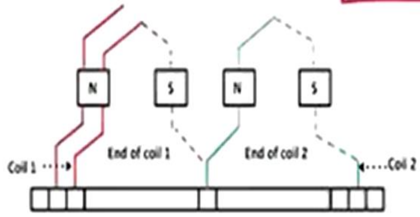
For Wave Winding :

$Z = 96$, $P = 4$
No. of parallel path, $\boxed{A = 2}$
So, total no. of conductors in single path:
$\frac{Z}{A} = \frac{96}{2} = 48$

parallel paths (A=2)

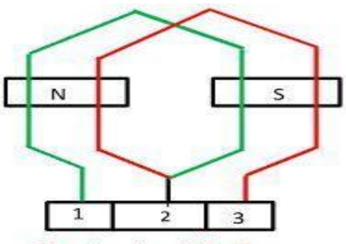


Total armature current, $\boxed{I_a = 2 \times \frac{I_a}{2}}$

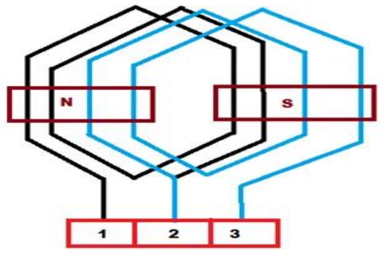


The lap winding is mainly classified into two types. They are the Simplex lap winding and the Duplex Lap winding.

- **Simplex Lap Winding** – In this winding, the number of parallel paths is equal to the number of poles.
- **Duplex Lap Winding** – In duplex lap winding the number of parallel paths is twice to the number of poles.



Simplex Lap Winding



Duplex lap winding

Wave windings can be further classified into:

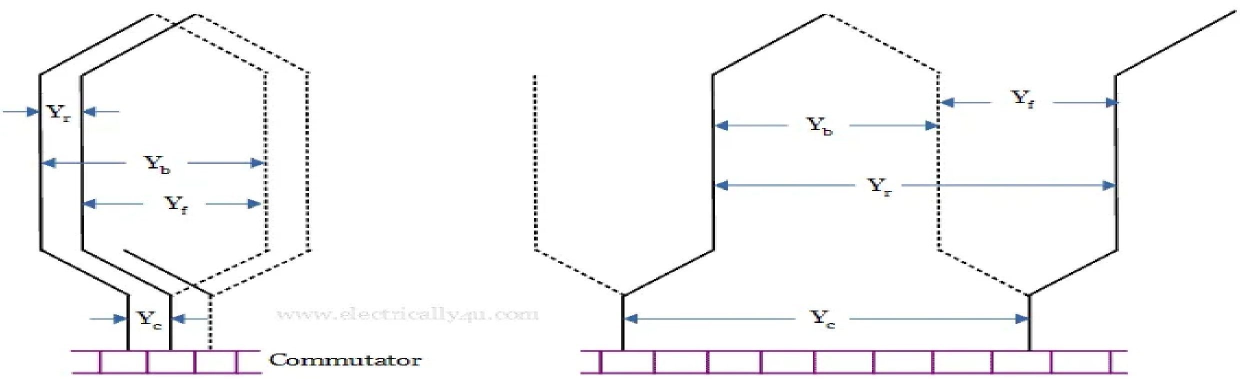
- Simplex wave windings
- Duplex wave windings
- Retrogressive wave windings
- Progressive wave windings

Back Pitch Y_b

- The distance at which a coil advances on the back of the armature is called back pitch, denoted by Y_b. It can also be defined as the distance between the first and the last conductors of a coil. It is the same as coil span and is shown in the below figure(a) and (b).

Front Pitch Y_f.

- It is the distance between the second conductor of one coil and the first conductor of the next coil. Both the coils should be connected to the same commutator segments on the front, as shown in the figure (a) and (b) below. It is denoted by Y_f.



(a)
(b)

Resultant Pitch Y_r

It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected. It is illustrated in the above figure (a) and (b), denoted by Y_r.

Commutator Pitch Y_c

It is the distance between the Commutator segments to which the two ends of a coil are connected. From the figure, you can observe, for lap winding, Commutator pitch (Y_c) is the difference of back pitch(Y_b) and front pitch(Y_f). For wave winding, it is the sum of the back pitch and front pitch.

Rules for Design Development of Lap-Winding for a DC Armature

(a) Back pitch (Yb) and front pitch (Yf) are odd. They are not equal. They differ by 2 or multiples thereof. In general $Yb = Yf \pm 2m$, where "m" is the plex of the winding (1 for simplex, 2 for duplex, 4 for quadraplex etc.)

If $Yb = Yf + 2m$, it is progressive winding and If $Yb = Yf - 2m$, it is retrogressive winding.

(b) Both Yf and Yb should be nearly equal to pole pitch.

(c) Average pitch (Ya) = $\frac{Yf + Yb}{2}$ which equals pole pitch $= \frac{Z}{P}$ where "Z" is the total number of conductors and "P" is the number of poles.

(d) Resultant pitch (Yr) = Yb – Yf will always be even since arithmetical difference of two odd numbers is even.

(e) Number of coils is equal to number of commutator segments.

(f) Number of parallel paths in armature is equal to "mP", where "P" is number of poles and "m" is the plex of winding.

(g) Commutator pitch $Yc = \pm 1m$, "+1" for progressive and "–1" for retrogressive windings.

(h) $Yb = \frac{Z}{P} + 1$ and $Yf = \frac{Z}{P} - 1$ for Progressive winding

$Yb = \frac{Z}{P} - 1$ and $Yf = \frac{Z}{P} + 1$ for Retrogressive winding.

Example for 4 Pole, 16 Slot DC Machine with Progressive Simplex Double Layer Lap Winding (Refer Fig. 3.7)

Number of Poles (P) = 4;

Total number of conductors (Z) = slots × conductors/slot = 16 × 2 = 32

For Progressive winding, Back Pitch (Yb) = $\frac{Z}{P}+1 = \frac{32}{4}+1 = 9$

and Front Pitch (Yf) = $\frac{Z}{P}-1 = \frac{32}{4}-1 = 7$

In Double Layer winding, top conductors in slots are given odd numbers (1, 3,.......31) andbottom conductors are given even numbers (2, 4.........32)

To start with top conductor in slot no.1 is connected to bottom conductor of (1 + Yb) = (1 + 9) = 10 on one end. The other end of conductor "10" is connected to (10 – Yf) = (10 – 7) = 3 and it goes on accordingly as per the following table.

How to Draw the Lap Winding Diagram

Now conductors/pole = Z/P = 32/4 = 8. and no. of brush arms = no. of poles = 4.

Pole No.	1	2	3	4
Polarity	North	South	North	South
Slot Nos. under the Pole	1,2,3,4	5,6,7,8	9,10,11,12	13,14,15,16
Cond. Nos.	1 to 8 (8nos)	9 to 16 (8nos)	17 to 24 (8nos)	25 to 32 (8nos)
Polarity of Induced EMF	+V	-V	+V	-V
No. of coils	4	4	4	4
No. of Comm-Segments	4	4	4	4
No. of Brush arms	1	1	1	1

Sequential Steps:

(a) A graph sheet is taken and 32 conductors are marked and numbered

(b) Represent 4 poles indicating polarities N, S, N, S covering all 32 conductors

(c) Represent direction of induced emf on each conductor by an arrow as per polarity

(d) All 16 commutator segments are represented and numbered

(e) Comm-segment no.1 is connected to one end of top conductor no.1 and its other end is connected to bottom conductor no.10

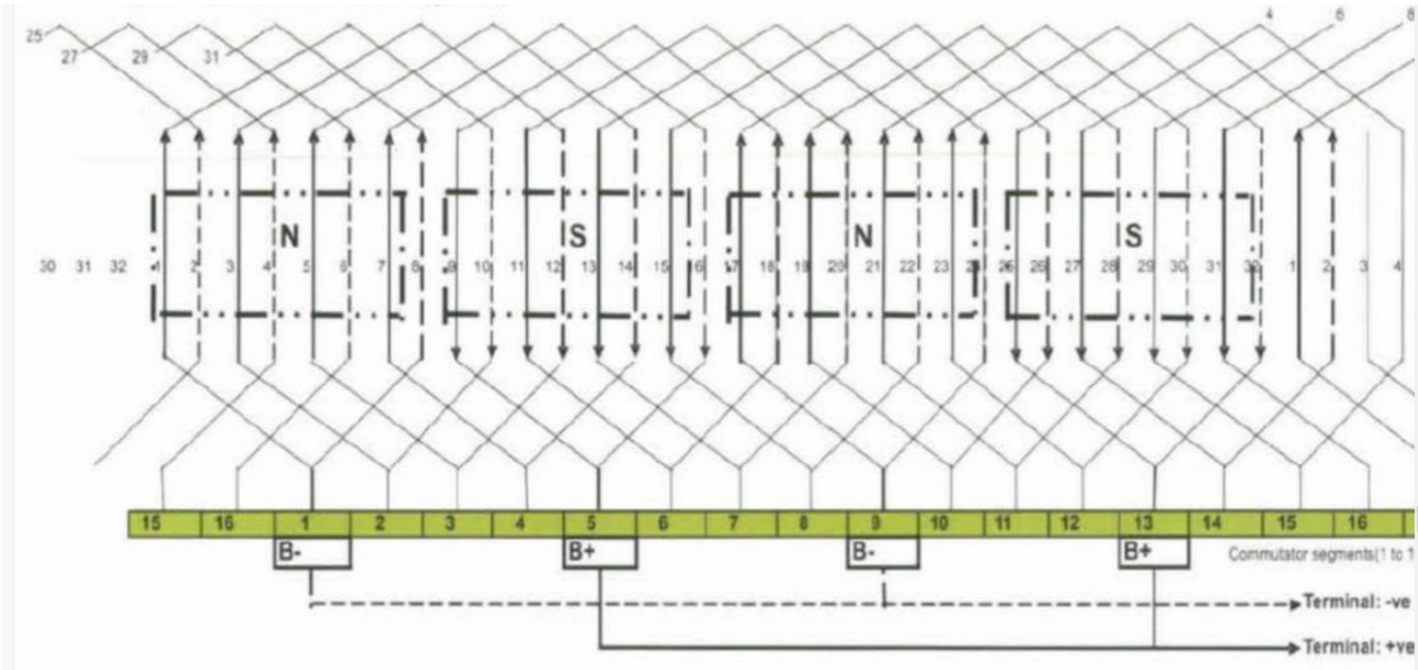
(f) Other end of bottom conductor no.10 is connected to commutator segment no.2 to which top conductor no.3 is also connected

(g) Other end of top conductor no.3 is connected to bottom conductor no.12

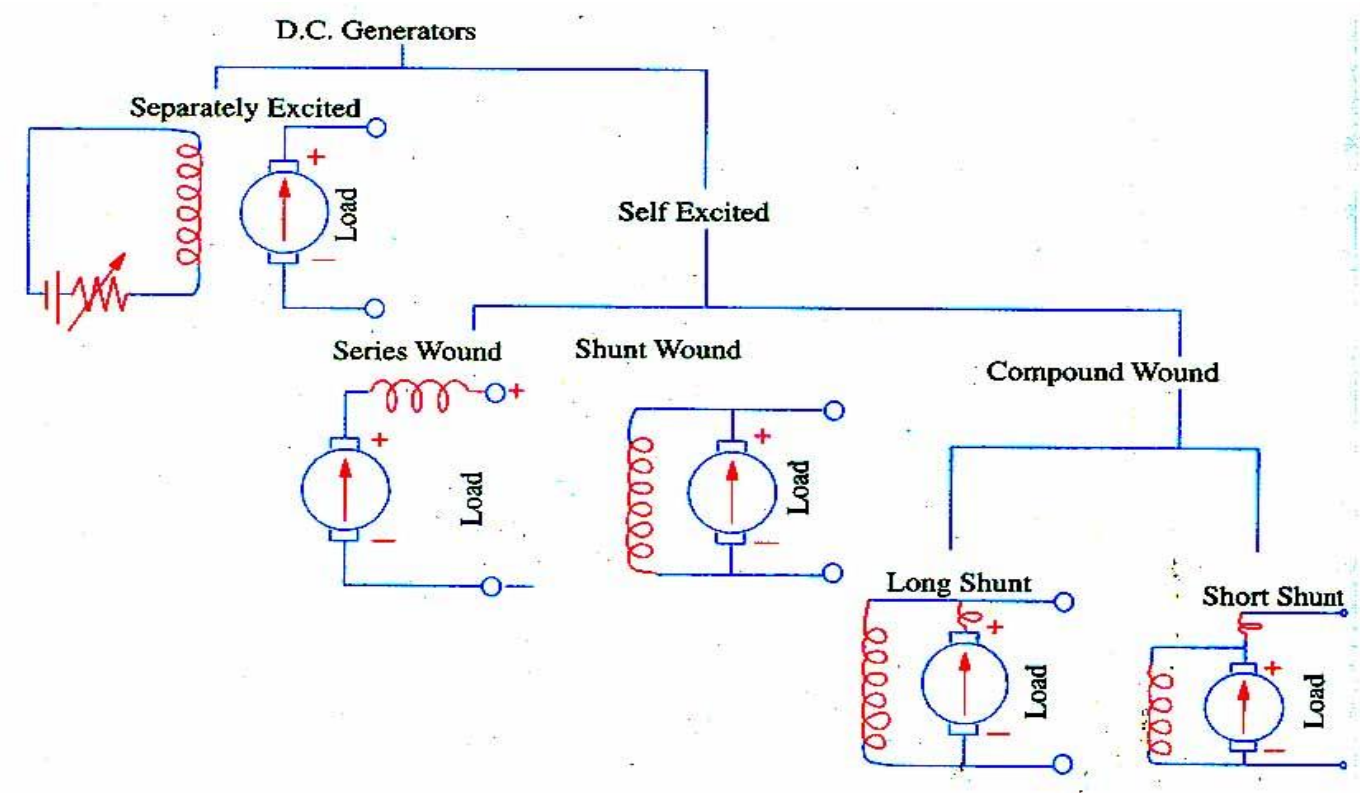
(h) Other end of bottom conductor no.12 is connected to commutator segment no.3 to which top conductor no.5 is also connected

(i) Following this procedure all connections are to be completed as per drawing shown in Fig. 3.7.

Sr. No	No. of Top Conductor (Zt)	No. of Bottom Conductor (Zb) Zb = Zt + Yb	No of Top Conductor (Zt) Zt = Zb – Yf
1	1	1 + 9 = 10	10 – 7 = 3
2	3	3 + 9 = 12	12 – 7 = 5
3	5	5 + 9 = 14	14 – 7 = 7
4	7	7 + 9 = 16	16 – 7 = 9
5	9	9 + 9 = 18	18 – 7 = 11
6	11	11 + 9 = 20	20 – 7 = 13
7	13	13 + 9 = 22	22 – 7 = 15
8	15	15 + 9 = 24	24 – 7 = 17
9	17	17 + 9 = 26	26 – 7 = 19
10	19	19 + 9 = 28	28 – 7 = 21
11	21	21 + 9 = 30	30 – 7 = 23
12	23	23 + 9 = 32	32 – 7 = 25
13	25	25 + 9 = 34 (= 34 – 32 = 2)	34 – 7 = 27
14	27	27 + 9 = 36 (= 36 – 32 = 4)	36 – 7 = 29
15	29	29 + 9 = 38 (= 38 – 32 = 6)	38 – 7 = 31
16	31	31+ 9 = 40 (= 40 – 32 = 8)	40 – 7 = 33(33 – 32 = 1)



Clasifications of Generators

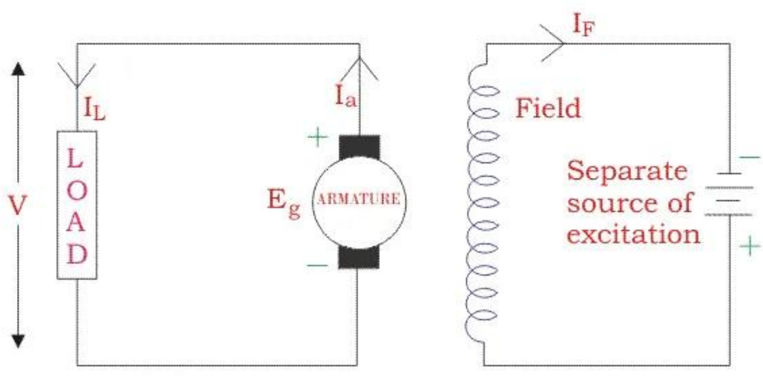


Separately Excited DC Generator

These are the generators whose field magnets are energized by some external DC source, such as a battery.

A circuit diagram of separately excited DC generator is shown in the figure below. The symbols below are:

- **I_a = Armature current**
- **I_L = Load current**
- **V = Terminal voltage**
- **E_g = Generated EMF (Electromagnetic Force)**



Separately Excited DC Generator

Let,

$$I_a = I_L = I \ (say)$$

Then,

$$voltage \ across \ the \ load, V = IR_a$$

Power generated is equal to

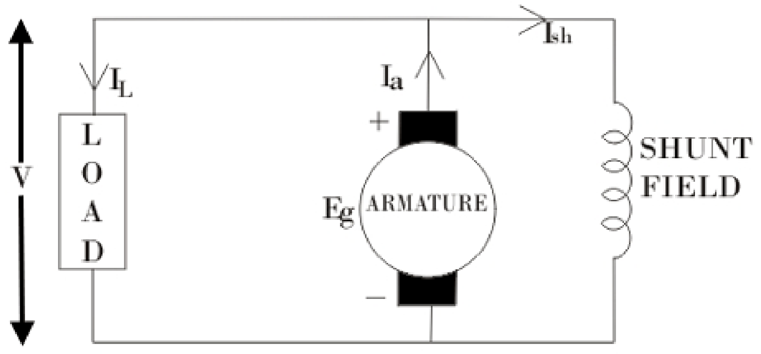
$$P_g = E_g \times I$$

And power delivered to the external load is equal to

$$P_L = V \times I$$

Self-excited DC generators

- **Self-excited DC generators are generators whose field magnets are energized by the current supplied by themselves. In these type of machines, field coils are internally connected with the armature.**
- **Due to residual magnetism, some flux is always present in the poles. When the armature is rotated, some EMF is induced. Hence some induced current is produced. This small current flows through the field coil as well as the load and thereby strengthening the pole flux.**
- **As the pole flux strengthened, it will produce more armature EMF, which cause the further increase of current through the field. This increased field current further raises armature EMF, and this cumulative phenomenon continues until the excitation reaches the rated value.**



Shunt Wound Generators

According to the position of the field coils, self-excited DC generators may be classified as:

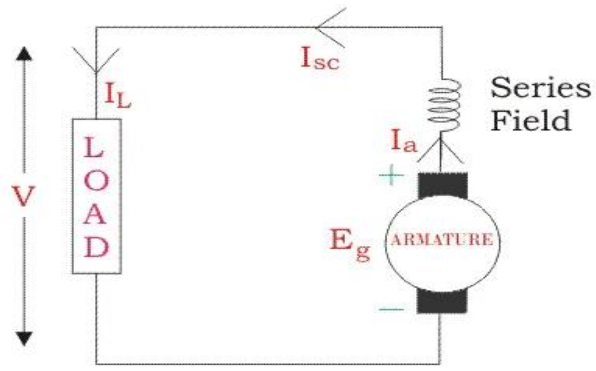
- **Series Wound Generators**
- **Shunt Wound Generators**
- **Compound Wound Generators**

Series Wound Generators

- **Whole current flows through the field coils as well as the load.**
- **As series field winding carries full load current it is designed with relatively few turns of thick wire.**
- **The electrical resistance of series field winding is therefore very low (nearly 0.5Ω).**

Here:

- R_{sc} = Series winding resistance
- I_{sc} = Current flowing through the series field
- R_a = Armature resistance
- I_a = Armature current
- I_L = Load current
- V = Terminal voltage
- E_g = Generated EMF



Series Wound Generator

Then,

$$I_a = I_{sc} = I_L = I \ (say)$$

Voltage across the load is equal to,

$$V = E_g - I(I_a \times R_a)$$

Power generated is equal to,

$$P_g = E_g \times I$$

Power delivered to the load is equal to,

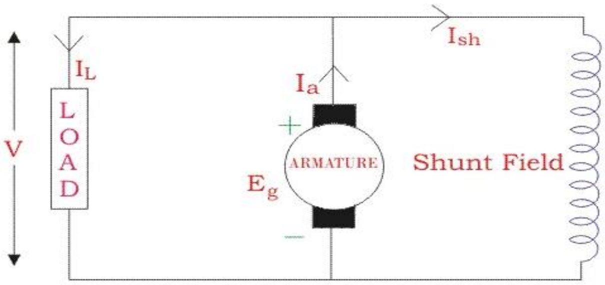
$$P_L = V \times I$$

Shunt Wound DC Generators

In these type of DC generators, the field windings are connected in parallel with armature conductors, as shown in the figure below. In shunt wound generators the voltage in the field winding is same as the voltage across the terminal.

Here:

- R_{sh} = Shunt winding resistance
- I_{sh} = Current flowing through the shunt field
- R_a = Armature resistance
- I_a = Armature current
- I_L = Load current
- V = Terminal voltage
- E_g = Generated EMF



Shunt Wound Generator

Here armature current I_a is dividing in two parts – one is shunt field current I_{sh}, and another is load current I_L.

So,

$$I_a = I_{sh} + I_L$$

The effective power across the load will be maximum when I_L will be maximum. So, it is required to keep shunt field current as small as possible. For this purpose the resistance of the shunt field winding generally kept high (100 Ω) and large no of turns are used for the desired EMF.

Shunt field current is equal to,

$$I_{sh} = \frac{V}{R_{sh}}$$

Voltage across the load is equal to,

$$V = E_g - I_a R_a$$

Power generated is equal to,

$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

Compound Wound DC Generator

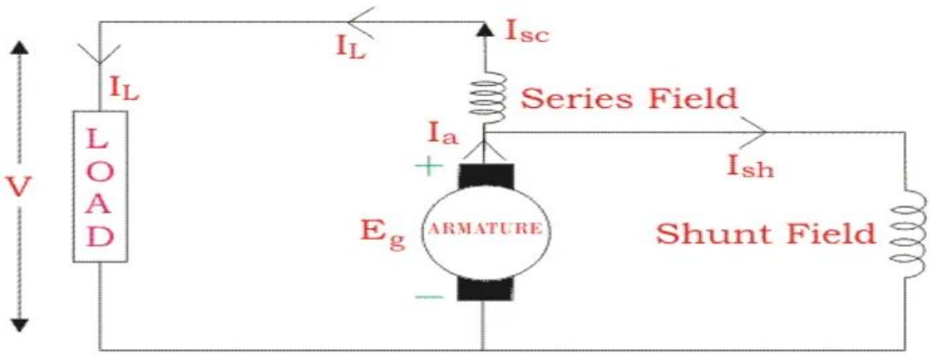
In series wound generators, the output voltage is directly proportional with load current. In shunt wound generators, the output voltage is inversely proportional with load current.

A combination of these two types of generators can overcome the disadvantages of both. This combination of windings is called compound wound DC generator.

Compound wound generators have both series field winding and shunt field winding. One winding is placed in series with the armature, and the other is placed in parallel with the armature. This type of DC generators may be of two types- short shunt compound-wound generator and long shunt compound-wound generator.

Short Shunt Compound Wound DC Generator

Short Shunt Compound Wound DC Generators are generators where only the shunt field winding is in parallel with the armature winding, as shown in the figure below.



Short Shunt Compound Wound Generator

$$I_{sc} = I_L$$

Shunt field current is equal to,

$$I_{sh} = \frac{(V + I_{sc}R_{sc})}{R_{sh}}$$

Armature current is equal to,

$$I_a = I_{sh} + I_L$$

Voltage across the load is equal to,

$$V = E_g - I_a R_a - I_{sc}R_{sc}$$

Power generated is equal to,

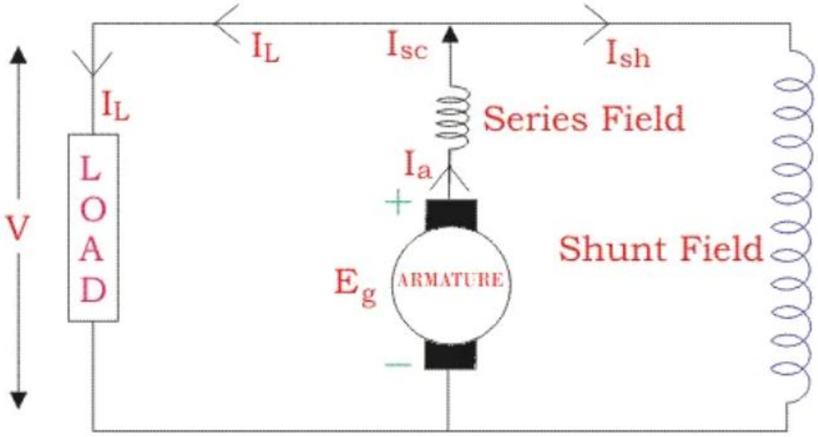
$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

Long Shunt Compound Wound DC Generator

Long Shunt Compound Wound DC Generator are generators where the shunt field wind is in parallel with both series field and armature winding, as shown in the figure below.



Long Shunt Compound Wound Generator

$$I_{sh} = \frac{V}{R_{sh}}$$

Armature current, I_a = series field current,

$$I_{sc} = I_L + I_{sh}$$

Voltage across the load is equal to,

$$V = E_g - I_a R_a - I_{sc} R_{sc} = E_g - I_a (R_a + R_{sc}) \; [\because I_a = I_{cs}]$$

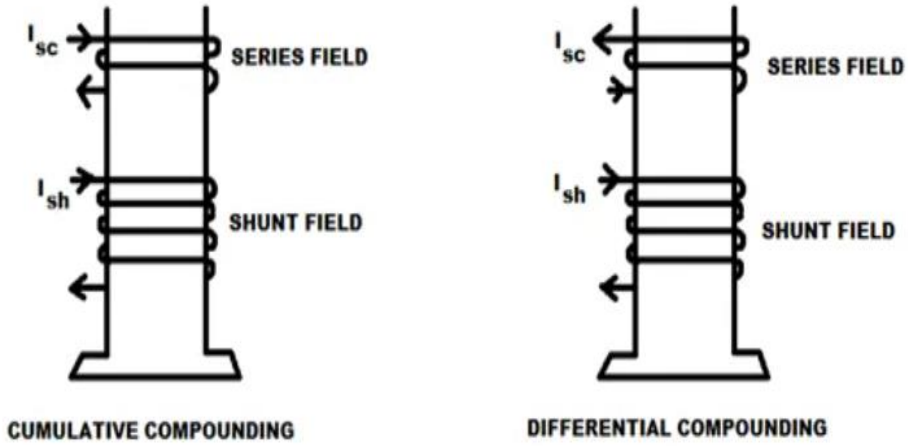
Power generated is equal to,

$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

In a compound wound generator, the shunt field is stronger than the series field. When the series field assists the shunt field, generator is said to be **commutatively compound wound**.



On the other hand, if the series field opposes the shunt field, the generator is said to be **differentially compound wound**.

Basis for Comparison	Slip Ring	Split Ring
Definition	The slip ring is used for transferring the power between the rotating and stationary structure of an AC machine	The split ring is used for reversing the direction of current.
Uses	It is used in AC machine.	It is used in DC machine.
Design	Continuous Ring	The ring is split into two or more parts.
Application	It supplies power from an AC generator to the AC motor.	For supplying pulsating voltage to the DC motor.

DISTINGUISH BETWEEN TERMINAL VOLTAGE AND INDUCED EMF.

As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the Generated emf or Armature emf and is denoted as **$E_r = E_g$**. In the case of a motor, the emf of rotation is known as Back emf or Counter emf and represented as $E_r = E_b$.

Terminal voltage is the potential difference that you get at the output terminals of the generator.

When current starts flowing the IR drop takes place in the winding and the terminal voltage is somewhat less than the generated EMF.

Armature resistance voltage drop: $V_T = E_r - I_A R_A$