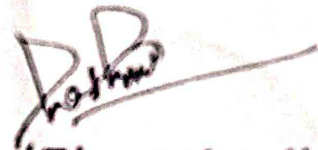


SUBJECT – EC-1

BRANCH-ELECTRICAL

SEMESTER-4th SEM

PREPARED BY- PRABHAT RASHMI MALLIK

A handwritten signature in black ink, appearing to read 'Prabhat Rashmi Mallik', with a long horizontal flourish extending to the right.

Lect.(Electrical)

DC Generator

An electric generator is a machine that converts mechanical energy into electrical energy.

Working Principle :-

⇒ An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed.

⇒ The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule. Therefore, the essential components of a generator are :-

- (a) a magnetic field
- (b) conductor or a group of conductors.
- (c) motion of conductor w.r.t. magnetic field.

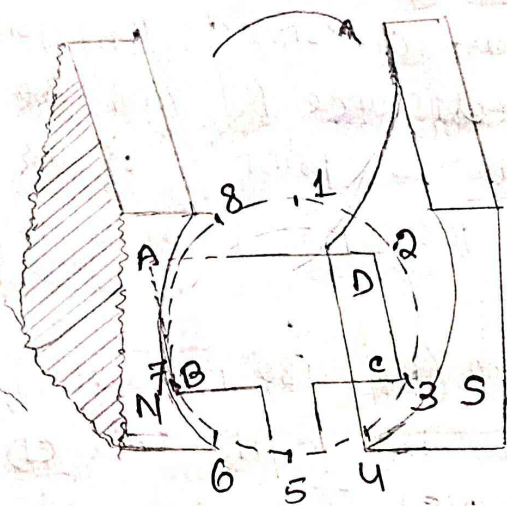
* Fleming's Right hand rule :- Stretch the thumb, fore-finger and middle finger of your right hand so that they are at right angles to each other. If the thumb points in the direction of field, fore-finger points in the direction of motion of the conductor, then middle finger will point in the direction of induced e.m.f.

Simple Loop Generator :-

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig. 1(a). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.

- (i) When the loop is in position no. 1 (Fig 1(a)), the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it.
- (ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and therefore, a low e.m.f. is generated as indicated by point 2 in Fig (1b).
- (iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig (1b).
- (iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.
- (v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig (1b).
- (vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e. reverse direction, Fig 1(b)) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.

* Note :- The e.m.f. generated in the loop is alternating one. It is because any coil side, say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load. The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator.
A commutator is a mechanical rectifier.



(Fig 1a)

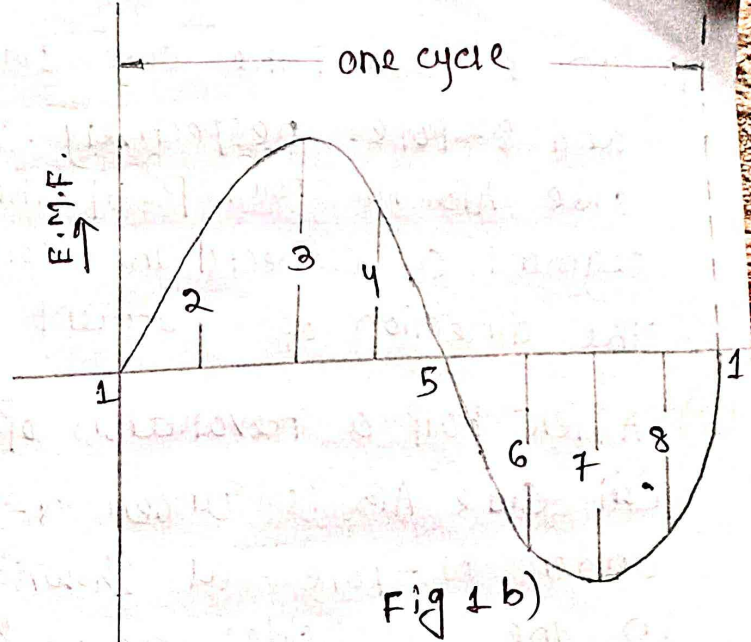


Fig 1b)

Action of Commutator :-

⇒ If somehow, connection of the coil side to the external load is reversed at the same instant the current in the coil side reverses, the current through the load will be direct current. This is what a commutator does.

⇒ Fig 2(a) shows a commutator having two segments C_1 and C_2 . It consists of a cylindrical metal ring cut into two halves or segments C_1 and C_2 respectively separated by a thin sheet of mica.

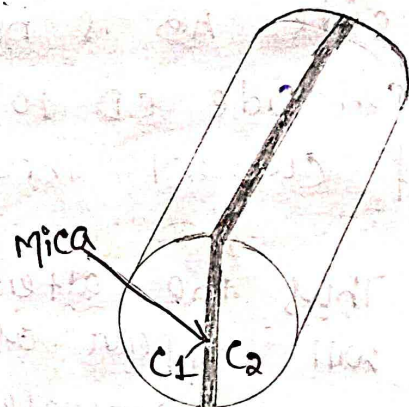


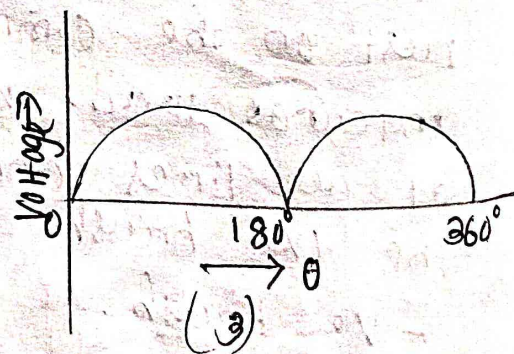
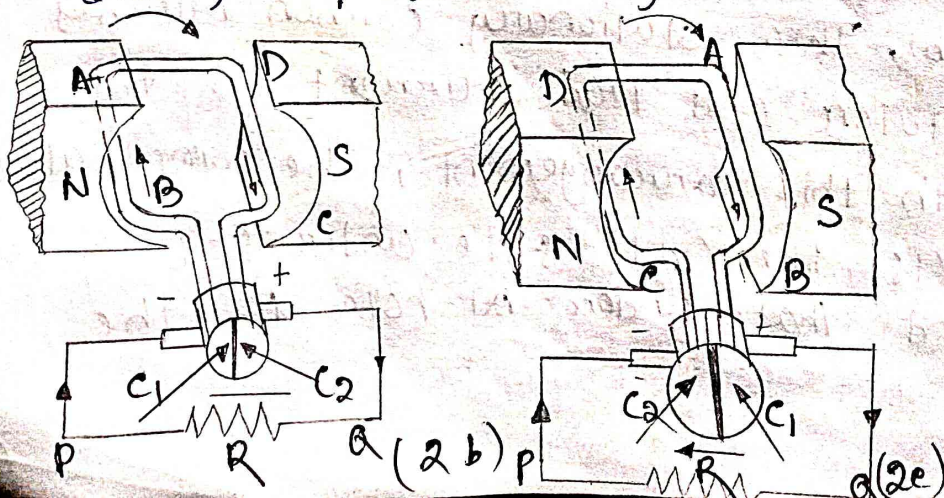
Fig 2(a)

⇒ The commutator is mounted on but insulated from the rotor shaft. The ends of coil sides AB and CD are connected to the segments C_1 and C_2 respectively as shown in Fig 2(b). Two stationary carbon brushes rest on the commutator and lead current to the external load. With this arrangement, the commutator at all times connects the coil side under S-pole to the +ve brush and that under N-pole to the -ve brush.

(i) In Fig 2(b), the coil sides AB and CD are under N-pole and S-pole respectively. The segment C_1 connects the coil side AB to point P of the load resistance R and the segment C_2 connects the coil side CD to point Q of the load. The direction of current through load is from Q to P.

(ii) After half a revolution of the loop (i.e. 180° rotation), the coil side AB is under S-pole and the coil side CD under N-pole as shown in Fig 2(c). The currents in the coil sides now flow in the reverse direction but the segments C_1 and C_2 have also moved through 180° i.e. segment C_1 is now in contact with +ve brush and segment C_2 in contact with -ve brush. The commutator has reversed the coil connections to the load i.e. coil side AB is now connected to point Q of the load and coil side CD to the point P of the load. The direction of current through the load is again from Q to P.

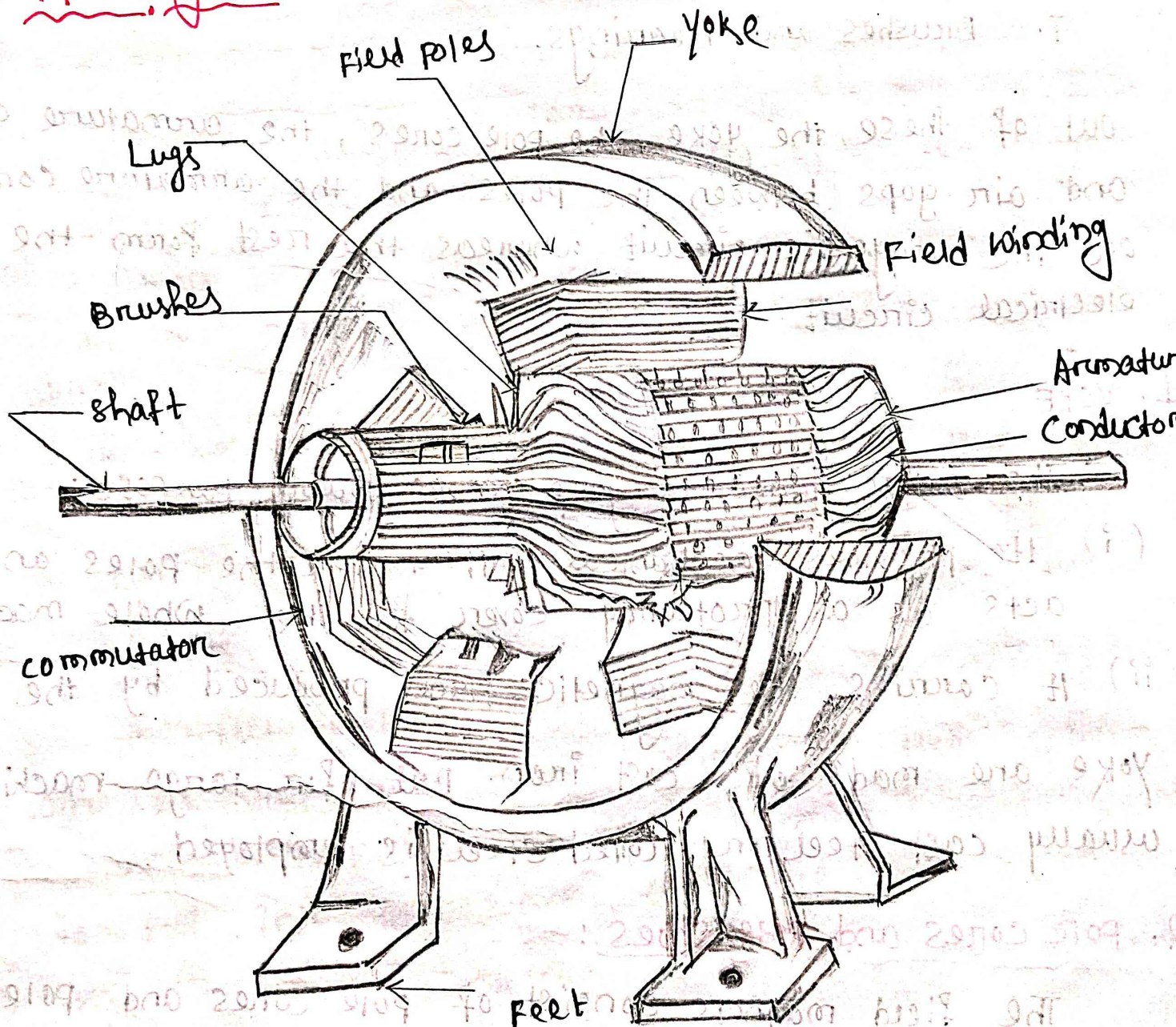
$\Rightarrow$ Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes. The e.m.f. generated in the armature winding of a d.c. generator is alternating one. It is by the use of commutator that we convert the generated alternating e.m.f. into direct voltage. The purpose of brushes is simply to lead current from the rotating loop or winding to the external stationary load.



Construction of D.C. Generator:-

- The d.c. generators and d.c. motors have the same general construction. Any d.c. generator can be run as a d.c. motor and vice-versa.
- ⇒ All d.c. machines have five principal components i.e.
- (i) field system (ii) armature core (iii) armature winding
 - (iv) commutator (v) brushes

(i) Field system:-



Construction of DC Generator :-

It consists of the following essential parts :

1. Magnetic Frame or Yoke
2. Pole-cores and pole-shoes
3. Pole coils or Field coils
4. Armature core
5. Armature windings or conductors
6. Commutator
7. Brushes and Bearings.

Out of these, the yoke, the pole cores, the armature core and air gaps between the poles and the armature core or the magnetic circuit whereas the rest form the electrical circuit.

1. YOKE :-

The outer frame or yoke serves double purpose :-

- (i) It provides mechanical support for the poles and acts as a protecting cover for the whole machine
 - (ii) It carries the magnetic flux produced by the poles
- ⇒ Yoke are made of cast iron. But for large machines usually cast steel or rolled steel is employed.

2. Pole cores and Pole shoes :-

The field magnets consist of pole cores and pole shoes. The pole shoes serve two purposes

- (i) they spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path

(ii) they support the exciting coils (or field coils)

There are two main types of pole construction.

(a) The pole core itself may be a solid piece made out of either cast iron or cast steel but the pole shoe is laminated and is fastened to the pole face by means of countersunk screws.

(b) In modern design, the complete pole cores and pole shoes are built of thin laminations of annealed steel which are rivetted together under hydraulic pressure. The thickness of laminations varies from 1mm to 0.25mm. The laminated poles may be secured to the yoke in any of the following two ways:-

(i) Either the pole is secured to the yoke by means of screws bolted through the yoke and into the pole body
or

(ii) The holding screws are bolted into a steel bar which passes through the pole across the plane of laminations.

3. POLE COILS:-

The field coils or pole coils, which consist of copper wire or strip, are former-wound for the correct dimension. Then, the former is removed and wound coil is put into place over the core.

⇒ When current is passed through these coils, they electromagnetise the poles which produce the necessary flux that is cut by revolving armature conductors.

4. Armature core :-

- ⇒ It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of the field magnets. In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a N-pole to a S-pole.
- ⇒ It is cylindrical or drum-shaped and is built up of usually circular sheet discs or laminations approximately 0.5mm thick. It is keyed to the shaft.
- ⇒ The laminations are individually coated with a thin insulating film so that they do not come in electrical contact with each other. The purpose of laminating the core is to reduce the eddy current loss.
- ⇒ Thinner the laminations, greater is the resistance offered to the induced e.m.f., smaller the current and hence lesser the I^2R loss in the core.

5. Armature winding :-

- ⇒ The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding. This is the winding in which "working" e.m.f. is induced.
- ⇒ The armature conductors are connected in series-parallel, the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.
- ⇒ The armature winding of a d.c. machine is a closed-circuit winding, the conductors being connected in a symmetrical manner forming a closed loop.

6. Commutator :-

- ⇒ The function of the commutator is to facilitate collection of current from the armature conductors. It rectifies i.e. converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit.
- ⇒ It is of cylindrical structure. The commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine.
- ⇒ The number of segments is equal to the number of armature coils.

7. Brushes and Bearings :-

- ⇒ The brushes whose function is to collect current from commutator are usually made of carbon or graphite and are in the shape of a rectangular block.
- ⇒ These brushes are housed in brush-holders usually of the box-type variety. The brush pressure is adjusted by means of adjustable springs.
- ⇒ If the brush pressure is very large, the friction produces heating of the commutator and the brushes on the other hand, if it is too weak, the imperfect contact with the commutator may produce sparking.
- ⇒ Ball-bearings are frequently employed, though for heavy duties, roller bearings are preferable. The ball and rollers are generally packed in hard oil for quieter operation and for reduced bearing wear.

DC Armature winding:-

- (i) A d.c. machine (generator or motor) generally employs windings distributed in slots over the circumference of the armature core. Each conductor lies at right angles to the magnetic flux and to the direction of its movement. Therefore, the induced emf in the conductor is given by:-

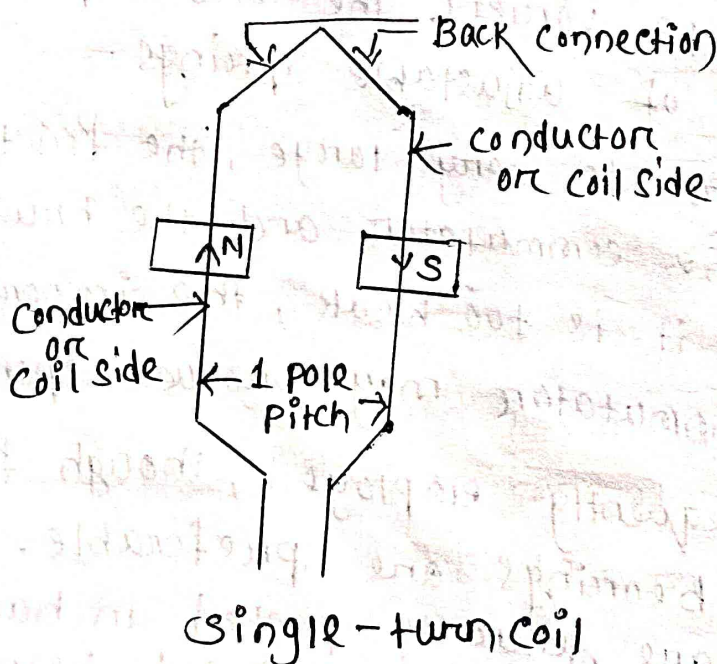
$$e = Blv \text{ volts}$$

where B = magnetic flux density in wb/m^2

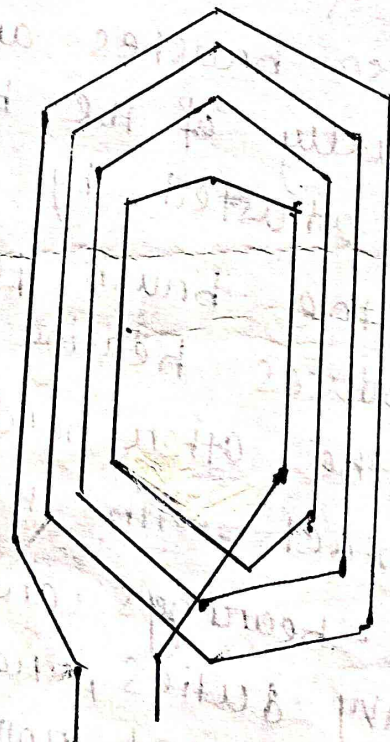
l = Length of the conductor in metres

v = velocity (in m/s) of the conductor.

- (ii) The armature conductors are connected to form coils. The basic component of all types of armature windings is the armature coil. Fig (i) shows a single-turn coil. It has two conductors on coil sides connected at the back of the armature. Fig (ii) shows a 4-turn coil which has 8 conductors or coil sides.



(i)



4-turn coil

(ii)

⇒ The coil sides of a coil are placed a pole span apart i.e. one coil side of the coil is under N-pole and the other coil side is under the next S-pole at the corresponding position as shown in Fig(i) & (ii). Consequently the e.m.f.s of the coil sides add together.

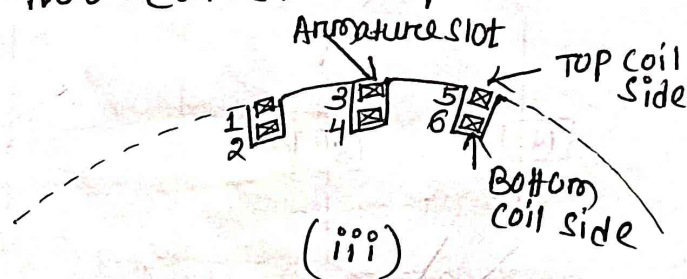
⇒ If the e.m.f. induced in one conductor is 2.5 volts, then the e.m.f. of a single-turn coil will be $= 2 \times 2.5 = 5$. For the same flux and speed, the e.m.f. of a 4-turn coil will be $= 8 \times 2.5 = 20V$.

(iii) Most of d.c. armature windings are double layer windings i.e. there are two coil sides per slot as shown in Fig (iii).

one coil side of a coil lies at the top of a slot and the other coil side lies

at the bottom of some other slot.

The coil ends will then lie side by side.



⇒ In two-layer winding, it is desirable to number the coil sides rather than the slots. The coil sides are numbered as indicated in Fig (iii). The coil sides at the top of slots are given odd numbers and those at the bottom are given even numbers.

Commutator Pitch (γ_c) :-

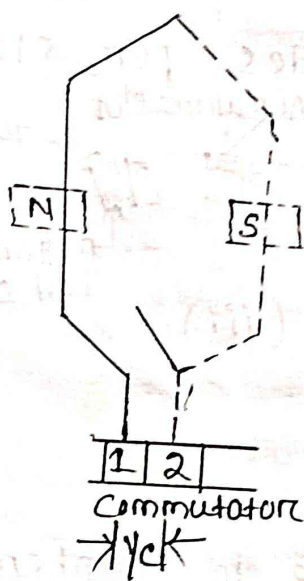
The commutator pitch is the number of commutator segments spanned by each coil of the winding. It is denoted by γ_c .

⇒ In Fig (a), one side of the coil is connected to commutator segment 1 and the other side connected to commutator segment 2. Therefore, the number of

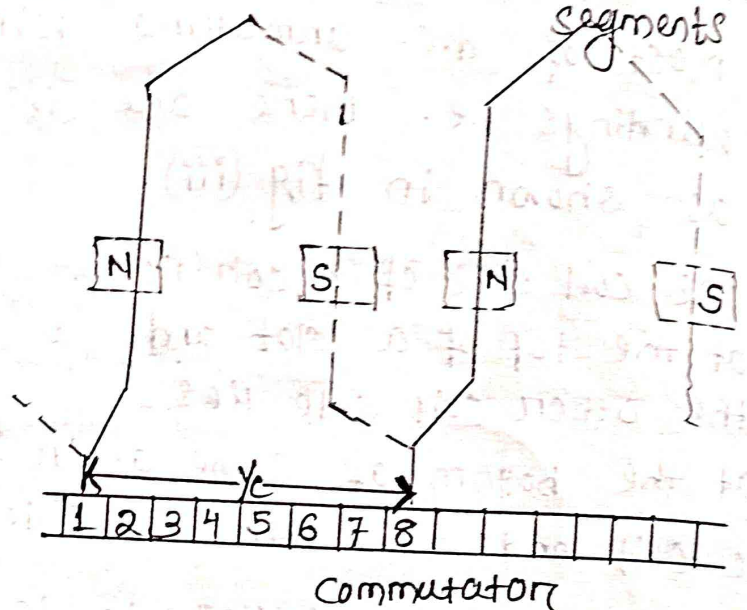
Commutator segments spanned by the coil is 1 i.e. $y_c = 1$. In Fig (b), one side of the coil is connected to commutator segment 1 and the other side to commutator segment 8. Therefore, the number of commutator segments spanned by the coil = $8 - 1 = 7$ segments, i.e. $y_c = 7$.

⇒ The commutator pitch of a winding is always a whole number. Since each coil has two ends and as two coil connections are joined at each commutator segment.

∴ Number of coils = Number of commutator segments



(a)



(b)

For example, if an armature has 30 conductors, the number of coils will be $30/2 = 15$. Therefore, number of commutator segments is also 15.

Pole-pitch:-

It is the distance measured in terms of number of armature slots (or armature conductors) per pole.

Thus if a 4-pole generator has 16 coils, then no. of slots = 16.

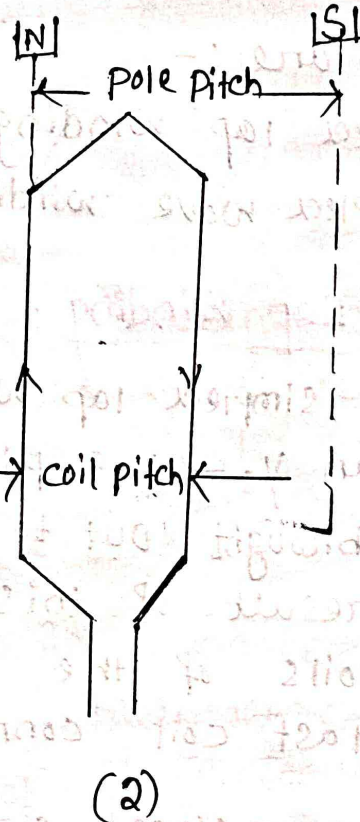
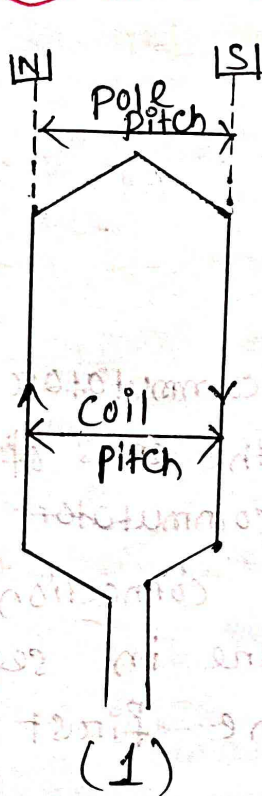
$$\text{Pole pitch} = \frac{16}{4} = 4 \text{ slots}$$

$$\text{Also pole pitch} = \frac{\text{No. of conductors}}{\text{No. of poles}} = \frac{16 \times 2}{4} = 8 \text{ conductors}$$

Coil span or coil pitch (γ_s) :-

It is the distance measured in terms of the number of armature slots (or armature conductors) spanned by a coil. Thus if the coil span is 9 slots, it means one side of the coil is in slot 1 and the other side in slot 10.

Full-pitched coil :-



$\Rightarrow$ If the coil span or coil pitch is equal to pole pitch (i.e. distance between the two sides of a coil is 180° electrical), it is called full-pitched coil. In other words, a full-pitched coil means that when one coil side is under the centre of N-pole, the other coil side must be under the centre of next S-pole as shown in fig (1).

Fractional Pitched coil :- If the coil span or coil pitch is less than the pole pitch (i.e. coil pitch is less than 180° electrical), then it is called fractional pitched coil.

Types of D.C. Armature windings:-

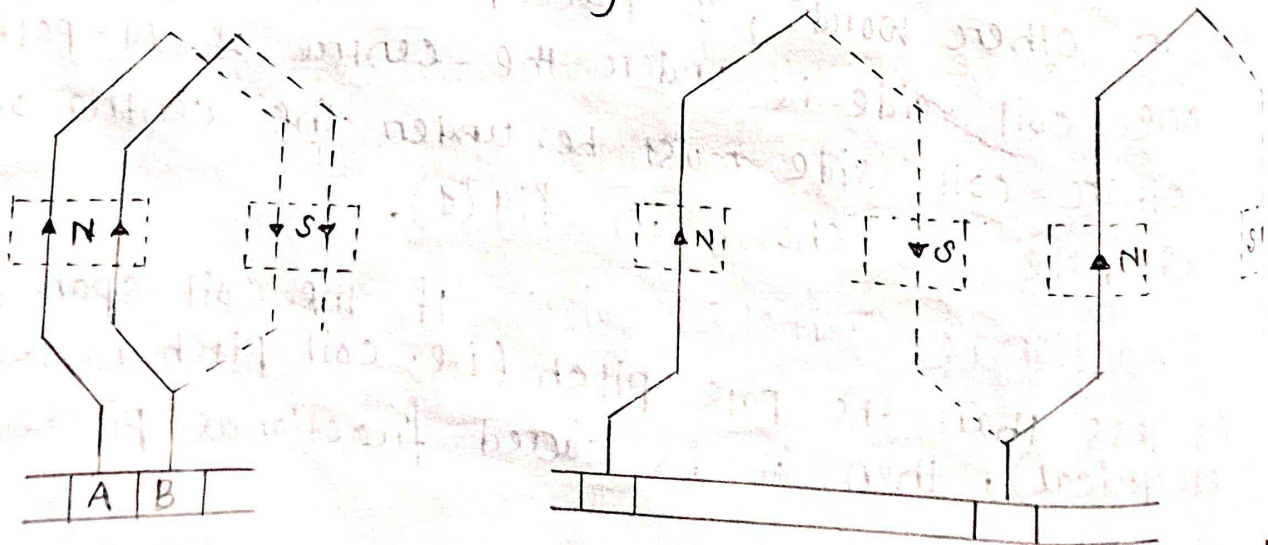
The different armature coils in a d.c. armature winding must be connected in series with each other by means of end connections (back connection and front connection) in a manner so that the generated voltages of the respective coils will aid each other in the production of the terminal e.m.f. of the winding. Two basic methods of making these end connections are:-

1. Simplex lap winding.
2. Simplex wave winding.

1. Simplex Lap Winding:-

⇒ For a simplex lap winding, the commutator pitch Y_c and coil span $Y_s \approx$ pole pitch. Thus the ends of any coil are brought out to adjacent commutator segments and the result of this method of connection is that all the coils of the armature are in sequence with the last coil connected to the first coil.

⇒ Consequently, closed circuit winding results. This is shown in Fig (a) where a part of the lap winding is shown. Only two coils are shown for simplicity. The name lap comes from the way in which successive coils overlap the preceding one.



2. Simplex wave winding :-

For a simplex wave winding, the commutator pitch $y_c \approx 2$ pole pitches and coil span $\approx$ pole pitch. The result is that the coils under consecutive pole pairs will be joined together in series thereby adding together their e.m.f.s. This winding is called wave winding from the appearance (wavy) of the end connections.

Back pitch (y_B) :- It is the distance measured in terms of armature conductors between the two sides of a coil at the back of the armature in Fig (i) & (ii). It is denoted by y_B .

$\Rightarrow$ Ex :- if a coil is formed by connecting conductor 1 (upper conductor in a slot) to conductor 12 (bottom conductor in another slot) at the back of the armature then back pitch is $y_B = 12 - 1 = 11$ conductors.

Front pitch (y_F) :- It is the distance measured in terms of armature conductors between the coil sides attached to any one commutator segment. It is denoted by y_F .

$\Rightarrow$ Ex :- If coil side 12 and coil side 3 are connected to the same commutator segment, then $y_F = 12 - 3 = 9$ conductors.

Resultant pitch (y_R) :- It is the distance measured in terms of armature conductors between the beginning of one coil and the beginning of the next coil to which it is connected. It is denoted by y_R . Therefore, the resultant pitch is the algebraic sum of the back / front pitches.

Commutator Pitch (y_c) :- It is the number of commutator segments spanned by each coil of the armature winding.

For simplex lap winding, $y_c = 1$

For simplex wave winding $y_c \approx 2$ pole pitches (segments)

Dummy coils :-

- ⇒ These are used with wave-winding and are resorted to when the requirements of the winding are not met by the standard armature punchings available in armature-winding shops.
- ⇒ These dummy coils do not influence the electrical characteristics of the winding because they are not connected to the commutator.
- ⇒ They are exactly similar to the other coils except that their ends are cut short and taped. They are there simply to provide mechanical balance for the armature because an armature having some slots without windings would be out of balance mechanically.
- ⇒ For example - Let no. of armature slots is 15, each containing 4 sides and the no. of poles is 4.

For a simplex wave - windings,

$$Y_A = \frac{Z \pm 2}{P} = \frac{60 \pm 2}{4} = \frac{62}{4} \text{ or } \frac{58}{4}$$

which does not come out to be an integer as required by this winding. However, if we make one coil dummy so that we have 58 active conductors, then

$$Y_A = \frac{58 \pm 2}{4} = 14 \text{ or } 15$$

This makes the winding possible.

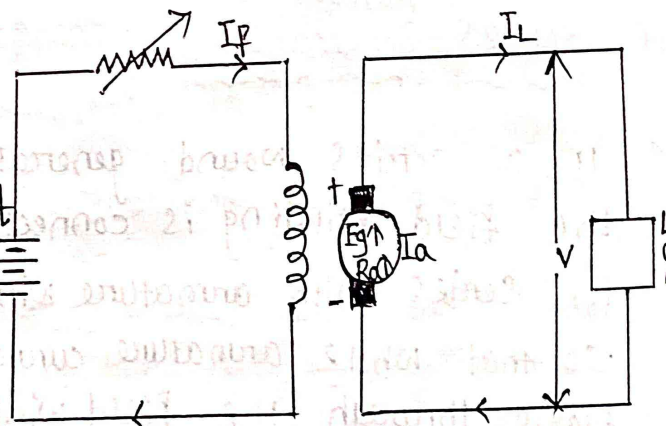
Types of D.C. Generators :-

Generators are generally classified according to their methods of field excitation. on this basis, d.c. generator are divided into the following two classes :-

- (i) separately excited d.c. generators.
- (ii) self - excited d.c. generators.

Separately Excited D.C. Generators :-

⇒ A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (a battery) is called a separately excited generator.



⇒ Fig (1) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g = \frac{P\phi ZN}{60A}$). The greater the speed and field current, greater is the generated e.m.f.

⇒ It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.

Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_a R_a$

Electric power developed = $E_g I_a$

Power delivered to load = $E_g I_a - I_a^2 R_a$

= $I_a (E_g - I_a R_a) = V I_a$

Self-Excited D.C. Generators :-

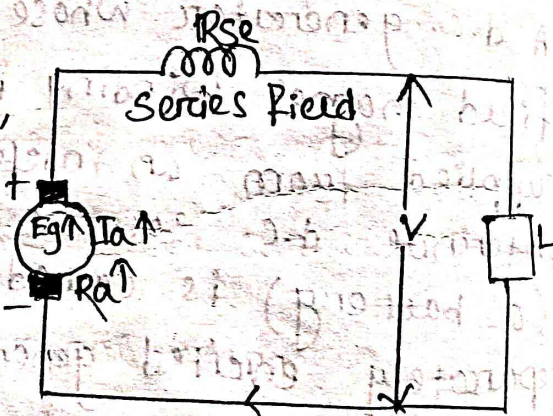
⇒ A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator.

⇒ There are 3 types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely :-

(i) series generator (ii) shunt generator (iii) compound generator

(i) series Generator :-

⇒ In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load.



⇒ Fig(2) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance.

series generators are used for special purposes e.g. as boosters.

Armature current, $I_a = I_{se} = I_L = I$

Terminal voltage, $V = E_g - I(R_a + R_{se})$

power developed in armature = $E_g I_a$

power delivered to load = $E_g I_a - I_a^2 (R_a + R_{se})$
 $= I_a [E_g - I_a (R_a + R_{se})]$
 $= V I_a \text{ or } V I_L$

(ii) shunt generator:

⇒ In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it.

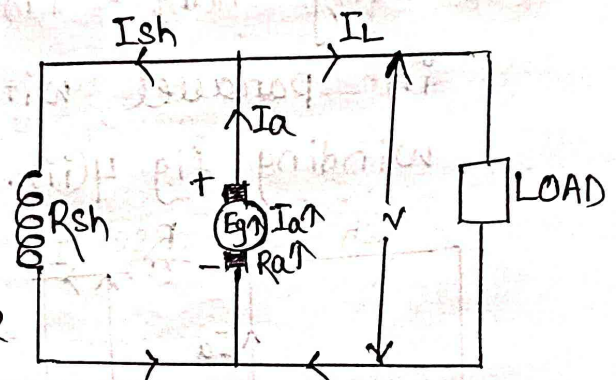


Fig (3)

⇒ The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load.

⇒ Fig (3) shows the connections of a shunt-wound generator.

Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_a R_a$

power developed in armature = $E_g I_a$

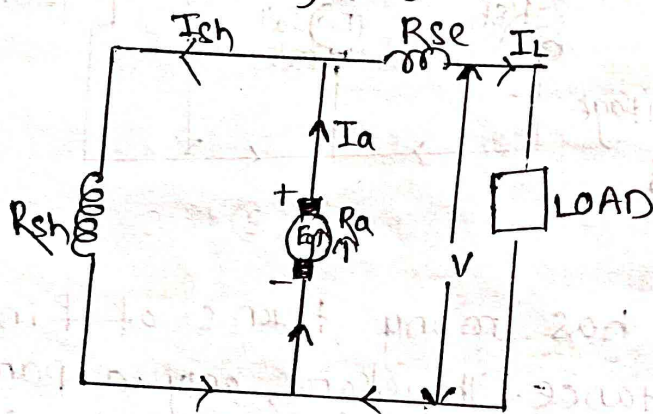
power delivered to load = $V I_L$

(iii) Compound Generator :-

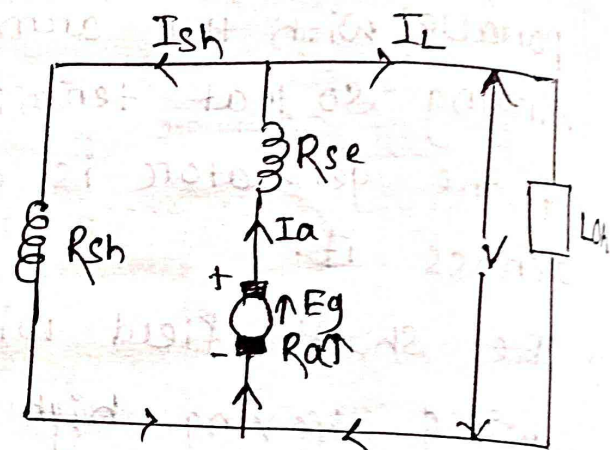
→ In a compound wound generator, there are two sets of field windings on each pole - one is in series with the armature and the other in parallel with the armature. Compound wound generator may be :-

(a) short shunt - in which only shunt field winding is in parallel with the armature winding.

(b) Long shunt - in which shunt field winding is in parallel with both series field and armature winding. Fig 4(ii).



4(i) [short shunt]



4(ii) [Long shunt]

Series field current $I_{se} = I_L$

Shunt field current,

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

Terminal voltage, $V = E_g - I_a R_a - I_{se} R_{se}$

Power developed in armature = $E_g I_a$

power delivered to load = $V I_L$

Series field current, $I_{se} = I_a = I_L$

Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$

Terminal voltage, $V = E_g - I_a R_a - I_{se} R_{se}$

Power developed in armature = $E_g I_a$

power delivered to load = $V I_L$

Brush contact Drop:-

⇒ It is the voltage drop over the brush contact resistance when current passes from commutator segments to brushes and finally to the external load.

⇒ Its value depends on the amount of current and the value of contact resistance. This drop is usually small and includes brushes of both polarities.

⇒ However, in practice, the brush contact drop is assumed to have following constant values for all loads.

0.5V for metal-graphite brushes.

2.0V for carbon brushes.

Generated E.M.F or E.M.F. Equation of a Generator

Let ϕ = flux/pole in weber

Z = Total no. of armature conductors
= NO. of slots $\times$ NO. of conductors/slot

P = NO. of generator poles

A = NO. of parallel paths in armature

N = armature rotation in revolutions per minute (r.p.m)

E = e.m.f induced in any parallel path in armature

Generated e.m.f, E_g = e.m.f generated in any one of the parallel paths
i.e. E

Average e.m.f. generated / conductor = $\frac{d\phi}{dt}$ volt ($\because n =$

Now, Flux cut/conductor in one revolution $d\phi = \phi P \omega$

$$\text{No. of revolutions / second} = \frac{N}{60}$$

$\therefore$ Time for one revolution, $dt = \frac{60}{N}$ second.

Hence, according to Faraday's Laws of Electromagnetic Induction,

$$\text{E.M.F. generated / conductor} = \frac{d\phi}{dt} = \frac{\phi P}{60/N} = \frac{\phi P N}{60} \text{ volt}$$

For a simplex wave-wound generator :-

$$\text{No. of parallel paths} = 2$$

$$\text{No. of conductors (in series) in one path} = \frac{Z}{2}$$

$$\therefore \text{E.M.F. generated / path} = \frac{\phi P N}{60} \times \frac{Z}{2} = \frac{\phi Z P N}{120} \text{ volt}$$

For a simplex lap-wound generator :-

$$\text{No. of parallel paths} = P$$

$$\text{No. of conductors (in series) in one path} = \frac{Z}{P}$$

$$\therefore \text{E.M.F. generated / path} = \frac{\phi P N}{60} \times \frac{Z}{P} = \frac{\phi Z N}{60} \text{ volt}$$

$$\text{In general generated e.m.f. } E_g = \frac{\phi Z N}{60} \times \left(\frac{P}{A}\right) \text{ volt}$$

where $A = 2$ - For simplex wave-winding
 $= P$ - For " Lap - "

$$\text{Also, } E_g = \frac{1}{2\pi} \left(\frac{2\pi N}{60}\right) \phi Z \left(\frac{P}{A}\right) = \frac{\omega \phi Z}{2\pi} \left(\frac{P}{A}\right) \text{ volt}$$

For a given d.c. machine, Z , P and A are constant,

Hence putting $K_a = \frac{ZP}{A}$, we get

$$E_g = K_a \phi N \text{ Volts — where } N \text{ is in r.p.s.}$$

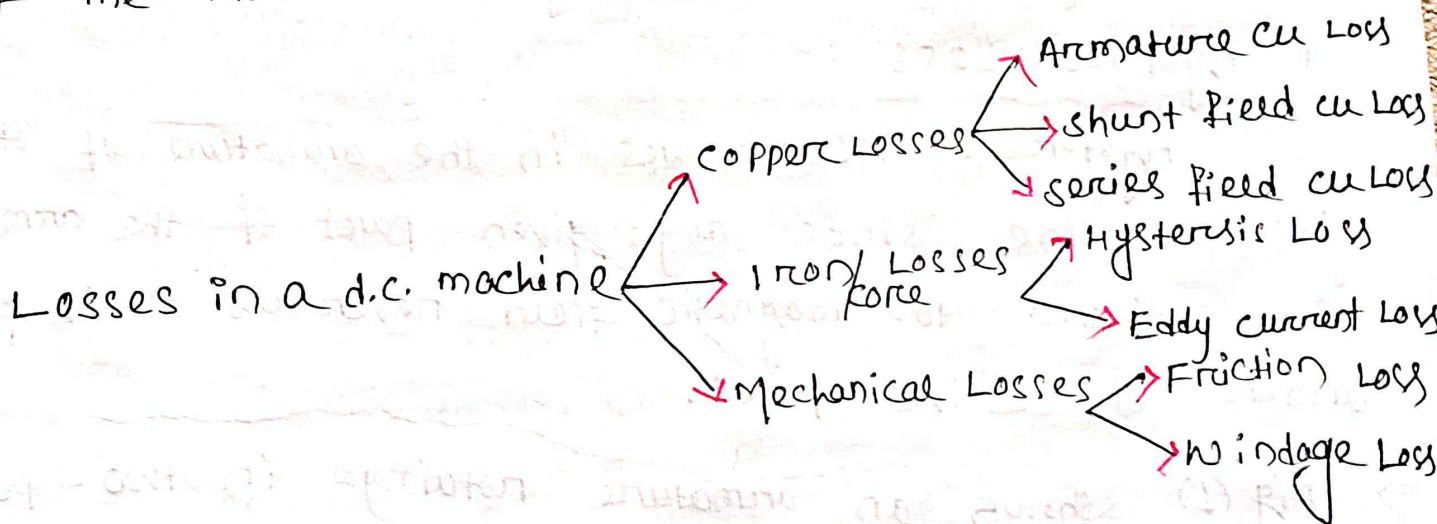
Losses in a D.C. machine :-

The losses in a d.c. machine may be divided into three classes i.e. (i) Copper Losses

(ii) Iron or core losses

(iii) Mechanical losses.

All these losses appear as heat and thus raise the temperature of the machine. They also lower the efficiency of the machine.



1. COPPER LOSSES :- These losses occur due to currents in the various windings of the machine.

(i) Armature copper loss $= I_a^2 R_a$

(ii) Shunt Field copper loss $= I_{sh}^2 R_{sh}$

(iii) Series Field copper loss $= I_{se}^2 R_{se}$

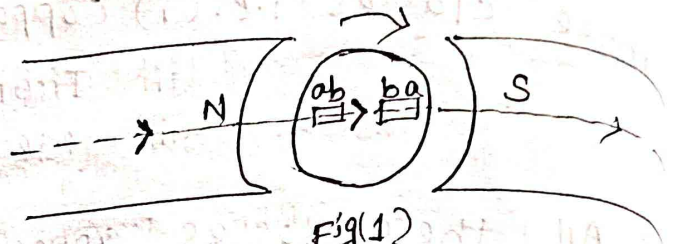
Copper losses also occur in interpole field winding and compensating field winding and must be accounted for if required. These windings are connected in series

with armature of the d.c. machine and therefore, carry armature current (I_a).

* There is also brush contact loss due to brush resistance (i.e. resistance between the surface of commutator and surface of commutator). This loss is generally included in armature copper loss.

2. IRON OR CORE LOSSES :-

These losses occur in the armature of a d.c. machine and are due to the rotation of armature in the magnetic field of the poles. They are of two types i.e. (i) hysteresis loss (ii) eddy current loss.



Fig(1)

(i) Hysteresis Loss :-

Hysteresis loss occurs in the armature of the d.c. machine since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles.

⇒ Fig (1) shows an armature rotating in two-pole machine. Consider a small piece ab of the armature. When the piece ab is under N-pole, the magnetic lines pass from a to b . Half a revolution later, the same piece of iron is under S-pole and magnetic lines pass from b to a so that magnetism in the iron is reversed.

⇒ In order to reverse continuously, the molecular magnets in the armature core, some amount

of power has to be spent which is called hysteresis loss. It is given by Steinmetz Formula. This Formula is

$$\text{Hysteresis loss, } P_h = \eta B_{\max}^{1.6} f V \text{ watts}$$

where $B_{\max}$ = Maximum flux density in armature.

f = Frequency of magnetic reversals

$$= \frac{NP}{120} \text{ where } N \text{ is in r.p.m}$$

V = volume of armature in m^3

η = Steinmetz hysteresis co-efficient

In order to reduce this loss in a d.c. machine, armature core is made of such materials which have a low value of Steinmetz hysteresis co-efficient i.e. silicon steel = 191 J/m^2 , good dynamo sheet steel = 502 J/m^2 , Hard cast steel = 7040 J/m^2 etc.

(ii) Eddy Current Loss :-

⇒ In addition to the voltages induced in the armature conductors, there are also voltages induced in the armature core. These voltages produce circulating currents in the armature core as shown in Fig. These are called eddy currents and power loss due to their flow is called eddy current loss. The eddy current loss appears as heat which raises the temperature of the machine and lowers its efficiency.

⇒ If a continuous solid iron core is used, the resistance to eddy current path will be small to large cross-sectional area of the core.

Consequently, the magnitude of eddy current and hence eddy current loss will be large.

⇒ The magnitude of eddy current can be reduced by making core resistance as high as practical. The core resistance can be greatly increased by constructing the core of thin, round iron sheets called laminations [Fig].

⇒ The laminations are insulated from each other with a coating of varnish. The insulating coating has a high resistance, so very little current flows from one lamination to the other. Also, because each lamination is very thin, the resistance to current flowing through the width of a lamination is also quite large. Thus laminating a core increases the core resistance which decreases the eddy current and hence the eddy current loss.

$$\text{Eddy current loss, } P_e = K_e B_{\max}^2 f^2 t^2 V \text{ watts}$$

Where K_e = constant depending upon the electric resistance of core and system of units used

$B_{\max}$ = max^m flux density in wb/m^2

f = frequency of magnetic reversals in Hz

t = Thickness of lamination in m

V = volume of core in m^3

Eddy current loss depends upon the square of lamination thickness. For this reason, lamination thickness should be kept as small as possible.

3. Mechanical Losses :-

These losses are due to friction and windage.

- (i) Friction loss e.g. bearing friction, brush friction etc.
- (ii) windage loss i.e. air friction of rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

* Iron losses and mechanical losses together are called rotational losses.

Constant and Variable Losses :-

The losses in a d.c. generator (or d.c. motor) may be sub-divided into (i) constant losses (ii) variable losses.

- (i) Constant Losses :- Those losses in a d.c. generator which remain constant at all loads are known as constant losses. The constant losses in a d.c. generator are :-
 - (a) iron losses (b) mechanical losses (c) shunt field losses.

- (ii) Variable losses :- Those losses in a d.c. generator which vary with load are called variable losses. The variable losses in a d.c. generator are :-

- (a) copper loss in armature winding ($I_a^2 R_a$)
- (b) copper loss in series field winding ($I_{se}^2 R_{se}$)

Total losses = constant losses + variable losses

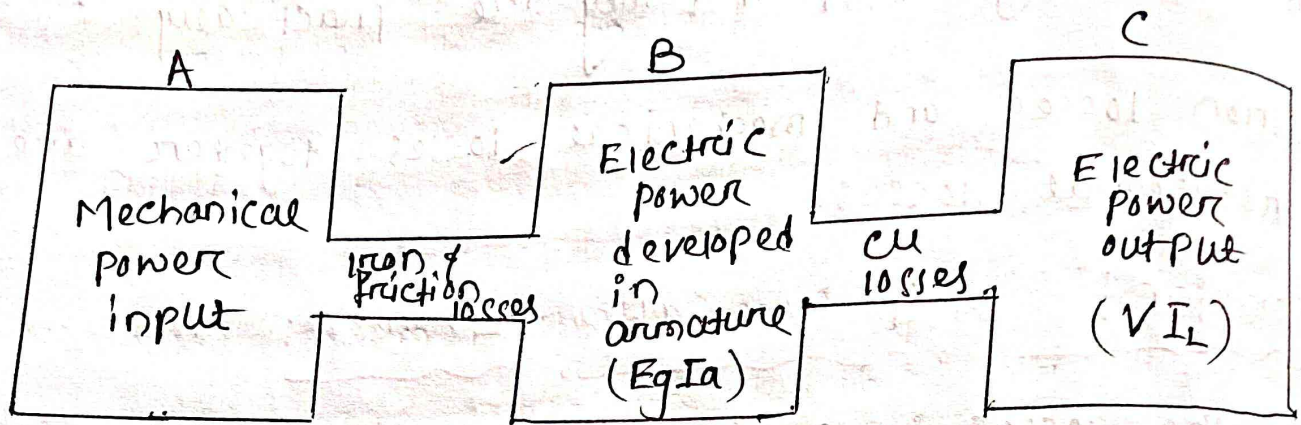
* Field cu loss is constant for shunt and compound generators.

Power Stages :-

The various power stages in a d.c. generator represented diagrammatically in Fig.

A - B = Iron and friction losses

B - C = copper losses



(i) mechanical efficiency

$$\eta_m = \frac{B}{A} = \frac{E_g I_a}{\text{Mechanical power input}}$$

(ii) Electrical efficiency

$$\eta_e = \frac{C}{B} = \frac{V I_L}{E_g I_a}$$

(iii) commercial or overall efficiency

$$\eta_c = \frac{C}{A} = \frac{V I_L}{\text{Mechanical power input}}$$

Clearly, $\eta_c = \eta_m \times \eta_e$

$$\text{Now, } \eta_c = \frac{C}{A} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}}$$

condition for maximum Efficiency:

The efficiency of a d.c. generator is not constant but varies with load. Consider a shunt generator delivering a load current I_L at a terminal voltage V .

$$\text{Generator output} = VI_L$$

$$\text{Generator input} = \text{output} + \text{Losses}$$

$$= VI_L + \text{variable losses} + \text{constant losses}$$

$$= VI_L + I_a^2 R_a + W_c$$

$$= VI_L + (I_L + I_{sh})^2 R_a + W_c$$

The shunt field current I_{sh} is generally small as compared to I_L and therefore, can be neglected.

$$\therefore \text{Generator input} = VI_L + I_L^2 R_a + W_c$$

$$\text{Now } \eta = \frac{\text{output}}{\text{input}} = \frac{VI_L}{VI_L + I_L^2 R_a + W_c}$$

$$= \frac{1}{1 + \left(\frac{I_L R_a}{V} + \frac{W_c}{VI_L} \right)} \quad \text{--- (1)}$$

The efficiency will be maximum when the denominator of eq (1) is minimum i.e.,

$$\frac{d}{dI_L} \left(\frac{I_L R_a}{V} + \frac{W_c}{VI_L} \right) = 0$$

$$\Rightarrow \frac{R_a}{V} - \frac{W_c}{VI_L^2} = 0$$

$$\Rightarrow \frac{R_a}{V} = \frac{W_c}{VI_L^2}$$

$$\Rightarrow I_L^2 R_a = W_c \quad \text{i.e. } \boxed{\text{variable loss} = \text{constant loss}}$$

The load current corresponding to maximum efficiency is given by ;

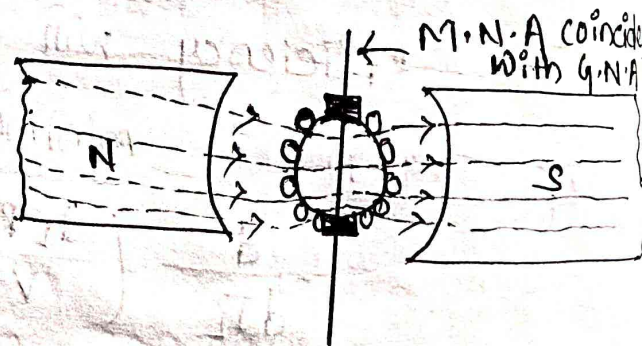
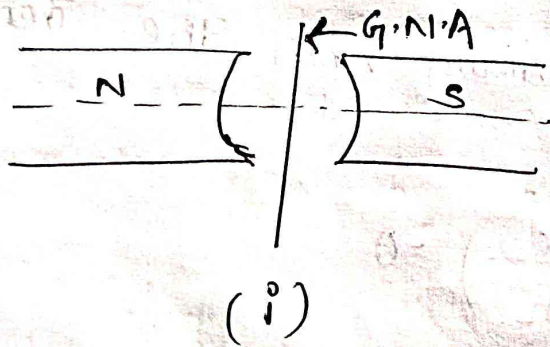
$$I_L = \sqrt{\frac{W_c}{R_a}}$$

Hence, the efficiency of a d.c. generator will be maximum when the load current is such that variable loss is equal to the constant loss.

Armature Reaction :-

We have assumed that the only flux acting in a d.c. machine is that due to the main poles called main flux. However, current flowing through armature conductors also creates a magnetic flux (called armature flux) that distorts and weakens the flux coming from the poles. The action of armature flux on the main flux is known as armature reaction.

Geometrical and Magnetic Neutral Axes :-



- i) The geometrical neutral axis (G.N.A.) is the axis that bisects the angle between the centre line of adjacent poles.

(ii) The magnetic neutral axis (M.N.A) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. Clearly, no e.m.f. is produced in the armature conductors along this axis because ^{then} they cut no flux. With no current in the armature conductors, the M.N.A. coincides with G.N.A. as shown in fig(ii). In order to achieve sparkless commutation, the brushes must lie along M.N.A.

Explanation of Armature Reaction :-

→ With no current in armature conductors, the M.N.A. coincides with G.N.A. However, when current flows in armature conductors, the combined action of main flux and armature flux shifts the M.N.A. from G.N.A.

⇒ In case of a generator, the M.N.A. is shifted in the direction of rotation of the machine. In order to achieve sparkless commutation, the brushes have to be moved along the new M.N.A. Under such a condition, the armature reaction produces the following 2 effects.

1. It demagnetises or weakens the main flux.
2. It cross-magnetises or distorts the main flux.

~~Let~~ consider a 2-pole generator.

(i) Fig 1(i) shows the flux due to main poles (main flux) when the armature conductors carry no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented in magnitude and direction by the vector OF_m in Fig 1(i). Note that OF_m is perpendicular to G.N.A.

(ii) Fig 1(ii) shows the flux due to current flowing in armature conductors alone (main poles unexcited). The armature conductors to the left of G.N.A. carry current "in" (x) and those to the right carry current "out" (·). It is clear that armature flux is directed downwards parallel to the brush axis. The m.m.f. producing the armature flux is represented in magnitude and direction by the vector OF_a in Fig 1(ii).

(iii) Fig 1(iii) shows the flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OF_m and OF_a as shown in Fig 1(iii). Since M.N.A. is always perpendicular to the resultant m.m.f., the M.N.A. is shifted through an angle θ . Note that M.N.A. is shifted in the direction of rotation of the generator.

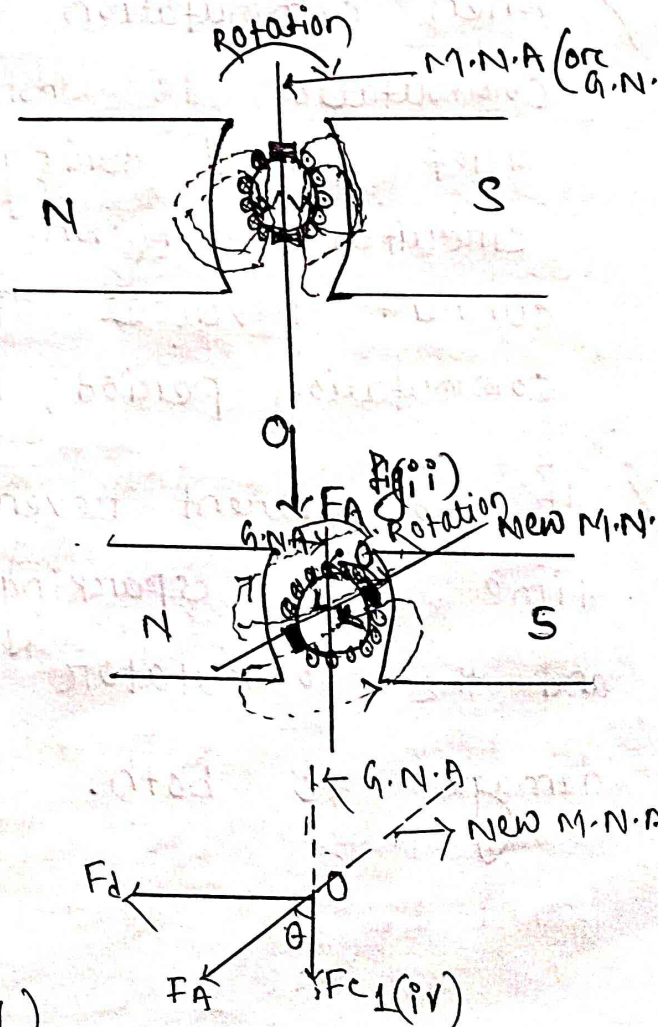
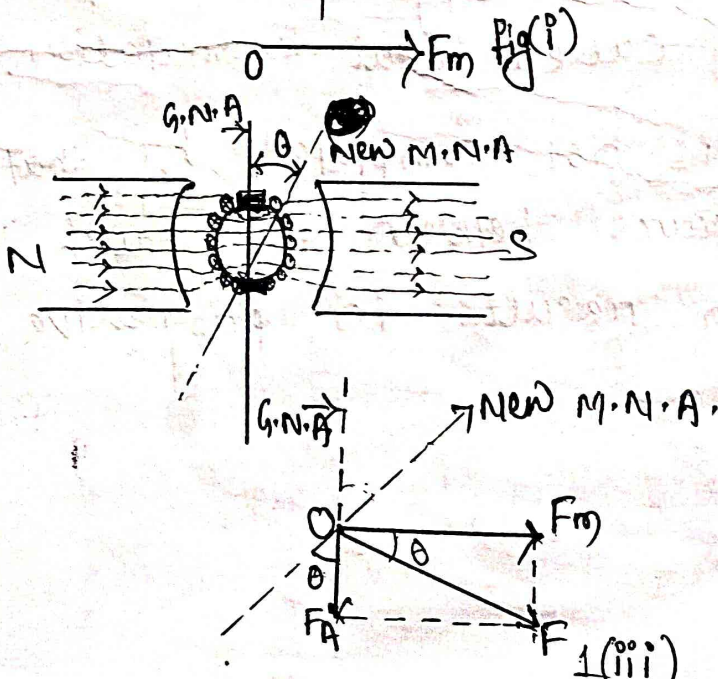
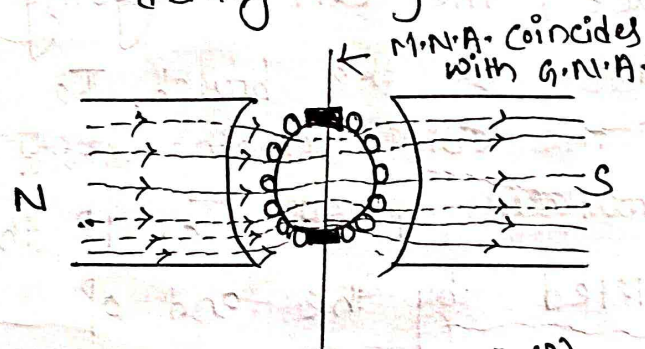
(iv) In order to achieve sparkless commutation, the brushes must lie along the M.N.A. Consequently, the brushes are shifted through an angle θ so as to lie along the new M.N.A. as shown in Fig 1(iv). Due to brush shift, the m.m.f. F_a of the armature is also rotated through the same angle θ .

It is because some of the conductors which were earlier under N-pole now come under S-pole and vice-versa. The result is that armature m.m.f. F_A will no longer be vertically downward but will be resolved into rectangular components F_c and F_d .

(a) The component F_d is in direct opposition to the m.m.f. $O F_m$ due to main poles. It has a demagnetising effect on the flux due to main poles. For this reason, it is called the demagnetising or weakening component of armature reaction.

(b) The component F_c is at right angles to the m.m.f. $O F_m$ due to main poles. It distorts the main field. For this reason, it is called the cross-magnetising or distorting component of armature reaction.

* With the increase of armature current, both demagnetising and distorting effects will increase.



Commutation :-

Fig(1) shows the schematic diagram of 2-pole lap-winding generator. There are two parallel paths between the brushes. Therefore, each coil of the winding carries one half ($I_a/2$ in this case) of the total current (I_a) entering or leaving the armature.

⇒ The currents in the coils connected to a brush are either all towards the brush (positive brush) or all directed away from the brush (negative brush). Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes a brush is called commutation.

The reversal of current in a coil as the coil passes the brush axis is called commutation.

⇒ When commutation takes place, the coil undergoing commutation is short-circuited by the brush. The brief period during which the coil remains short-circuited is known as commutation period T_c . If the current reversal is completed by the end of commutation period, it is called ideal commutation.

⇒ If the current reversal is not completed by that time, then sparking occurs between the brush and the commutator which results in progressive damage to both.

Ideal commutation :-

Let we consider the coil A. The brush width is equal to the width of one commutator segment and one mica insulation. Suppose the total armature current is $40A$. Since there are 2 parallel paths, each coil carries a current of $20A$.

(i) In Fig 2(i), the brush is in contact with segment 1 of the commutator. The commutator segment 1 conducts a current of $40A$ to the brush, $20A$ from coil A and $20A$ from the adjacent coil as shown. The coil A has yet to undergo commutation.

(ii) As the armature rotates, the brush will make contact with segment 2 and thus short-circuits the coil A as shown in Fig 2(ii). There are now 2 parallel paths into the brush as long as the short-circuit of coil A exists. Fig 2(ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. For this condition, the resistance of the path through segment 2 is three times the resistance of the path through segment 1. The brush again conducts a current of $40A$, $30A$ through segment 1 and $10A$ through segment 2. Note that current in coil A (the coil undergoing commutation) is reduced from $20A$ to $10A$.

(iii) Fig 2(iii) shows the instant when the brush is one-half on segment 2 and one-half on segment 1. The brush again conducts $40A$, $20A$ through segment 1 and $20A$

through segment 2.
Note: - Now current in coil A is zero.

(iv) Fig 2(iv) shows the instant when the brush is $\frac{1}{4}$ fourth on segment 2 and one-fourth on segment 1. The brush conducts a current of 40A, 30A through segment 2 and 10A through segment 1.

Note: - The current in coil A is 10A but in reverse direction to that before the start of commutation.

(v) Fig 2(v) shows the instant when the brush is in contact only with segment 2. The brush again conducts 40A, 20A from coil A and 20A from the adjacent coil to coil A.

Note: - Now current in coil A is 20A but in the reverse direction. Thus the coil A has undergone commutation.

Each coil undergoes commutation in this way as it passes the brush axis. Note that during commutation the coil under consideration remains short-circuited by the brush.

⇒ Fig (3) shows the current - time graph for the coil undergoing commutation. The horizontal line AB represents a constant current of 20A upto the beginning of commutation. From the finish of commutation, it is represented by another horizontal line CD on the opposite side of the zero line and at the same distance from it as AB i.e.

the current has exactly reversed (-20A). The way in which current changes from B to C depends upon the conditions under which the coil undergoes commutation. If the current changes at a uniform rate (i.e. BC is a straight line), then it is called ideal commutation. Under such conditions, no sparking will take place between the brush and the commutator.

Practical Difficulties:-

⇒ The ideal commutation (i.e. straight line change of current) can not be attained in practice. This is mainly due to the fact that armature coils have inductance. When the current in the coil undergoing commutation changes, self-induced e.m.f. is produced in the coil. This is generally called reactance voltage.

⇒ This reactance voltage opposes the change of current in the coil undergoing commutation. The result is that the change of current in the coil undergoing commutation occurs more slowly than it would be under ideal commutation. This is illustrated in Fig (4).

⇒ The straight line BC represents the ideal commutation whereas the curve BE represents the change in current when self-inductance of the coil is taken into account. Note that current CE ($= 8\text{A}$ in Fig 4) is flowing from the commutator segment 1 to the brush at the instant. ~~when~~

this results in sparking just as when any current-carrying circuit is broken. The sparking results in overheating of commutator-brush and causing damage to both.

- ⇒ Fig (5) shows how sparking takes place between the commutator segment and the brush. At the end of commutation of short-circuit period, the current in coil A is reversed to a value of 12 A (instead of 20 A) due to inductance of the coil.
- ⇒ When the brush breaks contact with segment 1, the remaining 8 A current jumps from segment 1 to the brush through air causing sparking between segment 1 and the brush.

Methods of Improving Commutation :-

Improving commutation means to make current in the short-circuited coil as sparkless as possible. The following are the two methods of improving commutation :-

- (i) Resistance commutation.
- (ii) E.M.F. commutation.

Resistance Commutation :-

- ⇒ The reversal of current in a coil (i.e. commutation) takes place while the coil is short-circuited by the brush. Therefore, there are two parallel paths for the current as long as the short circuit exists.
- ⇒ If the contact resistance between the brush and the commutator is made large, then current would divide in the inverse ratio of contact resistances (as for any two resistances in parallel). This is the key point in improving commutation.
- ⇒ This is achieved by using carbon brushes (instead of Cu brushes) which have high contact resistance. This method of improving commutation is called resistance commutation.
- ⇒ Fig (1) & (2) illustrates how high contact resistance of carbon brush improves commutation in coil A. In Fig 1(i), the brush is entirely on segment 1 and therefore, the current in coil A is 20A.

The coil A is yet to undergo commutation.

⇒ As the armature rotates, the brush short-circuits the coil A and there are two parallel paths for the current into the brush. Fig 1(ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. The equivalent electric circuit is shown in Fig 1(iii) where R_1 & R_2 represent the brush contact resistances on segments 1 and 2. A resistor is not shown for coil A since it is assumed that the coil resistance is negligible as compared to the brush contact resistance. The values of current in the parallel paths of the equivalent circuit are determined by the respective resistances of the paths.

⇒ For the condition shown in Fig 1(ii), resistor R_2 has three times the resistance of resistor R_1 . Therefore the current distribution in the paths will be as shown. Current in coil A is reduced from 20A to 10A due to division of current in the inverse ratio of contact resistances. If the Cu brush is used (which has low contact resistance), $R_1 \approx R_2$ and the current in coil A would not have reduced to 10A.

⇒ As the carbon brush passes over the commutator, the contact area with segment 2 increases and that with segment 1 decreases i.e. R_2 decreases and R_1 increases. Therefore more and more current passes to the brush through segment 2.

This is shown in figs 2(i) and 2(ii). When the break between the brush and the segment 1 occurs (in fig 2(iii)), the current in the coil is reversed and commutation is achieved.

It may be noted that the main cause of sparking during commutation is the production of reactance voltage and carbon brushes cannot prevent it. Nevertheless carbon brushes do help in improving commutation. The other minor advantages of carbon brushes are :-

- (i) The carbon lubricates and polishes the commutator.
- (ii) If sparking occurs, it damages the commutator less than with copper brushes and the damage to the brush itself is of little importance.

E.M.F. Commutation :-

→ In this method, an arrangement is made to neutralise the reactance voltage by producing a reversing voltage in the coil undergoing commutation. The reversing voltage acts in opposition to the reactance voltage and neutralises it to some extent.

⇒ If the reversing voltage is equal to the reactance voltage, the effect of the latter is completely wiped out and we get sparkless commutation. The reversing voltage may be produced in the following two ways :-

(i) By brush shifting

(ii) By using interpoles or compoles.

(i) By brush shifting :-

In this method, the brushes are given sufficient forward lead to bring the short-circuited coil under the influence of the next pole of opposite polarity. Since the short-circuited coil is now in the reversing field, the reversing voltage produced cancels the reactance voltage. This method suffers from the following drawbacks.

(a) The reactance voltage depends upon armature current. Therefore, the brush shift will depend on the magnitude of armature current which keeps on changing. This necessitates frequent shifting of brushes.

(b) The greater the armature current, the greater must be the forward lead for a generator. This increases the demagnetising effect of armature reaction and further weakens the main field.

(ii) By using interpoles or compoles :-

The best method of neutralising reactance voltage is by using interpoles or compoles.

Interpoles or compoles :-

The best way to produce reversing voltage to neutralise the reactance voltage is by using interpoles.

or compoles. These are small poles between the main poles (fig 3) and spaced mid-way. They are wound with comparatively few turns and connected in series with the armature so that they carry armature current. Their polarity is the same as the next main pole ahead in the direction of rotation for a generator. Connections for a d.c. generator with interpoles is shown in fig(4).

Function of Interpoles :-

The machines fitted with interpoles have their brushes set on geometrical neutral axis. The interpoles perform the following two functions.

- (i) As their polarity is the same as the main pole ahead (for a generator), they induce an e.m.f. in the coil (undergoing commutation) which opposes reactance voltage. This leads to sparkless commutation. The e.m.f. induced by compoles is known as commutating or reversing e.m.f., since the interpoles carry the armature current and the reactance voltage is also proportional to armature current, the neutralisation of reactance voltage is automatic.
- (ii) The m.m.f. of the compoles neutralises the cross-magnetising effect of armature reaction in small region in the space between the main poles. It is because the two m.m.f.s oppose each other in this region.

→ Fig (5) shows the circuit diagram of a shunt generator with commutating winding and compensating winding. Both these windings are connected in series with the armature and so they carry the armature current.

→ The main function of commutating winding is to produce reversing (or commutating) e.m.f. in order to cancel the reactance voltage. In addition to this, the m.m.f. of the commutating winding neutralises the cross-magnetising amp-turns in the space between the main poles. The compensating winding neutralises the cross-magnetising effect of armature reaction under the pole faces.

Characteristics of DC Generator:-

(1) open circuit characteristic (O.C.C) :-

This curve shows the relation between the generated e.m.f. at no-load (E_0) and the field current I_f at constant speed. It is also known as magnetic char. or no-load saturation curve. Its shape is practically the same for all generators whether separately or self-excited. The data for O.C.C curve are obtained experimentally by operating the generator at no load and constant speed and recording the change in terminal voltage as the field current is varied.

(2) Internal or Total characteristic (E/I_a) :-

This curve shows the relation between the generated emf on load (E) and the armature current. The e.m.f. E is less than E_0 due to the demagnetising effect of armature reaction. Therefore, this curve will lie below the open circuit characteristic (O.C.C.). The internal characteristic can be obtained from external characteristic if winding resistances are known because armature reaction effect is included in both char.

(3) External characteristic (V/I_L) :-

This curve shows the relation between terminal voltage (V) and load current (I_L). The terminal voltage V will be less than E due to voltage drop in the armature circuit. Therefore, this curve will lie below the internal characteristic. It can be obtained by measurements of terminal voltage and load current (with voltmeter and ammeter) of a loaded generator.

Characteristics of a separately Excited D.C. Generator :-

(i) Open circuit characteristic :-

The O.C.C. of a separately excited generator is determined in a manner described in fig(1).

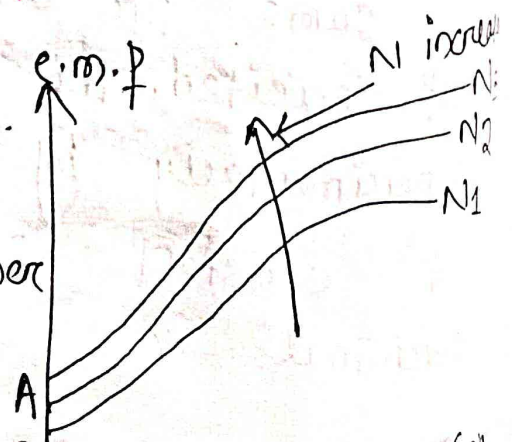


Fig (1) shows the variation of generated e.m.f. on no load with field current for various fixed speeds. If the value of constant speed is increased, the steepness of the curve also increases. When the field current is zero, the residual magnetism in the poles will give rise to the small initial emf as shown.

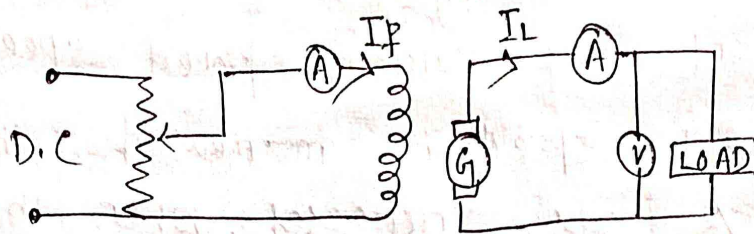
(ii) Internal and External characteristics:-

→ The external characteristic of a separately excited generator is the curve between the terminal voltage (V) and the load current I_L (which is the same as armature current in this case).
→ In order to determine the external char. the circuit set up is as shown in Fig 2(i).

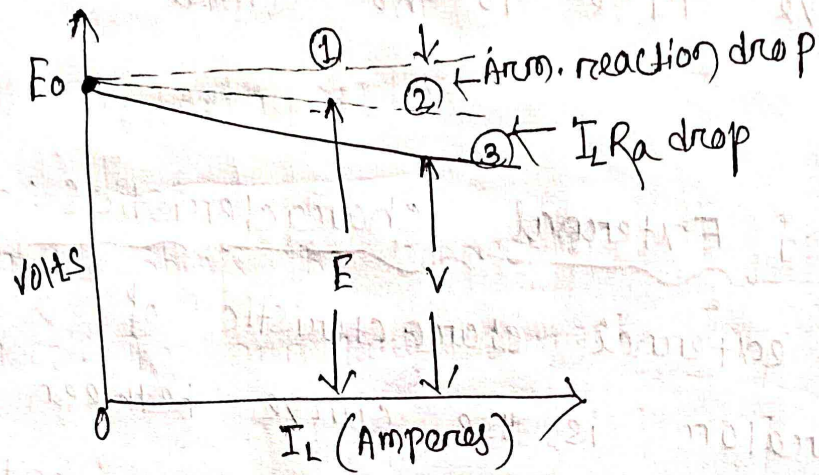
As the load current increases, the terminal voltage falls due to 2 reasons:-

- (a) The armature reaction weakens the main flux so that actual e.m.f. generated E on load is less than that generated (E_0) on no load.
- (b) There is voltage drop across armature resistance
($= I_L R_a = I_a R_a$)

Due to these reasons, the external char. is a drooping curve [curve 3 in Fig 2(ii)]. Note that in the absence of armature reaction and armature drop, the generated e.m.f. would have been E_0 (curve 1)



(i)



(ii)

⇒ The internal char. can be determined from external char. by adding $I_L R_a$ drop to the external char. It is because arm. reaction drop is included in the external char. curve 2 is the internal char. of the generator and should obviously lie above the external char.

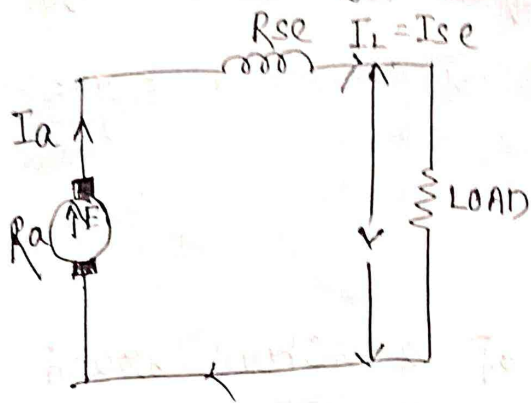
Characteristics of self-excited DC generator

Series Generator:-

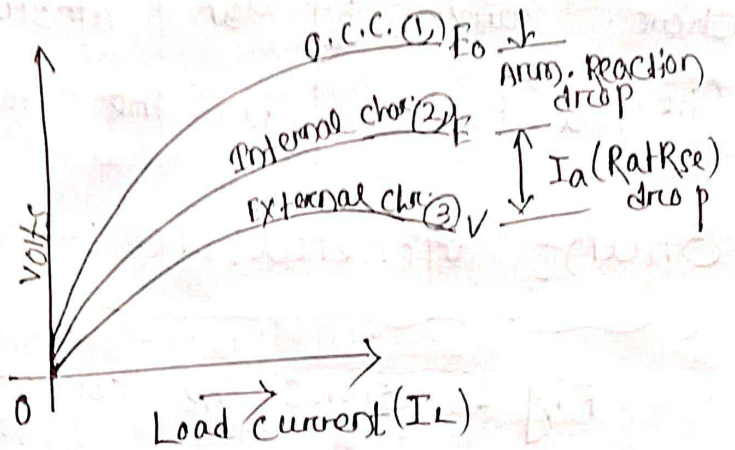
Fig (1) shows the connections of a series wound generator. Since there is only one current (which flows through the whole machine), the load current is the same as the exciting current.

(i) O.C.C :-

curve 1 shows the open circuit characteristic (O.C.C) of a series generator.



(1)



(2)

(ii) Internal Characteristic :-

curve 2 shows the total or internal char. of a series generator. It gives the relation between the generated e.m.f E on load and armature current. [In case of series generator, $I_a = I_{se} = I_L$].

⇒ Due to armature reaction, the flux in the machine will be less than the flux at no load. Hence e.m.f E generated under load conditions will be less than the e.m.f E_0 generated under no load conditions. Consequently internal characteristic curve lies below the O.C.C curve, the difference between them representing the effect of armature reaction [Fig 2].

(iii) External characteristic :-

curve 3 shows the external char. of a series generator. It gives the relation between terminal voltage V and load current I_L .

$$V = E - I_a(R_a + R_{se})$$

Therefore, external char. curve will lie below int. char. curve by an amount equal to ohmic drop [i.e., $I_a(R_a + R_{se})$] in the machine as shown in fig (1).

Shunt Generator :-

Fig (1) shows the connections of a shunt wound generator. The armature current I_a splits up into 2 parts, a small fraction I_{sh} flowing through shunt field winding while the major part I_L goes to the external load.

(i) O.C.C :-

The o.c.c of a shunt generator is similar in shape to that of a series generator as shown in fig (2). The line OA represents the shunt field circuit resistance. When the generator is run at normal speed, it will build up a voltage OM. At no-load the terminal voltage of the generator will be constant ($= OM$) represented by the horizontal dotted line MC.

(ii) Internal Characteristic :-

When the generator is loaded, flux per pole is reduced due to armature reaction. Therefore, e.m.f. E generated on load is less than the e.m.f. generated at no load. As a result, the internal

characteristic (E/I_a) drops down slightly as shown in fig

(2)

(iii) External characteristic :-

curve 2 shows the external characteristic of a shunt generator. It gives the relation between terminal voltage V and load current I_L .

$$V = E - I_a R_a \\ = E - (I_L + I_{sh}) R_a$$

Therefore, external char. curve will lie below the internal char. curve by an amount equal to drop in the armature circuit [i.e. $(I_L + I_{sh}) R_a$] as shown in fig(2).

* The external char. that change in terminal voltage from no-load to full-load is small. The terminal voltage can always be maintained constant by adjusting the field rheostat R_f automatically.

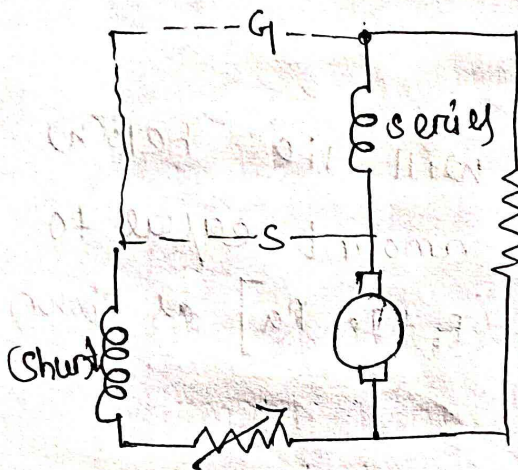
Compound Generator :-

In a compound generator, both series and shunt excitation are combined as shown in fig(1). The shunt winding can be connected either across the armature only (short-shunt connection S) or across armature plus series field (long-shunt connection G).

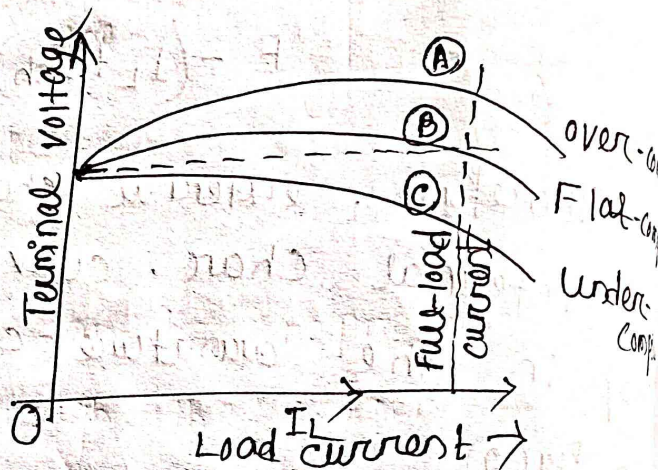
-> The compound generator can be cumulatively compounded or differentially compounded generator. The latter is rarely used in practice.

External char. :-

Fig (2) shows the external char. of a cumulatively compounded generator. The series excitation adds the shunt excitation. The degree of compounding depends upon the increase in series excitation with the increase in load current.



(1)



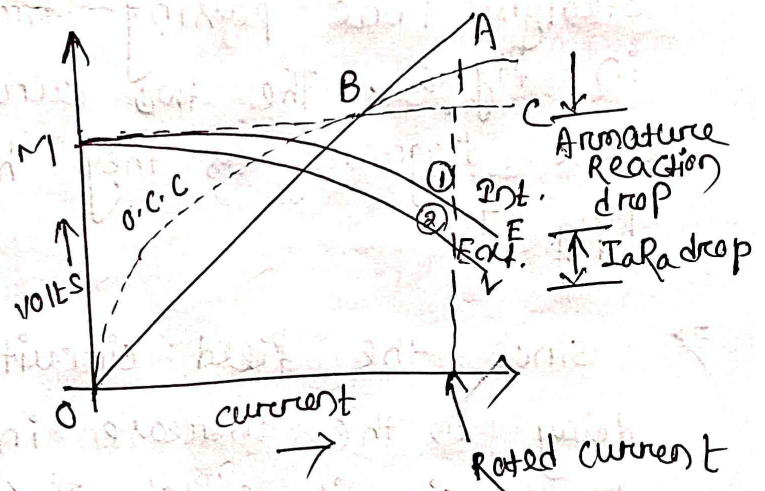
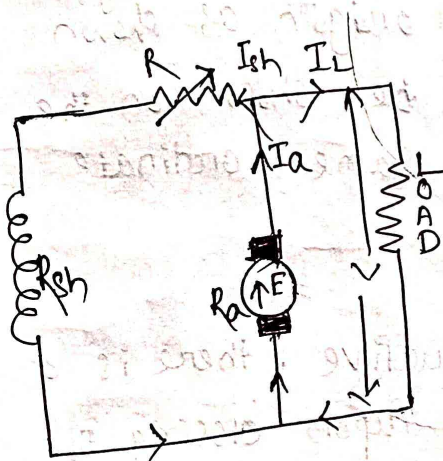
(i) If series winding turns are so adjusted that with increase in load current the terminal voltage increases, it is called over-compounded generator. In such a case, as the load current increases, the series field m.m.f. increases and tends to increase the flux and hence the generated voltage. The increase in generated voltage is greater than the $I_a R_a$ drop so that instead of decreasing, the terminal voltage increases as shown by curve A in fig(2).

(ii) If series winding turns are so adjusted that with the increase in load current, the terminal voltage substantially remains constant, it is called flat-compounded generator. The series winding of such a machine has lesser no. of turns

than the one in over-compounded machine and therefore, does not increase the flux as much for a given load current. Consequently, the full-load voltage is nearly equal to the no-load voltage as indicated by curve B in Fig (2).

(iii) If series field winding has lesser number of turns than for a flat-compounded machine, the terminal voltage falls with increase in load current as indicated by curve C in Fig (2). Such a machine is called under-compounded generator.

* Shunt Generator Diagram :-

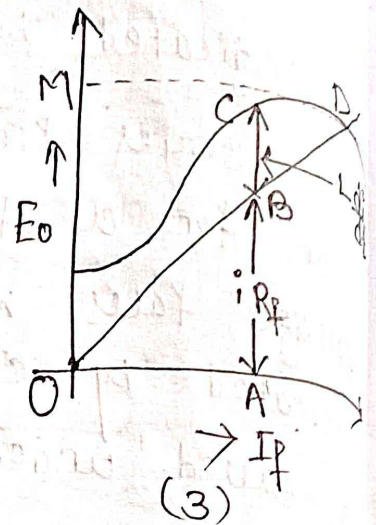
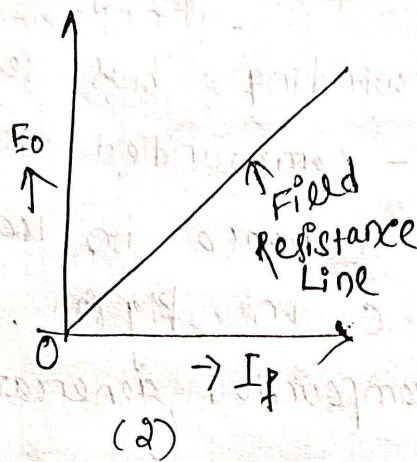
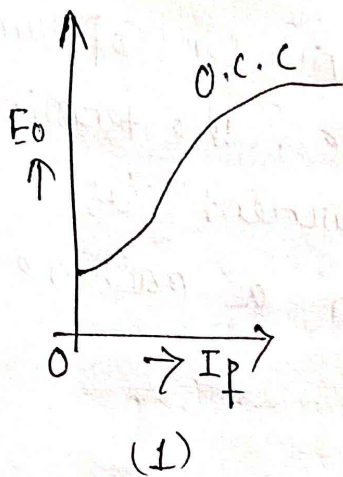


Voltage Build-up in a self-excited Generator:-

(i) Shunt Generator:-

Consider a shunt generator. If the generator is run at a constant speed, some e.m.f. will be generated due to residual magnetism in the main poles. This small e.m.f. circulates a field current in turn produces additional flux to reinforce the original residual flux

(Provided field winding connections are correct).
 Process continues and the generator builds up the normal generated voltage following the O.C.C. as shown in Fig (1).



⇒ The field resistance R_f can be represented by a straight line passing through the origin as shown in Fig (2). The two curves can be shown on the same diagram as they have the same ordinate [Fig 3].

⇒ Since the field circuit is inductive, there is a delay in the increase in current upon closing the field circuit switch. The rate at which the current increases depends upon the voltage available for increasing it.

⇒ Let at any instant, the field current is $i (= i_A)$ and is increasing at the rate $\frac{di}{dt}$. Then,

$$E_o = i R_f + L \frac{di}{dt}$$

where R_f = total field circuit resistance
 L = inductance of field current.

⇒ At the considered instant, the total e.m.f. available is AC. An amount AB of the e.m.f. AC is absorbed by the voltage drop iR_f and the remainder part BC is available to overcome $L \frac{di}{dt}$. Since this surplus voltage is available, it is possible for the field current to increase above the value OA. However, at point D, the available voltage is OM and is all absorbed by iR_f drop. Consequently, the field current can not increase further and the generator build up stops.

(ii) Series generator :-

During initial operation, with no current yet flowing, a residual voltage will be generated exactly as in the case of a shunt generator. The residual voltage will cause a current to flow through the whole series circuit when the circuit is closed. There will then be voltage build up to an equilibrium point exactly analogous to the build up of a shunt generator. The voltage build up graph will be similar to that of shunt generator except that now load current (instead of field current for shunt generator) will be taken along X-axis.

(iii) Compound generator :-

When a compound generator has its series field flux aiding its shunt field flux, the machine is said to be cumulative compound. When the series field is connected in reverse so that its field flux

opposes the shunt field flux, the differential compound.

⇒ The easiest way to build up voltage in a compound generator is to start under no load conditions. At no load, only the shunt field is effective. When no-load voltage build up is achieved, the generator is loaded. If load, the voltage rises, the series field connection is cumulative. If the voltage drop significantly, the connection is differential compound.

Critical Field Resistance For a Shunt Generator

⇒ voltage build up in a shunt generator depends upon field circuit resistance. If the field circuit resistance is R_1 (line OA), then generator will build up a voltage OM as shown in fig.

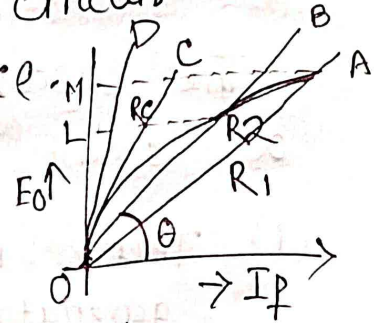
⇒ If the field circuit resistance is increased to R_2 (line OB), the generator will build up a voltage OL, slightly less than OM. As the field circuit resistance is increased, the slope of resistance line also increases.

⇒ When the field resistance line becomes tangent (line OC) to O.C.C., the generator would just excite. If the field circuit resistance is increased beyond this point (line OD), the generator will fail to excite. The field circuit resistance represented by line OC (tangent to O.C.C.) is the critical field resistance.

is called critical field resistance R_c for the shunt generator. It may be defined as under:-

The maximum field circuit resistance (for a given speed) with which the shunt generator would just excite is known as its critical field resistance.

* It should be noted that shunt generator will build up voltage only if field circuit resistance is less than critical field resistance.

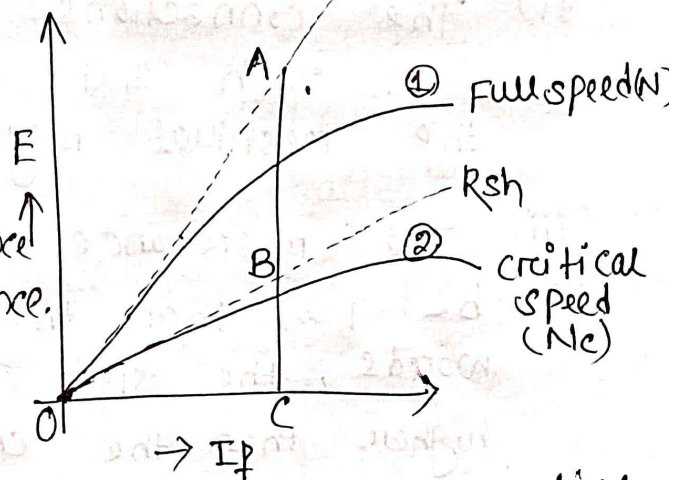


Critical speed (N_c) :-

⇒ The critical speed of a shunt generator is the minimum speed below which it fails to excite.

⇒ It is the speed for which the given shunt field resistance represents the critical resistance.

In fig curve (2) corresponds to critical speed because the shunt field resistance (R_{sh}) line is tangential to it.



⇒ If the generator runs at full speed N , the new o.c.c. upward and the R_{sh} line represents critical resistance for this speed.

∴ speed & critical resistance

In order to find critical speed, take any convenient point C on excitation axis and erect a perpendicular so as to cut R_{sh} and R_{sh}' lines at points B and A respectively.

Then,

$$\frac{B_c}{A_c} = \frac{N_c}{N_l}$$

$$\Rightarrow N_c = N \times \frac{B_c}{A_c}$$

Conditions for voltage build-up of a shunt generator :-

The necessary conditions for voltage build-up in a shunt generator are :-

- (i) There must be some residual magnetism in generator poles.
- (ii) The connections of the field winding should be such that the field current strengthens the residual magnetism.
- (iii) The resistance of the field circuit should be less than the critical resistance. In other words, the speed of the generator should be higher than the critical speed.

Need for parallel operation of D.C. Generator

In a d.c. power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator. This is due to following reasons :-

- (i) Continuity of service :- If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down. However, if power is supplied

From a number of small units operating in parallel then in case of failure of one unit, the continuity of supply can be maintained by other healthy unit.

(ii) Efficiency: - Generators run most efficiently when loaded to their rated capacity. Electric power costs less per kWh when the generator producing it is efficiently loaded. Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

(iii) Maintenance and repair: - Generators generally require routine maintenance and repair. Therefore, if generators are operated in parallel, the routine or emergency operations can be performed by isolating the affected generator while load is being supplied by other units. This leads to both safety and economy.

(iv) Increasing Plant capacity: - In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units.

(v) Non-availability of single large unit: - In many situations, a single unit of desired large capacity may not be available. In that case a number of

smaller units can be operated in parallel to meet the load requirement. Generally a single unit is more expensive.

Condition for parallel operation :-

There are two main conditions to be met when d.c. generators (shunt, compound or series) are to be parallel i.e.

- (i) All polarities must be correct. (The positive terminals of all generators must be connected to the positive bus bar and the negative terminals must be connected to the negative bus bar).
- (ii) The terminal voltages of the generators being paralleled must be the same.

⇒ The generators in a power plant are connected in parallel through bus-bars. The bus-bars are heavy thick copper bars and they act as +ve and -ve terminals. The positive terminals of the generators are connected to the +ve side of bus-bars and negative terminals to the negative side of bus-bars.

2) Fig shows shunt generator G_1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this generator, the second shunt generator G_2 is connected in parallel with the first to meet the increased load demand. The procedure for paralleling generator G_2 with generator G_1 is as under :-

- (i) The prime mover of generator G_2 is brought up to the rated speed. Now switch S_4 in the field circuit of the generator G_2 is closed.
- (ii) Next circuit breaker CB-2 is closed and the excitation of generator G_2 is adjusted till it generates voltage equal to the bus-bar voltage. This is indicated by voltmeter V_2 .
- (iii) Now the generator G_2 is ready to be paralleled with generator G_1 . The main switch S_3 is closed, thus putting generator G_2 in parallel with generator G_1 . * generator G_2 is not supplying

any load because its generated e.m.f. is equal to bus-bars voltage. The generator is said to be "floating" (i.e. not supplying any load on the bus-bars).

(iv) If G_2 is to deliver any current, then its generated voltage E should be greater than the bus-bar voltage V . In that case, current supplied by it is $I = \frac{E - V}{R_a}$ where R_a is the resistance of the armature circuit. Increasing the field current (and hence induced e.m.f. E), the generator G_2 can be made to supply proper amount of load.

(v) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if generator G_1 is to be shut down, the whole load can be shifted onto generator G_2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator G_1 to zero (this will be indicated by ammeter A_1), open $CB-1$ and then open the main switch S_1 .

Load sharing:-

The load sharing between shunt generators in parallel can be easily regulated because of their drooping char. The load may be shifted

from one generator to another merely by adjusting the field excitation.

Let the load sharing of 2 generators which have unequal no-load voltages, then

Let E_1, E_2 = no-load voltages of the two generators

R_1, R_2 = their armature resistances

V = common terminal voltage (bus-bar voltage)

then, $I_1 = \frac{E_1 - V}{R_1}$ & $I_2 = \frac{E_2 - V}{R_2}$

Thus current output of the generators depends upon the values of E_1 & E_2 .

uses of D.C. Generators :-

(1) Shunt Generators :- with field regulators are used for ordinary lighting and power supply purposes. They are also used for charging batteries because their terminal voltages are almost constant or can be kept constant.

(2) series Generators :- are not used for power supply because of their rising characteristics. However, their rising characteristic makes them suitable for being used as boosters in certain types of distribution systems particularly in railway service.

(3) Compound Generators :-

The cumulatively - compound generator is the most widely used d.c. generator because its external characteristic can be adjusted for compensating the voltage drop in line resistance. Hence such generators are used for which a d.c. supply at constant voltage, for lamp and for heavy power service such as electric railways.

The differential - compound generator has an external characteristic similar to that of a shunt generator but with large demagnetization armature reaction. Hence, it is widely used in arc welding where larger voltage drop is desirable with increase in current.