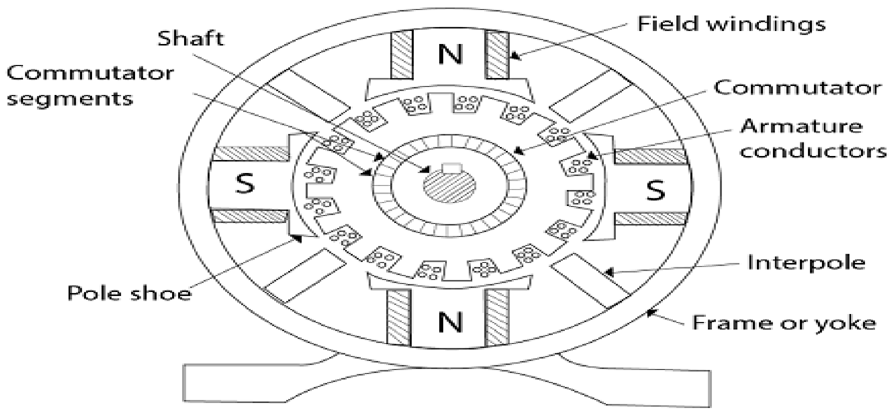
DC machine

Introduction

- A DC machine is an electromechanical energy alteration device The DC machine can be classified into two types namely DC motors as well as DC generators.
- The main function of the DC generator is to convert mechanical power to DC electrical power, whereas a DC motor converts DC power to mechanical power.
- The AC motor is invariably applied in the industry for conversion of electrical power into mechanical power, but at the places where the wide range of speeds and good speed regulation is required, like in electric traction system, a DC motor is used.
- The construction of the DC motor and generator is nearly the same. The generator is employed in a very protected way. Hence there is an open construction type. But the motor is used in the location where they are exposed to dust and moisture, and hence it requires enclosures for example dirt proof, fireproof, etc. according to requirement.

Construction

The construction of DC machine can be done using some of the essential parts like Yoke, Pole core & pole shoes, Pole coil & field coil, Armature core, Armature winding otherwise conductor, commutator, brushes & bearings.



1) Yoke: The outer frame of a dc machine is called as yoke. The yoke is made up of low reluctance magnetic material like iron and silicon steel. Generally, the yoke is made up of iron because iron is cost-effective material than steel. But for large machines usually cast steel or rolled steel is employed. The yoke is used to provides mechanical protection to the machine. The second application of yoke is that it provides a low reluctance path to the flux. So, flux completes its path through the yoke.

2) Pole Cores and Pole Shoes: The field winding is placed on a pole. When current passes through the field winding, it will create an electric magnetic field and behaves as an electromagnet. Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and

(ii) spread out the flux in air gap uniformly. To reduce eddy current losses, pole and pole shoes are laminated.

3) Field Windings: The windings are wounded in the region of pole core & named as field coil. Whenever current is supplied through field winding then it electromagnetics the poles which generate required flux. The material used for field windings is copper. They are wound in such a way that, when energized, they form alternate North and South poles.

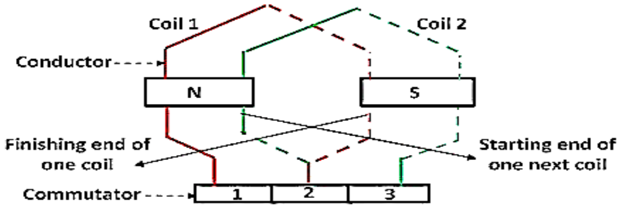
4) Armature Core: The armature core is cylindrical in shape and connected by a key with the shaft. So, it is a rotating part of the DC machine. The armature core consists of a number of slots on its outer periphery. It is made up of low reluctance and high permeability material like cast iron or cast steel. The armature core is laminated to reduce the eddy current. It may be provided with air ducts for the axial air flow for cooling purposes. The armature slots are used to house the armature winding.

5) **Armature Winding:** The armature winding can be formed by interconnecting the armature conductor. Whenever an armature winding is turned with the help of prime mover then the voltage, as well as magnetic flux, gets induced within it. This winding is allied to an exterior circuit. The materials used for this winding are conducting material like copper.

Armature winding can be wound by one of the two methods;

a) Lap Winding or b) Wave Winding

a) Lap Winding: In lap winding, the consecutive coils overlap each other. The first end of the winding is connected to the one segment of the commutator, and the starting end of the other coil is placed under the same magnet (different pole) and join with the same segment of the commutator.



Lap Winding

Consider the machine has P poles and Z armature conductors, then there will be P parallel paths, and each path will have Z/P conductors in series. The number of brushes is equivalent to the number of parallel paths. The half of the brush is positive, and the remaining is negative.

For lap winding, the number of a parallel path (A) is the same as the number of poles (P).

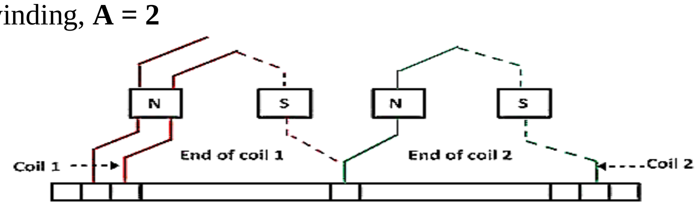
for LAP winding, A = P

Therefore, in lap winding, the number of parallel paths is more. And due to this, it is capable of supplying larger load current. So, lap winding is used for low voltage high current applications.

The simplex and duplex are the types of lap windings. In simplex winding, the number of parallel paths is equal to the pole, in duplex winding the pole is twice to that of a parallel path, whereas the progressive and the retrogressive are the types of the wave windings.

b) Wave Winding: The one end of the coil is connected to the starting end of the other coil which has the same polarity as that of the first coil. The coils are connected in the wave shape and hence it is called the wave winding. The conductor of the wave winding is split into two parallel paths, and each path had Z/2 conductors in series. The number of brushes is equal to 2, i.e., the number of parallel paths.

for Wave winding, **A = 2**



Wave Winding

So, in wave winding, a smaller number of parallel paths available compared to the lap winding. The wave winding is used for high voltage low current DC machine.

6) **Commutator:** The commutator is mounted on the shaft of a machine. The armature conductors are rotating. The commutator is used to connects the rotating armature conductor with a stationary external circuit. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. or It converts alternating torque produced in the armature into unidirectional torque. So, it works similar to the rectifier. 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.

7) Brush: The commutator connected the external circuit via brushes. The brushes are used to carry current from the armature conductors. Brushes are usually made from carbon or graphite.

EMF equation of DC machine

Consider a DC generator with the following parameters,

ϕ = magnetic flux per pole, weber Z = total number of armature conductors

P = Number of magnetic poles N = Speed of the armature in RPM

so, Average emf generated per conductor, $e = \frac{d\phi}{dt}$ …………..1)

where, magnetic flux cut by each conductor in one revolution = $d\phi = \phi P$ ………..2)

And, time taken for N revolution = 60 sec

So, time taken for 1 revolution, $dt = \frac{60}{N}$ sec …………..3)

So, from equation 1), 2) and 3)

Average emf generated per conductor = $\frac{d\phi}{dt} = \frac{\phi P}{\frac{60}{N}} = \frac{\phi\, P\, N}{60}$

Let, A = Number of parallel paths in armature winding, then number of conductors in series = $\frac{Z}{A}$

Therefore, total emf across brush $E = \frac{\phi\, P\, N}{60} * \frac{Z}{A}$

Or, $E = \frac{Z\,\phi\,\, N}{60} * \frac{P}{A}$ Volts,

Here, A= P in lap winding and A= 2 in wave winding

Torque equation/production

When armature conductors of a DC motor carry current in the presence of stator field flux, a mechanical torque is developed between the armature and the stator. Torque is given by the product of the force and the radius at which this force acts.

Torque $T_a = F \times r$ (N-m) ……………..1)

where, F = force and r = radius of the armature

Work done by this force in once revolution = Force × distance

= F × 2πr

where, 2πr = circumference of the armature

Net power developed in the armature $= \frac{workdone}{time} = \frac{F * 2\pi r}{\frac{60}{N}} = \frac{2\pi N}{60} * F*r$

$= \frac{2\pi N}{60} * T_a$ ……………..1)

{ $\frac{2\pi N}{60}$ = angular velocity ω in radian per second}

Net power developed in the armature = $P_a = T_a \times \omega$ (Joules per second)

Now, the mechanical power developed in the armature is converted from the electrical power. Therefore, mechanical power = electrical power

$$T_a \times \frac{2\pi N}{60} = E_b \times I_a = P$$

$$T_a \times \frac{2\pi N}{60} = \frac{Z\,\phi\,\, N}{60} * \frac{P}{A} * I_a$$

$$T_a = \frac{1}{2\pi} * Z * \phi * \frac{P}{A} * Ia \qquad \text{N-m}$$

This equation is called torque equation of DC motor. For a given DC machine *P Z* and *A* are constant,

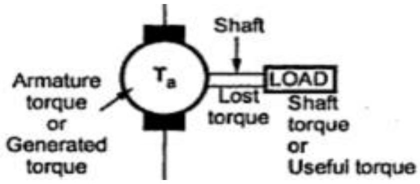
Therefore $Ta \propto \Phi.Ia$

Thus, armature torque is directly proportional to the product of the flux and the armature current.

Shaft Torque (Tsh)

Due to iron and friction losses in a dc machine, the total developed armature torque is not available at the shaft of the machine. Some torque is lost, and therefore, shaft torque is always less than the armature torque. Shaft torque of a DC motor is given as,

Tsh = output in watts / (2πN/60) ….(where, N is speed in RPM)



DC Machine Circuit Model

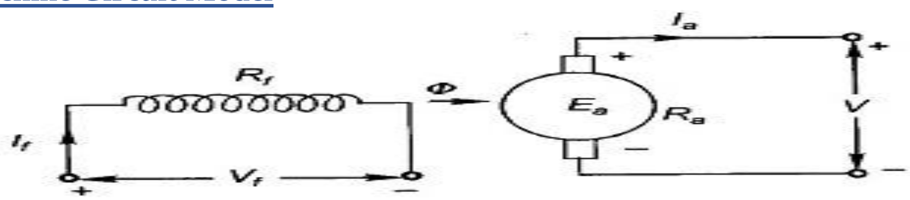


Fig. 7.5 *Circuit model of dc machine*

A) **Generating Mode**

The machine operates in generating mode (puts out electrical power) when I_a is in the direction of induced emf E_a. For the armature circuit, Terminal voltage $V = E_a - I_aR_a$, $E_a > V$

The mechanical power converted to electrical form is

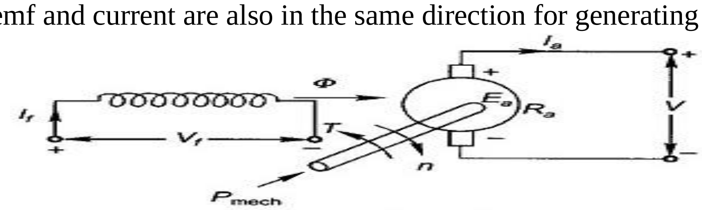
$$P_{mech}(in)_{net} = E_a I_a = P_{elec}(out)_{gross}$$

The net electrical power output is $P_0 = V I_a$

Also, $E_a I_a - VIa = I_a^2R_a$ = armature copper loss

$P_{mech}(in)_{gross}$ = gross power = $P_{mech}(in)_{net}$ + rotational loss

The conductor emf and current are also in the same direction for generating mode as shown in Fig



(a) Generating mode

B) **Motoring Mode:** In this mode, I_a flows in opposition to induced emf E_a . E_a is now known as the back emf to stress the fact that it opposes the armature emf. For the armature circuit

Terminal voltage V = Ea + IaRa, V>Ea

The electrical power converted to mechanical form is

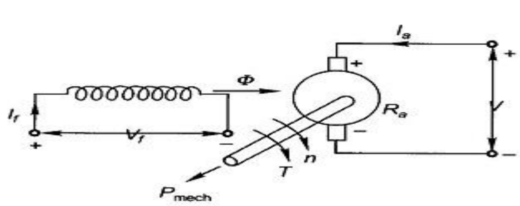
$$P_{elec}(in)_{net} = E_a I_a = P_{mech}(out)_{gross}$$

The electrical power input is Pi = Via

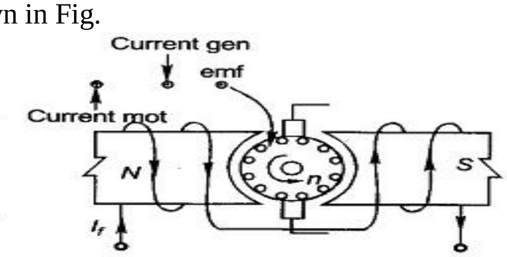
Also, VIa - $E_a I_a = I_a^2R_a$ = armature copper loss

$P_{mech}(out)_{net}$ = shaft power = $P_{mech}(out)_{gross}$ - rotational loss

mechanical power is put out and is absorbed by load (mechanical). Conductor emf and current are also in opposite directions for motoring mode as shown in Fig.



(b) Motoring mode



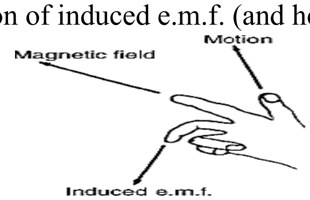
(c) Generating/motoring modes

DC Generator

Working principle

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The generator operates on the principle of the production of dynamically induced emf i.e., whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule.



Hence, the basic essential parts of an electric generator are:

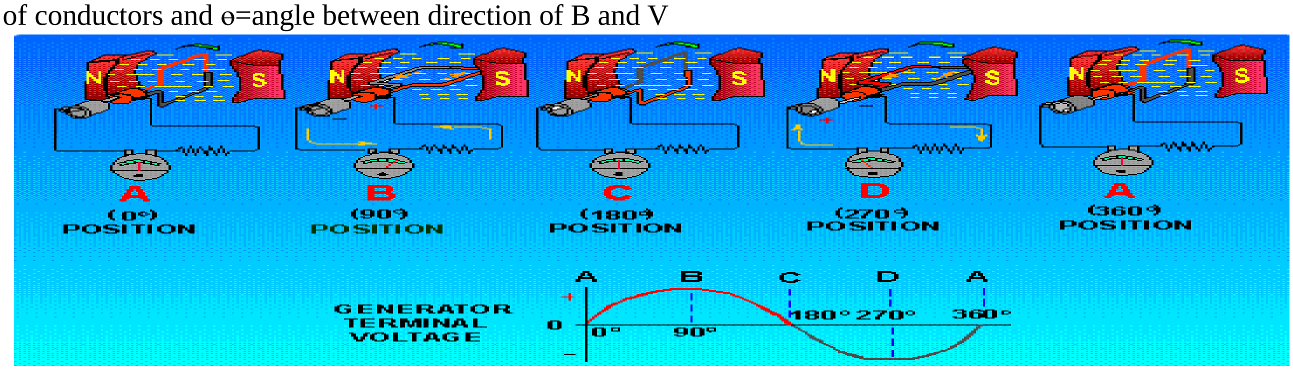
i) A magnetic field and

ii) A conductor or conductors which can so move as to cut the flux.

In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime-mover.

Now we study nature of emf induced in the armature coil. the magnitude of emf induced is given by equation ………E= B.l.V sinɵ

where, B=magnetic flux density wb/m^2 l=length of coil lying in magnetic field V= velocity of conductors and ɵ=angle between direction of B and V



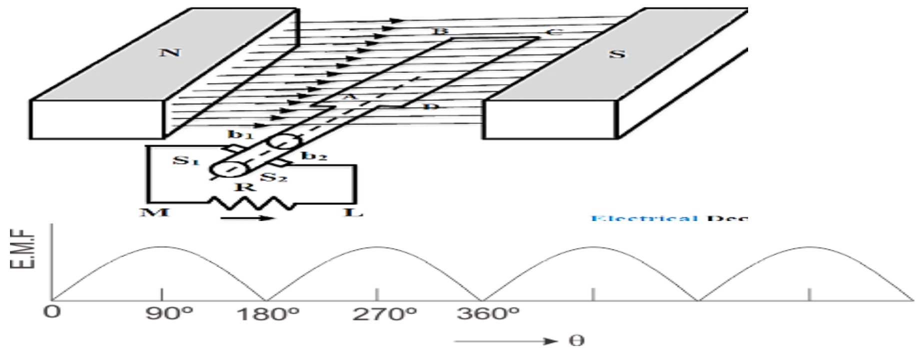
As the coil rotates in clock-wise direction and assumes successive positions in the field the, flux linked with it changes. Hence, an emf is induced in it which is proportional to the rate of change of flux linkages (e = $N\frac{d\Phi}{dt}$.
When the plane of the coil is at right angles to lines of flux i.e., when it is in position 1, then flux linked with the coil is maximum, but rate of change of flux linkages is minimum. Hence, there is no induced emf in the coil.

i.e., At θ=0, induced emf = o.

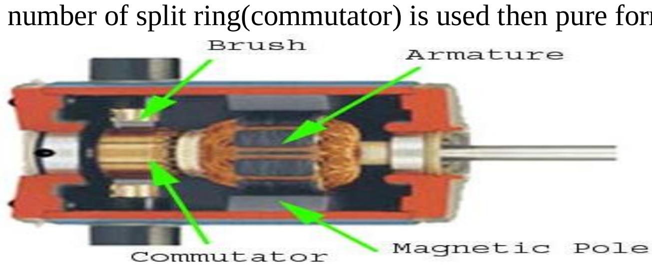
As the coil continues rotating further, the rate of change of flux linkages (and hence induced emf in it) increases, when $\theta = 90^o$, the coil plane is horizontal i.e. parallel to the lines of flux. The flux linked with the coil is minimum but rate of change of flux linkages is maximum. Hence, maximum emf is induced in the coil at this position.

i.e., At θ=90, induced emf = Em

From 90º to 180º, the flux linked with the coil gradually increases but the rate of change of flux linkages decreases. Hence, the induced emf decreases gradually, it is reduced to zero value.
From 180º to 360º, the variations in the magnitude of emf are similar to those in the first half revolution. But it will be found that the direction of the induced current is the reverse of the previous direction of flow.



For making the flow of current unidirectional in the external load circuit, the slip-rings are replaced by split-ring commutator (mechanical rectifier). The split-rings are made of a conducting cylinder, which is cut into two halves or segments insulated from each other and the shaft with (a thin mica sheet) insulating material. The two ends of the coil are connected to these segments (s_1, s_2) and the brushes (b_1, b_2) placed over these segments.
In the first half revolution of the coil the current flows along BAMLDCB i.e., the brush b_1, is in contact with segment S_1, acts as the +ve terminal of the supply, and brush b_2 is in contact with segment S_2 and acts as -ve terminal.
In the next half revolution, the direction of the induced current in the coil will be reversed. But at the same time, the position of segments S_1 and S_2 have also reversed, with the result that brush b_2 comes in contact with segment S_2 which is now +ve and the brush b_2 is in contact with segment S_1 which is now -ve. Thus, the current in the external load R again flows from M to L. This current is unidirectional. The dc current produced here is not pure dc but pulsating dc.
If a greater number of split ring(commutator) is used then pure form of DC output is obtained.



Q. Why the air gap between the pole pieces and the armature is kept very small?

Types of DC generator

DC generators are usually classified according to the way in which their fields are excited. The magnetic flux in a DC machine is produced by the field coils carry current. The circulating current in the field windings produces a magnetic flux. Thus, supplying current to the field winding is called excitation and the way of supplying the exciting current is called method of excitation. DC generators may be divided into,

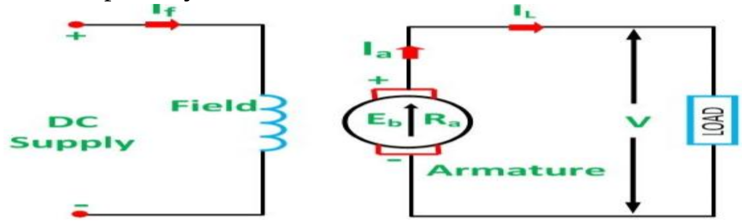
A) Separately excited dc generators,

B) Self-excited dc generators

a) Shunt Wound DC Generators;
b) Series Wound DC Generators and
c) Compound wound DC generators.
  i) Long Shunt-Wound DC Generators
  ii) Short Shunt-Wound DC Generators.

A) Separately Excited DC Generator

A DC generator whose field winding or coil is energized by a separate or external DC source like battery is called a separately excited DC Generator.



Here, $I_f = \frac{V}{Rf}$, $where,\ Rf = resistance\ of\ field\ winding$ I_f = current through field winding

And, $I_a = I_L$ where I_a is the armature current and I_L is the line current.

Terminal voltage is given as: $V = E - I_a R_a$

The terminal voltage V is always less than emf E because of voltage drop in armature winding resistance IaRa. To keep Ia Ra drop to minimum, the resistance Ra is designed to be very small. In addition to the drop, there is some voltage drop at the contacts of the brush called brush contact drop.

So, $V = E - I_aR_a - 2*$ voltage drop per brush

Also, power developed = E Ia

Power output = V Ia = VI_l

B) Self-Excited DC Generator

These are generators in which the field winding is excited by the output of the generator itself. In these types of machines, field coils are internally connected with the armature.

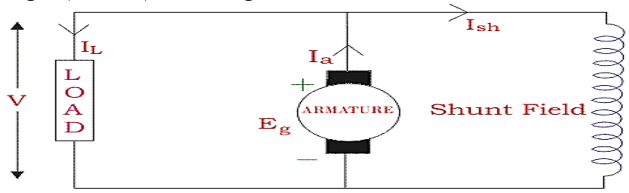
Practically though the generator is not working, without any current through field winding, the field poles possess some magnetic flux called residual flux. Thus, when the generator is started, due to such residual flux, it develops a small emf. which now drives a small current through the field winding. This tends to increase the flux produced. This in turn increases the induced e.m.f. This future increases the field current and the flux. The process is cumulative and continuous till the generator develops rated voltage across its armature. This is voltage building process in self-excited generators.

Based on how field winding is connected to the armature to derive its excitation, this type is further divided into following three types

a) Shunt Wound Generators

In a shunt-wound generator, the field winding is connected across the armature winding forming a parallel or shunt circuit. The field winding has large number of turns of thin wire so it has high resistance hence that only a part of armature current passes through field winding and the rest passes through load.

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 Wound Generator

Here, $Ish = \frac{V}{Rsh}$ $and\ \ IL = \frac{V}{RL}$

$I_a = I_{sh} + I_l$

$V = E_g – I_aR_a$

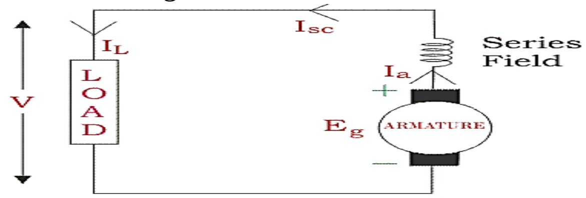
Also, power generated = $E_g\ I_a$

power delivered to load = VI_l

b) <u>Series Wound Generator</u>

A series-wound generator the field coils are connected in series with the armature winding. The series field winding carries the armature current.

The series field winding consists of a few turns of wire of thick wire of larger cross-sectional area and having low resistance usually of the order of less than 1 ohm because the armature current has a very large value. Whole current flows through the field coils as well as the load.



Series Wound Generator

Here,

$I_a = I_{sc} = I_l$

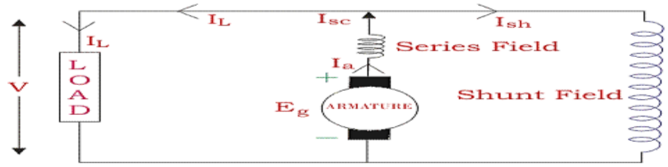
And, $V = E_g – I_a\ R_a – I_{sc}\ R_f$

c) <u>Compound Wound DC Generator</u>

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.

In a compound-wound generator, there are two field windings. One is connected in series, and another is connected in parallel with the armature windings. Depending upon the connection of shunt and series field winding, compound generator is further classified as,

i) **<u>Long Shunt Wound DC Generator</u>:** Long Shunt Compound Wound DC Generator are generators where the shunt field winding is in parallel with both series field and armature winding.



Long Shunt Compound Wound Generator

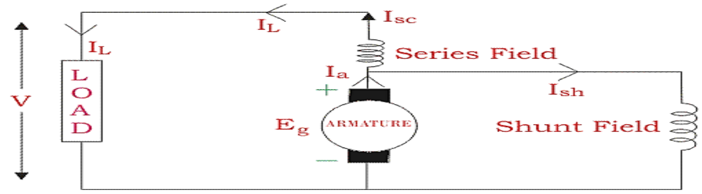
Here,

$\mathbf{I_{sh} = V/R_{sh}}$

$\mathbf{I_a = I_{sc} = I_L + I_{sh}}$

$\mathbf{V = E_g - I_aR_a - I_aR_{sc}}$

ii) **<u>Short Shunt Wound DC Generator</u>:** Short Shunt Compound Wound DC Generators are generators where only the shunt field winding is in parallel with the armature winding.



Short Shunt Compound Wound Generator

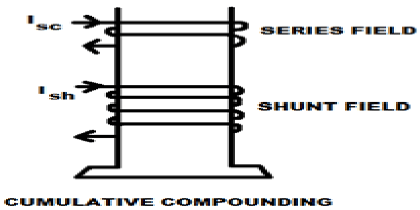
Here,

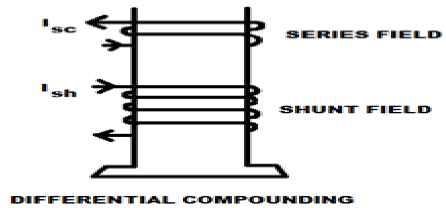
$I_{sc} = I_L$
$I_a = I_{sc} + I_{sh} = I_L + I_{sh}$
$I_{sh} = \frac{V + Isc\ Rsc}{Rsh} = \frac{Eg - IaRa}{Rsh}$
$V = E_g – I_aR_a - I_{sc}R_{sc}$

- NOTE:

  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.





Q. Why is series field winding has low resistance while the shunt field winding has high resistance?

Q. Why can't a DC series generator run under a no-load condition?

In DC series generators field winding is connected in series with armature and load. Hence, the field current is same as the load current. Now under no load condition the load terminals are open circuited thus there will be no current in the field winding and hence no excitation would be available. Thus, no emf would be induced.

Q. Why is a DC shunt generator never started on load?

In a DC shunt generator, we need to build up the voltage. In the process of building up the voltage we have a residual flux in the shunt field of DC generator. when a small current enters the shunt field it develops additional flux in it. Now this added flux links with the armature and increases the current. Again, this current enters the shunt field and same process is repeated. It hardly takes 3 to 4 seconds to build up the voltage.

Now if we consider the case when we have connected the load across the machine. when the current starts flowing from the armature, it has two paths to flow.

1. Towards the shunt field
2. Towards the load

As the resistance of the load side is very low (0.6 to 0.8 ohms) as compared to shunt field having a resistance in the range of 50 to 60 ohms. So negligible current will flow through the shunt field and flux will not build up in the shunt field and voltage build up is not possible.

This is the reason of starting DC generator on NO-LOAD.

Characteristics of DC generator

Generally, following three characteristics of DC generators are taken into considerations:

(i) Open Circuit / Magnetization Characteristic (O.C.C.)
(ii) Internal or Total Characteristic and
(iii) External Characteristic.

These characteristics of DC generators are explained below.

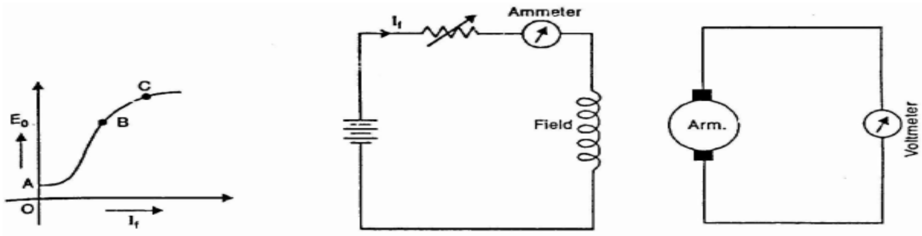
i) Open Circuit / Magnetization Characteristics (E_0/I_f)

This characteristic gives the variation of generating voltage or no-load voltage with field current at a constant speed. It is also called no-load or open circuit characteristic.

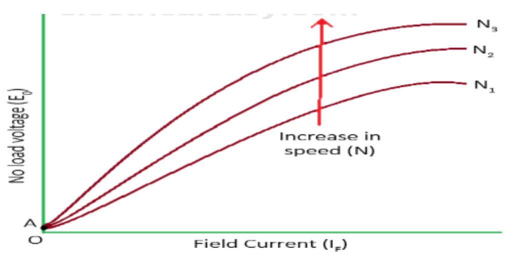
Its shape is practically the same for all generators whether separately or self-excited.

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.

The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.



The following points may be noted from O.C.C.:
1) When the field current is zero, there is some generated e.m.f. OA. This is due to the residual magnetism in the field poles. As we know that $E_g = k\phi$. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current).
2) Over a fairly wide range of field current (up to point B in the curve), the curve is linear. It is because, Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line.
3) After point B on the curve, Consequently, the curve deviates from linear relationship. After point C on the curve, the magnetic saturation of poles begins and E_0 tends to level off. It is because, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the I_f further, ϕ remains constant and hence, E_g also remains constant.
Figure shows no load characteristics at different speed.



Open Circuit Characteristic (O.C.C.)

ii) Internal Characteristics (E/I_{aL})

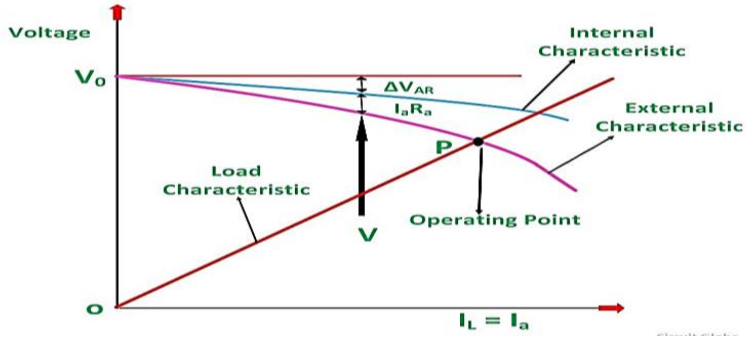
Internal characteristic of DC Generator plots the curve between the generated voltage and load current.
An internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (I_a). The on-load generated emf Eg is always less than E_0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0. Therefore, internal characteristic curve lies below the O.C.C. curve.
The internal characteristic is of interest chiefly to the designer. It cannot be obtained directly by experiment. It is because a voltmeter cannot read the e.m.f. generated on load due to the voltage drop in armature resistance. The internal characteristic can be obtained from external characteristic if winding resistances are known because armature reaction effect is included in both characteristics.

iii) External Characteristics / Load Characteristics (V/I_L)

External or load characteristics give the relation between the terminal voltage and load current at a constant speed. This curve shows the relation between the 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. This characteristic is very important in determining the suitability of a generator for a given purpose. It can be obtained by making simultaneous measurements of terminal voltage and load current (with voltmeter and ammeter) of a loaded generator.
Therefore, this type of characteristic is sometimes also called as performance characteristic or load characteristic.
Internal and external characteristic curves are shown below for each type of generator.

a) Characteristics of a Separately Excited D.C. Generator:

There is a voltage drop of ΔV_{AR} because of the armature reaction. The internal characteristic ($E_a \sim I_L$) is also shown in the above figure represented by a blue color line. There is a voltage drop IaRa across the armature resistance Ra. The generator, external characteristic ($V \sim I_L$) is also shown by the pink color line.



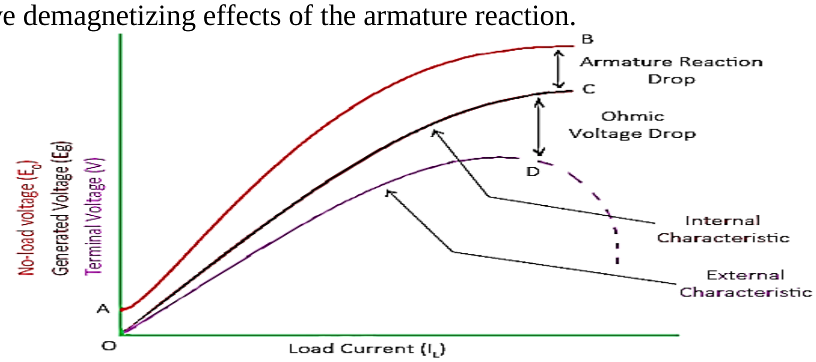
The point P is called as Operating Point, which is the intersection between the generator, external characteristic and the load characteristic given by the relation $V = I_L R_L$. This point P gives the operating values of the terminal voltage and load current.

b) **Characteristics Of DC Series Generator**

Since there is only one current (that which flows through the whole machine), the load current is the same as the exciting current.

It gives the relation between terminal voltage and load current IL V = E – Ia (Ra+Rse)

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. $I_L = I_f$). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.



Characteristics of DC series generator

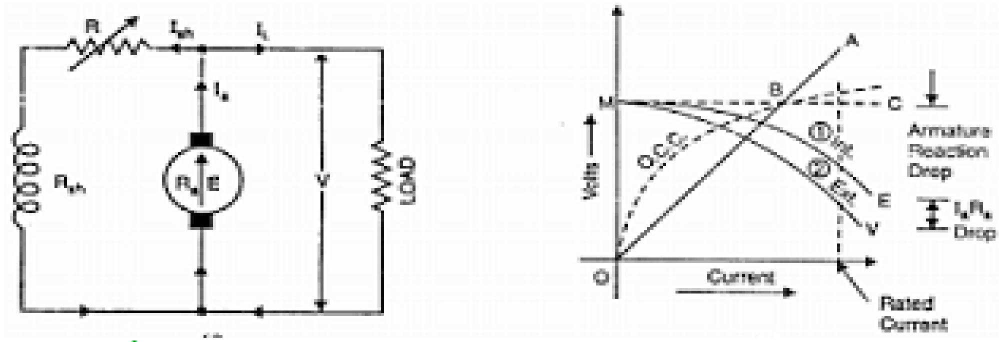
c) **Characteristics Of DC Shunt Generator:**

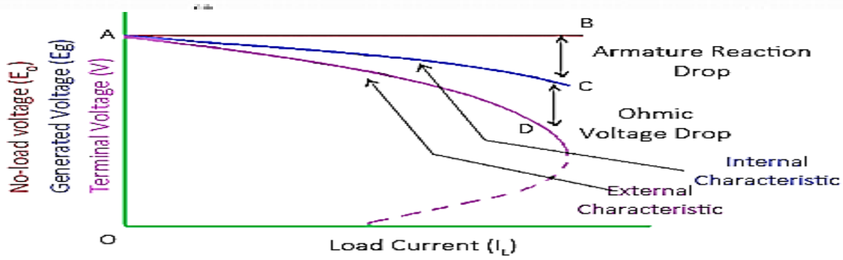
The armature current I_a splits up into two parts; a small fraction I_{sh} flowing through shunt field winding while the major part I_L goes to the external load.

External characteristic of a shunt generator gives relation between terminal voltage V and load current I_L as

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

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





Characteristics of DC shunt generator

Here, 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.

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls. So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses. Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the above figure.

iv) <u>Characteristics Of DC Compound Generator</u>

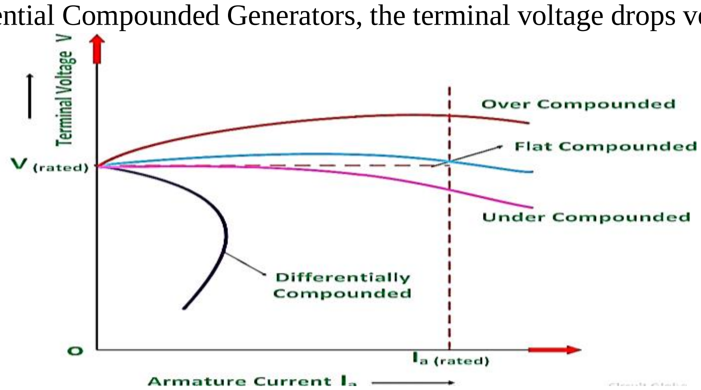
The Cumulatively Compound Generators can be Over Compounded, Flat Compounded and Under Compounded, depending upon the number of series field turns.

i) For over compounded generator, full load terminal voltage is higher than the no-load terminal voltage.

ii) In case of flat or level compounded generator, the terminal voltage at the full load is equal to the no-load terminal voltage.

iii) In an under-compound generator the terminal voltage at the full load is less than the no-load terminal voltage.

In Differential Compounded Generators, the terminal voltage drops very quickly with the increasing armature current.



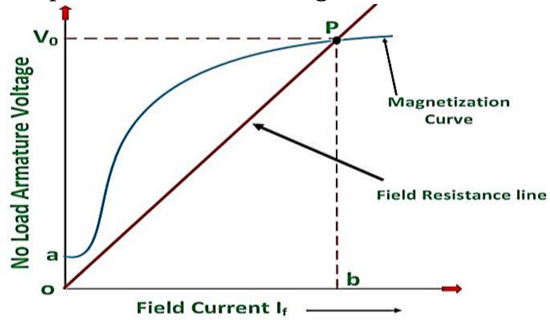
<u>Build-up of E.M.F process in DC shunt generator</u>

The residual flux present in the field poles of the DC generator is responsible for the voltage buildup. A small voltage Ear is generated and is given by the equation, Ear = k Φ_{res} ω

This voltage causes a current I_f to flow in the field winding of the generator. The field current is given by, $I_f = V/R_f$

The flux is increased by a magnetomotive force produced by the field current. As a result, of this, the generated voltage E_a increases. This increased armature voltage increases the terminal voltage. With the increase in the terminal voltage, the field current I_f increases further. This, in turn, increases flux and hence the armature voltage is further increases, and the process of voltage buildup continues.

The voltage builds up curve of a DC shunt generator is shown below:



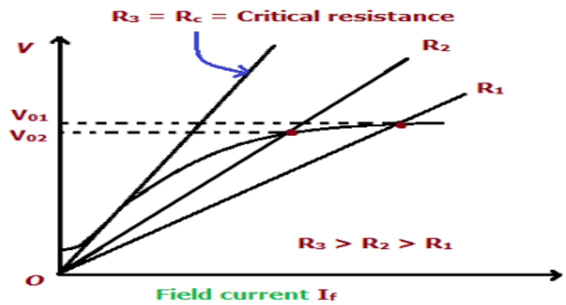
The generator is on no load during the process of voltage buildup, thus, the following equations shown below give the steady-state operation $I_a = I_f$ and, $V = E – I_aR_a$

Since the field current I_f in a shunt generator is very small, the voltage drops $I_f R_a$ can be neglected, so, $V = E_a$

The straight line given by $V= I_f R_f$ shown in the above figure is known as Field Resistance Line.

Beyond point of intersection of Field Resistance Line and Magnetization curve / Open Circuit Characteristics the voltage won't build up as in that case the generated voltage E_a will not be able to drive the required field current. Thus, the stable point at which the voltage will remain fix is the voltage E_a corresponding to point of intersection of Field Resistance Line and Magnetization curve / Open Circuit Characteristics.

<u>Effect of variation of field resistance of DC Shunt Generator in its Voltage Build up:</u>



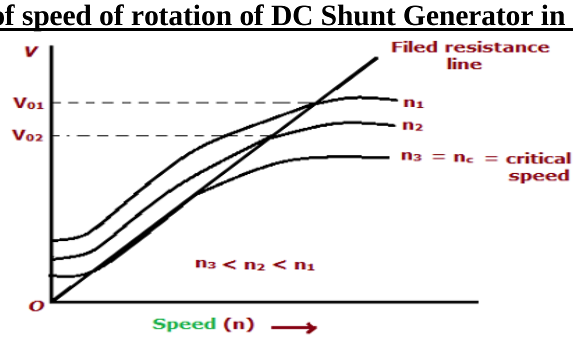
A decrease in the resistance of the field circuit reduces the slope of the field resistance line result in higher voltage.

If the speed remains constant, an increase in the resistance of field circuit increases the slope of field resistance line, resulting in a lower voltage.

If the field circuit resistance is increased to R_c which is terminal as the critical resistance of the field, the field resistance line becomes a tangent to the initial part of the magnetization curve. when the field resistance is higher than this value, the generator fails to excite.

If we find the slope (tanϴ) of the Field Resistance Line then we will get Field Resistance value which is known as **Critical Field Resistance**. The critical field resistance is defined as the maximum field circuit resistance (for a given speed) with which the shunt generator would excite. The shunt generator will build up voltage only if field circuit resistance is less than critical field resistance.

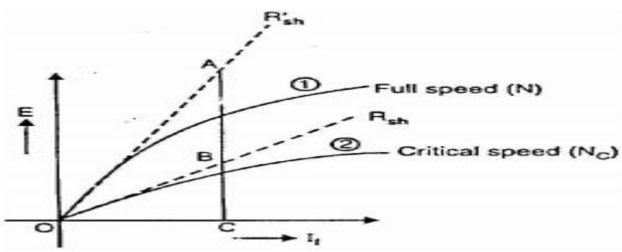
<u>Effect of variation of speed of rotation of DC Shunt Generator in its Voltage Build up:</u>



The magnetization curve varies with the speed and its ordinates for any field current is proportional to the speed of the generator. If the field resistance is kept constant and the speed is reduced, all the points on the magnetization curve are lowered.
At a particular speed, called the critical speed, the field resistance line becomes tangential to the magnetization curve. Below the critical speed, the voltage will not build up.
Thus, Critical Speed is that speed at which the DC Shunt Generator just fails to build up voltage with no external resistance in the field circuit. Clearly, it is the speed for which the given shunt field resistance represents the critical resistance
In Fig. below, 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. moves upward and the R'_{sh} line represents critical resistance for this speed. Therefore, Speed α 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,

$$\frac{BC}{AC} = \frac{Nc}{N}$$

or, $$N_c = N * \frac{BC}{AC}$$



Summary: The following conditions must be satisfied for voltage buildup
1. There must be a sufficient residual flux in the field poles.
2. Field winding and armature winding is to be connected in a way so that resultant flux will add
3. Field resistance < critical resistance
4. Speed > critical speed
5. Build up should be done at no load

Q. **What is field flashing?**
Ans: In case when the dc machine fails to build up the voltage due to lack of residual magnetism, filed coils are connected to the dc source (battery) for short while for magnetizing the filed poles. Application of external source of direct current to the field of the dc machine is called field flashing.
Q. Why is the emf not zero when the field current is reduced to zero in dc generator?
Even after the field current is reduced to zero, the machine is left out with some flux as residue so emf is available due to residual flux.

Armature reaction

In a DC machine, two kinds of magnetic fluxes are present; the first one is because of the stator poles called main field flux, while the second one is because of the current flowing in the armature called armature flux. The effect of armature flux on the main field flux is called as armature reaction.
When we excite the field winding, it produces a flux which links with the armature. This causes an emf and hence a current in the armature. This current in armature produces another flux which lags the main flux. This is referred to as armature reaction. The armature flux causes two effects on the main field flux.
i) It demagnetizes or reduces/weakens the strength of main flux. In dc generator weakening of the main flux reduces the generated voltage.
ii) It cross-magnetizes or distorts/bends the main flux line along the conductor. Hence the position of M.N.A. gets shifted. Brushes should be placed on the M.N.A., otherwise, it will lead to sparking at the surface of brushes. So, due to armature reaction, it is hard to determine the exact position of the MNA.

This distortion causes a shift in the neutral plane, which affects the commutation. This change in the neutral plan and reaction of magnetic field is given by armature reaction.
Let us discuss these effects of armature reaction in a dc generator

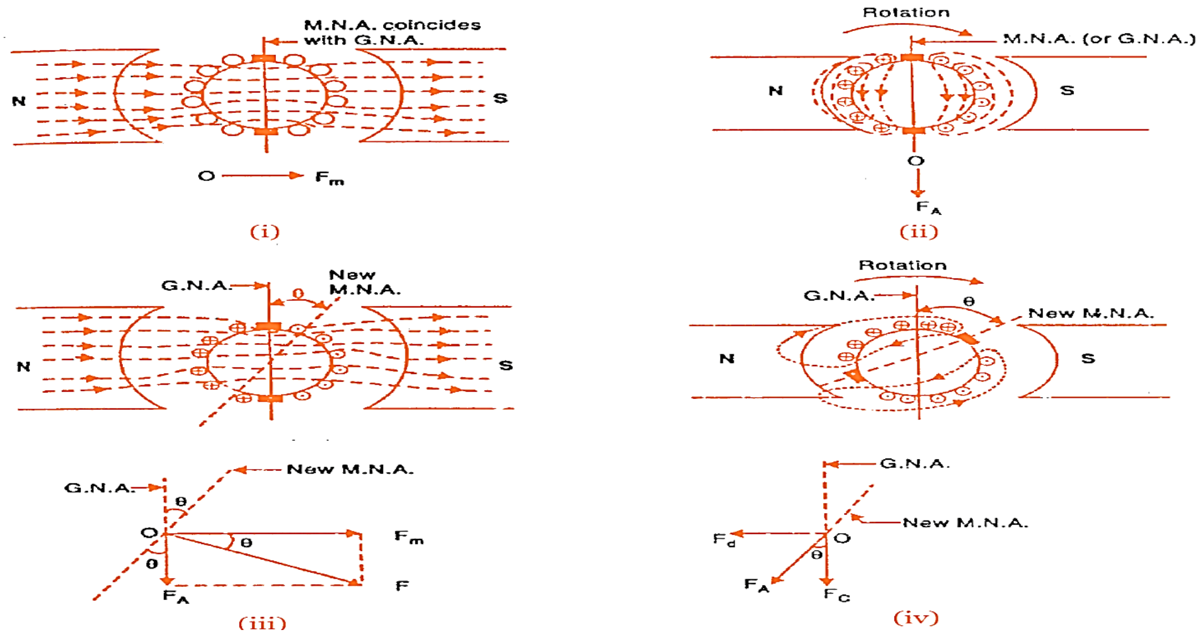


Fig (i) shows the flux due to main poles (main flux) when the armature conductors carry no current. In this case, magnetic flux lines of the field poles are uniform and symmetrical to the polar axis. The 'Magnetic Neutral Axis' (M.N.A.) coincides with the 'Geometric Neutral Axis' (G.N.A.).
Fig (ii) shows the flux due to the current flowing in armature conductors of dc generator alone (main poles unexcited). Armature flux is directed downward parallel to the brush axis. The mmf. producing the armature flux is represented in magnitude and direction by the vector OF_A
Fig (iii) shows the flux due to the main poles and that due to the current in armature conductors acting together. flux due to the armature conductors and flux due to the field winding) will be present at a time. The armature flux superimposes with the main field flux and, hence, disturbs the main field flux. The resultant mmf. OF is the vector sum of OF_m and OF_A. Since MNA is always perpendicular to the resultant mmf., the MNA is shifted through an angle θ in the direction of rotation of the generator.
In order to achieve sparkless commutation, the brushes must lie along the MNA. Consequently, **the brushes are shifted through an angle θ** so as to lie along the new MNA as shown in **Fig (iv)**. Due to the brush shift, the mmf. F_A of the armature is also rotated through the same angle θ.
Now F_A can be resolved into rectangular components F_c and F_d.

F_d = Component direct opposition to the mmf. OF_m due to main poles. It has a demagnetizing effect on the flux due to main poles. For this reason, it is called the demagnetizing or weakening component of armature reaction in dc machines.

Demagnetizing or back AT/pole = $\frac{4\theta_e}{360}$ [ATs per pole] = = $\frac{2\theta_e}{180}[\frac{I_a}{\alpha}\frac{Z}{2P}]$ where, $\theta_e = (P/2)\theta_m$

F_c = Component at right angles to the mmf. OF_m due to main poles. It distorts the main field. For this reason, it is called the cross magnetizing or distorting component of armature reaction in dc machines.

Cross-magnetizing AT/pole = $\frac{360-4\theta_e}{360}[\frac{I_a}{\alpha}\frac{Z}{2P}]$ = = $\frac{180-2\theta_e}{180}[\frac{I_a}{\alpha}\frac{Z}{2P}]$ where, $[\frac{1}{2}\frac{I_a}{\alpha}\frac{Z}{2P}] = F_A$

Methods to reduce armature reaction

1) **Higher reluctance pole tips: F**ield pole ends are designed in such a way that the higher flux density doesn't occur at the pole tips, thus avoiding saturation and hence armature reaction.
2) **Reduction of armature flux**: Another constructional technique of reducing armature flux is to create more reluctance in the path of armature flux without reducing main field flux noticeably. This can be achieved by using field pole lamination having several rectangular holes punched in them.

3) **Installing commutating poles/ inter poles**: The distortion of main field can be prevented by cancelling the effects of the flux produced by the armature current. This can be achieved by installing commutating poles in between two consecutive main poles. The commutating poles are connected in series with the armature winding, but in such a design that they cancel the effect of armature conductor flux and hence we have left only the main field flux.

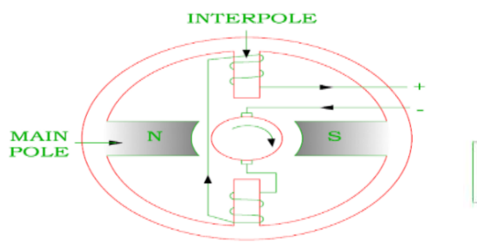
4) **Compensation windings**: Compensation windings are installed in slots of the poles faces of main field poles. These windings are connected in series with the armature winding in such a position that the current flowing in the compensation winding is exactly opposite to the current flowing in the armature winding at the same time. Thus, the compensating winding produces flux, which is completely opposite and equal in magnitude to the armature flux, hence both cancel the effect of each other and thus armature reaction is completely neutralized.

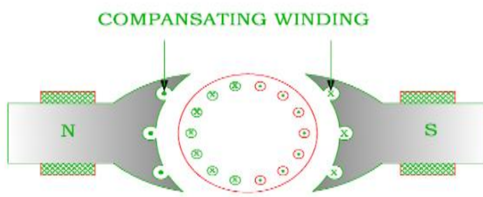
To Compensate the effect of armature mmf under the pole shoes, it is necessary that the compensating ampere turns are exactly equal to armature amp – turns.

so, number of armature turns / pole = Z / 2P

Number of armature turns / pole for compensating winding =

$$= Z / 2P \times (\text{Pole arc} / \text{Pole pitch})$$





Some important definition

1) Magnetic Neutral Axis: MNA may be defined as the axis along which no emf is generated in the armature conductors as they move parallel to the flux lines. Brushes are always placed along the MNA because reversal of current in the armature conductors takes place along this axis.

2) **Geometrical Neutral Axis**: GNA may be defined as the axis which is perpendicular to the stator field axis.

3) **Leading and Trailing Pole tip:** Tip of the pole from where armature conductors come into influence is called leading tip and the other tip opposite in direction to it will be trailing tip. Or, in dc generator, the pole tip which is first met during rotation of armature is known as leading pole tip and other as trailing pole tip

Commutation

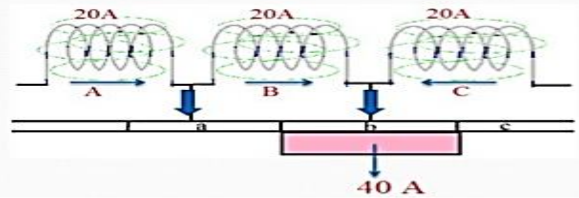
Commutation in DC generator is the process in which generated alternating current in the armature winding of a dc machine is converted into direct current after going through the commutator and the stationary brushes. Again, in DC Motor, the input DC is to be converted in alternating form in armature and that is also done through commutation.

When the conductors of the armature are under the north pole, the current which is induced flows in one direction. While the current flows in the opposite direction when they are under the south pole. As the conductor passes through the influence of the north pole and enters the south pole, the current in them is reversed. The reversal of current takes place along the MNA or brush axis. When the brush span has two commutator segments, the winding element connected to those segments is short-circuited. The term **Commutation** means the change that takes place in a winding element during the period of a short circuit by a brush.

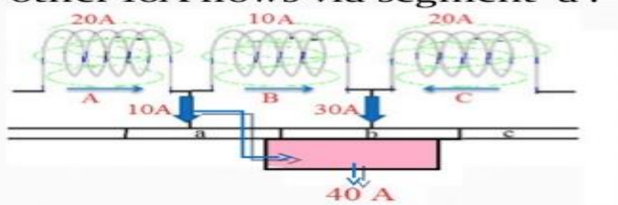
The brief period during which the coil remains short-circuited is known as commutation period Tc. If the current reversal is completed by the end of commutation period, it is called ideal **commutation**. If the current reversal is not completed by that time, then sparking occurs between the brush and the commutator which results in progressive damage to both.

Let us discuss the process of commutation or current reversal in more details with the help of given figure below.

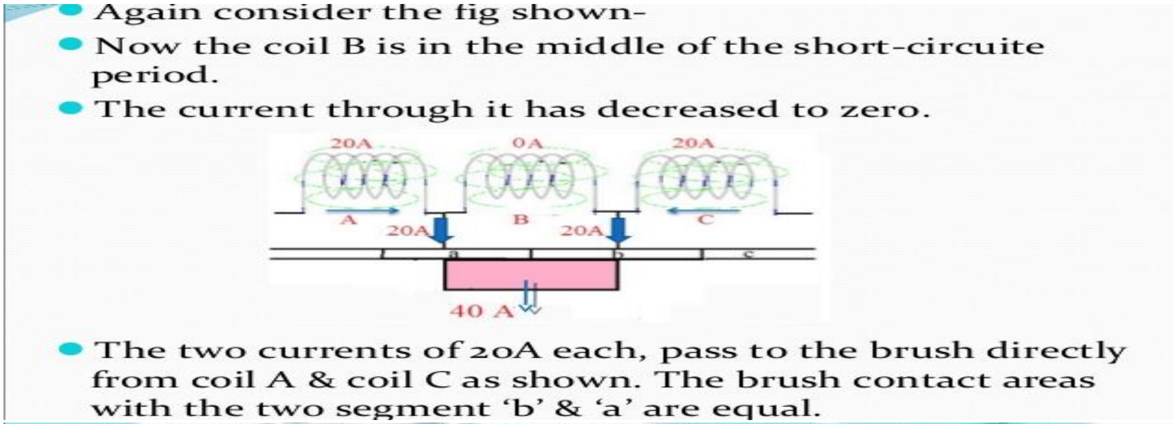
- Consider the fig shown below-
- Coil B is about to be short circuited because brush is about to come in contact with commutator segment 'a'.
- It is assumed that each coil carries 20A,so that brush current is 40A.
- Prior to the beginning of short-circuit, coil B belongs to the group of coils lying to the left of brush & carries 20A from left to right.

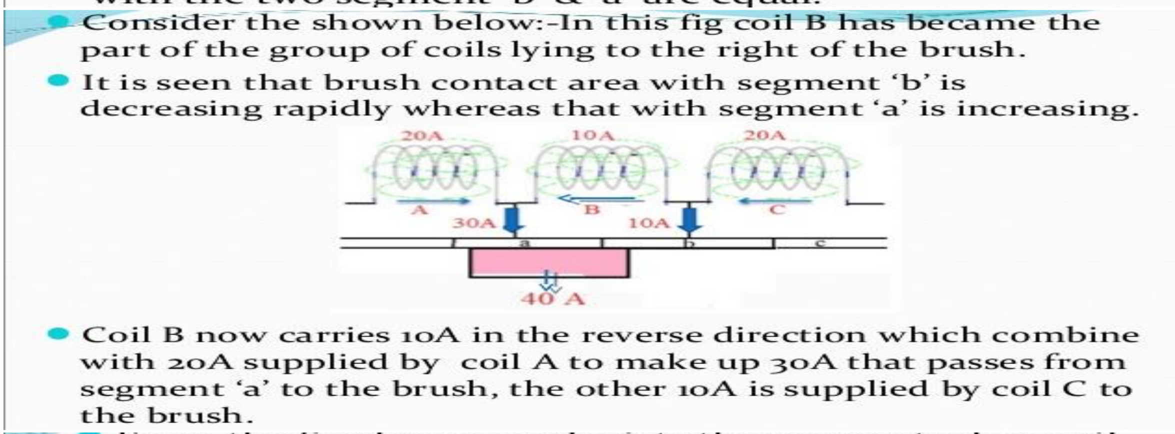


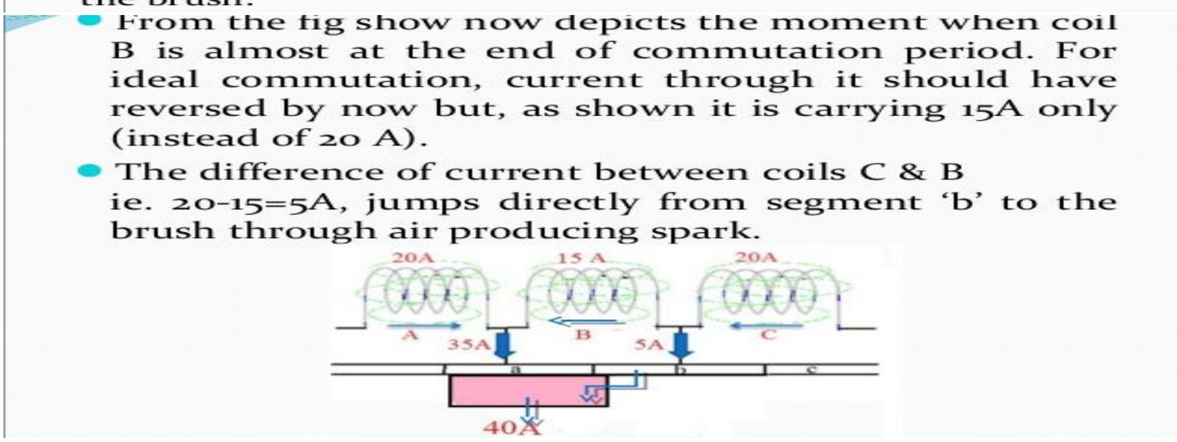
- In the fig shown here coil B has entered its period of short circuit and approximately at one-third of this period.
- The through coil B has reduced down from 20A to 10A because the other 10A flows via segment 'a'.

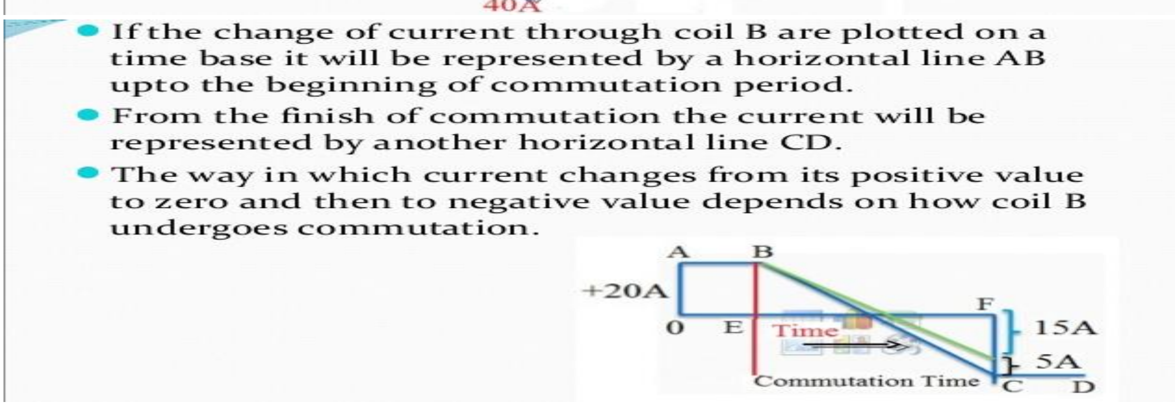


- As the area of contact of brush is more with segment 'b' than with segment 'a', it receives 30A from the former, the total again being 40A.









Methods of Improving Commutation

If the current reversal is completed during the commutation period, sparking occurs at the contact of brushes and overheating occurs damaging the surface of the commutator. **Improving commutation** means to make the current reversal in the short-circuited coil as sparkless as possible. The following are the two principal methods of improving commutation:

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

(i) **Resistance commutation**: In this method, copper brushes of lower resistance are replaced with carbon brushes of higher resistance. Resistance increases with the decreasing area of cross-section. So, the resistance of the trailing commutator segment increases as the brush moves towards the leading segment. Hence, the leading segment is most favored for the current path and large current takes the path provided by the leading segment to reach the brush. 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).

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, the carbon brushes do help in improving commutation in dc machines.

The other minor advantages of carbon brushes are:

(i) The carbon lubricates and polishes the commutator

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

(ii) **E.M.F. commutation:**

Induction property of the coil is one of the reasons for the slow reversal of current during commutation process. This problem can be tackled by neutralizing the reactance voltage produced by the coil by producing the reverse e.m.f in the short circuit coil during the commutation period. This EMF commutation is also known as Voltage commutation. This can be done in two methods.

- By Brush Shifting method.
- By Using commutating poles.

In brush shifting method, brushes are shifted forward for DC generator and backward in DC motor. This establishes a flux in the neutral zone. As the commutating coil is cutting the flux, a small voltage is induced. As brush position has to be shifted for every variation in load, this method is rarely preferred.

In the second method, commutating poles are used. These are the small magnetic poles placed between main poles mounted to the stator of the machine. These are attached in series connection with the armature. As load current causes back e.m.f., these commutating poles neutralizes the position of the magnetic field.

D.C Machine Losses

A generator is a machine for converting mechanical energy into electrical energy and a motor is a machine for converting electrical energy into mechanical energy. When such conversions take place, certain losses occur which are dissipated in the form of heat. The principal losses of machines are:

(i) **Copper loss**, due to I^2R heat losses in the armature and field windings. Armature copper loss is $I_a^2R_a$. And, Field copper loss In the case of shunt generators, it is practically constant and $I_{sh}{}^2R_{sh}$ (or VI_{sh}). In the case of series generator, it is = $I_{se}{}^2 R_{se}$ where R_{se} is resistance of the series field winding

(ii) **Iron (or core) loss**, due to hysteresis and eddy-current losses in the armature. This loss can be reduced by constructing the armature of silicon steel laminations having a high resistivity and low hysteresis loss. At constant speed, the iron loss is assumed constant.

(iii) **Mechanical losses:** Frication & windage losses, due to bearing and brush contact friction & losses due to air resistance against moving parts (i.e., windage). At constant speed, these losses are assumed to be constant.

(iv) **Brush contact loss** between the brushes and commutator & loss is approximately proportional to the load current.

Efficiency of a D.C generator

The efficiency of an electrical machine is the ratio of the output power to the input power and is usually expressed as a percentage.

$$\text{Efficiency, } \eta = \frac{\text{output power}}{\text{input power}} * 100\ \%$$

If the total resistance of the armature circuit (including brush contact resistance) is R_a , then the total loss in the armature circuit is ($I_a^2 * R_a$) . Armature Cu loss $I_a^2R_a$ is known as variable loss because it varies with the load current.

If the terminal voltage is (V) and the current in the field shunt circuit is I_f , then the loss in the shunt circuit or field copper loss is ($I_f \times V$) or $I_f^2 R_{sh.}$

If the sum of the iron, friction and windage losses is (C).

The total losses is given by= ($Ia^2 * R_a + I_f^2 R_{sh} + C$)

Condition for Maximum Efficiency

Hence, for shunt and compound generators:

Generator output = VI

Generator input = output +losses= $VI + I_a^2 R_a + W_C$ Wc = constant loss = $VI+(I + I_{sh})^2 R_a + W_c$ (because, $I_a = I + I_{sh}$)

However, if I_{sh} is negligible as compared to load current, then $I_a = I$ (approx.)

, $\eta = \frac{\text{output power}}{\text{input power}} = \frac{VI}{VI + I^2 R_a + Wc}$ because, $Ia \approx I$

Now, efficiency is maximum if, $\frac{d\eta}{dI} = 0$

or, $\frac{d}{dI}\left(\frac{VI}{VI + I^2 R_a + Wc}\right) = 0$

or, $I^2 R_a = W_c$

Hence, generator efficiency is maximum when

i.e. variables loss = constant loss

The load current corresponding to maximum efficiency is given by the relation

$$I = \sqrt{\frac{Wc}{Ra}}$$

Applications of DC Generators

1) **Applications of Separately Excited DC Generators**

These are generally more expensive because of their requirement of separate excitation source.

1. Gives wide range of voltage output, so generally used for testing purpose in laboratories.
2. Separately excited generators operate in a stable condition with any variation in field excitation. Because of this property they are used as supply source of DC motors, whose speeds are to be controlled for various applications. Example- Ward Leonard Systems of speed control.

2) **Applications of Shunt Wound DC Generators**

The terminal voltage of DC shunt generator is more or less constant from no load to full load. Therefore, these generators are used where constant voltage is required

1. General lighting purposes.
2. Battery charging
3. Providing the excitation to the alternators.

   The application of shunt generators is very much restricted for its dropping voltage characteristic. They are used to supply power to the apparatus situated very close to its position.

3) **Applications of Series-Wound DC Generators**

They give constant current in the dropping portion of the characteristic curve. For this property they can be used as constant current source.

The terminal voltage of series generator increases with load current from no load to full load. Therefore, these generators are.

1. Used for supplying field excitation current in DC locomotives for regenerative breaking.
2. Used as boosters to compensate the voltage drop in the feeder in various types of distribution systems such as railway service.
3. In series arc lightening this type of generators are mainly used.

   These types of generators are restricted for the use of power supply because of their increasing terminal voltage characteristic with the increase in load current from no load to full load.

4) **Applications of Compound Wound DC Generators**

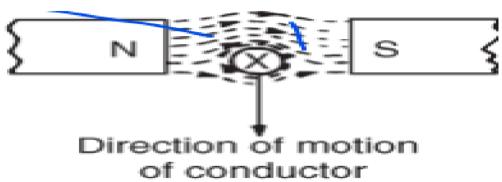
most widely used because of its compensating property. Depending upon number of series field turns, the cumulatively compounded generators may be over compounded, flat compounded and under compounded. We can get desired terminal voltage by compensating the drop due to armature reaction and ohmic drop in the in the line.

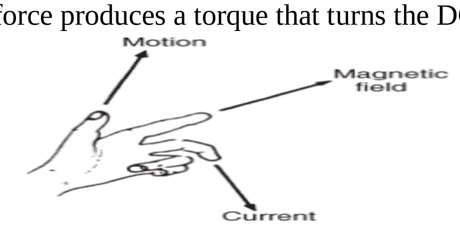
1. Over compounded cumulative generators are used in lighting and heavy power supply to compensate voltage drop in the feeder.
2. Level / Flat compounded generators are generally used for small distance operation, such as power supply for hotels, offices, homes and lodges.
3. Differential compound wound generators, because of their large demagnetization armature reaction, are used for arc welding where huge voltage drops and constant current is required.

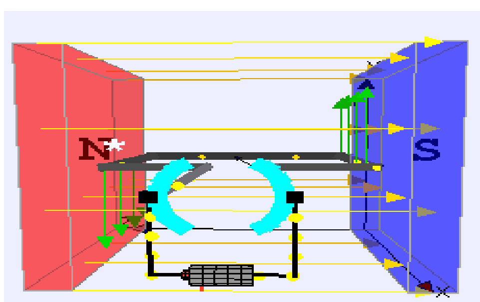
DC MOTOR

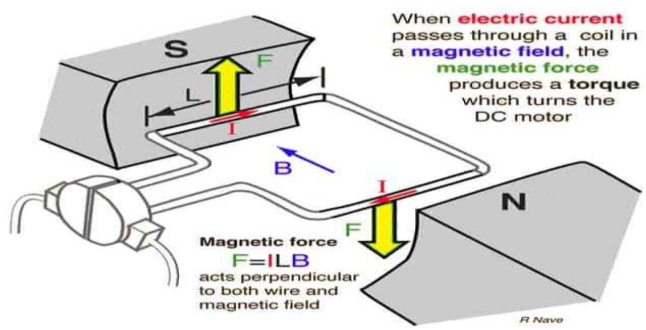
WORKING PRINCIPLE

DC motor is device which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that "the current-carrying conductor placed in a magnetic and electric field experience a force". The experienced force is called the Lorentz force. The force on the current-carrying conductor in a magnetic field depends upon: (a) The flux density of the field B (tesla). (b)The strength of the current, I (Amperes). (c) The length of the conductor perpendicular to the magnetic field, l (meters). (d)The direction of the field and current (angle).
When the magnetic field, the current and the conductor are mutually at right angles then Force F = B.I.L Newton's.
When the conductor and the field are at an angle (θ) to each other than F = B.I. LSIN θ
The Fleming left-hand rule gives the direction of the force. According to Fleming's left-hand rule when an electric current pass through a coil in a magnetic field, the magnetic force produces a torque that turns the DC motor.









Basic construction of dc motor contains a current carrying armature which is connected to the supply end through commutator segments & brushes and placed within the north south poles of a permanent or an electro-magnet.
When armature winding is connected to a DC supply, an electric current sets up in the winding. Permanent magnets or field winding (electromagnetism) provides the magnetic field. In this case, current carrying armature conductors experience a force due to the magnetic field, according to the principle stated above.
The Commutator is made segmented to achieve unidirectional torque. Otherwise, the direction of force would have reversed every time when the direction of movement of the conductor is reversed in the magnetic field.

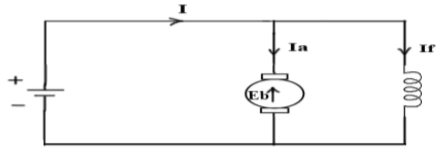
Q. **What Happens When a D.C Motor Is Connected Across An A.C Supply?**
Ans: The motor will run but it would not carry same load as it would on D.C supply.

1. More sparking at the brushes
2. Eddy currents will be high and will cause overheating and may eventually burn on A.C supply

Back e.m.f. and it's Significance

Emf induced in armature winding due to generating action which oppose supply voltage is back emf.

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, e.m.f. is induced in them whose direction, as found by Fleming's Right-hand Rule, is in opposition to supplied voltage. Because of its opposing direction, it is referred to as counter e.m.f. or back e.m.f. (E_b). V has to drive a I against the opposition of E_b. The power required to overcome this opposition is $E_b I_a$.



Voltage Equation of a Motor

The voltage V applied across the motor armature has to,

(a) Overcome the back emf E_b, and

(b) Supply the armature ohmic drop $I_a R_a$.

Hence, $V = E_b + I_a R_a$

This is known as voltage equation of a dc motor.

Now, multiplying both sides by I_a on both sides, we get

$V I_a = I_a E_b + I_a^2 R_a$

Where, V*Ia =Electrical power input to the armature

$E_b I_a$ =Electrical equivalent of mechanical power developed in the armature

$Ia^2 R_a$ = Copper loss in the armature

Condition for maximum efficiency

The gross mechanical power developed by motor is, $P_m = = I_a E_b = V I_a - I_a^2 R_a$

Differentiating both side w.r.t I_a and equating the result to zero, we get

$$\frac{dP_m}{dI_a} = 0$$

Or, $\frac{d}{dI_a}(V Ia - Ia^2 R_a) = 0$

Or, $V = 2 I_a R_a$

So, $Ia\ Ra = \frac{V}{2}$

As, $V = E_b + I_a R_a$

Or, $V = E_b + \frac{V}{2}$

Therefore, $E_b = \frac{V}{2}$

Thus, gross mechanical power developed by a motor is maximum when back emf is equal to half the supply voltage. This condition is, however, not realized in practice, because in that case current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent.

Significance of back EMF in DC Motor

Back emf plays an important role in operation of a dc motor.

1) As the back emf opposes supply voltage V, therefore, supply voltage has to force current through the armature against the back emf, to keep armature rotating. The electric work done in overcoming and causing the current to flow against the back emf is converted into mechanical energy developed in the armature.

It follows, therefore, that energy conversion in a dc motor is only possible due to the production of back emf. Mechanical power developed in the armature = $E_b I_a$

2) Due to action of back emf the motor is able to draw as much as current as it is required to develop the required load torque. Thus, the presence of back emf makes the d.c. motor a *self-regulating machine.*

Armature current (I_a), = $\frac{V - Eb}{R_a}$

V and R_a are fixed, therefore, armature current I_a depends on back emf, which in turn depends on speed of motor

The back emf is given by $E_b = \frac{Z\phi N}{60} * \frac{P}{A}$

3) At start N=0, so E_b=0. so Ia = $\frac{V}{Ra}$, the motor draws high armature current as Ra is very small, due to interaction of field flux and armature current, torque is produced as, T α ϕ Ia, so motor now start accelerating. The back emf start to develop as motor start to accelerate (as E_b is proportional to speed), magnitude of back emf is always less than applied voltage due to IaRa drop in armature. Thus, back emf protect the armature from short circuit.

4) Back emf helps to produce required amount of torque according to increase or decrease in mechanical load. When load is suddenly put on to the motor, motor tries to slow down. So, speed of the motor reduces due to which back e.m.f. also decreases. So, the net voltage across the armature (V- E_b) increases and motors draws more armature current. As F= B l I, due to increased current, force experienced by the conductors and hence the torque on the armature increases. The increase in the torque is just sufficient to satisfy increased load demand. The motor speeds stop decreasing when the armature current is just enough to produce torque demand by the new load.
When load on the motor is decreased, the speed of the motor tries to increase. Hence back e.m.f. increases. This causes (V- Eb) to reduce which eventually reduces the current drawn by the armature. The motor speed stops increasing when the armature current is just enough to produce the less torque required by the new load.
i.e., Adjust load torque to torque. If load torque increases, speed decreases so back emf decreases thus armature current increases increases.as motor torque = Ia*If, hence motor torque increases

Types of D.C Motors and its characteristics

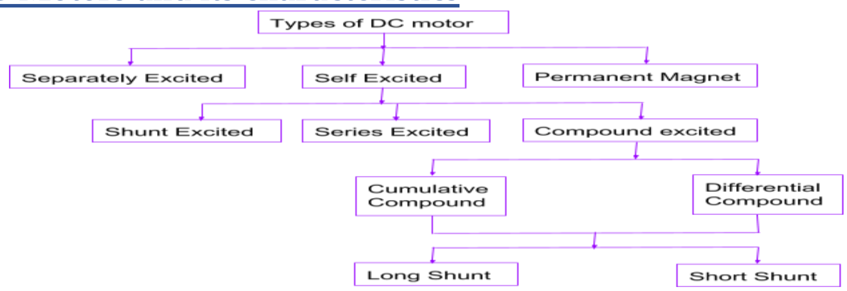


Fig: Motor Classification

The characteristic curves of a motor are those curves which shown relationship between the following quantities:

1. Torque and armature current i.e. (Tm Vs Ia) characteristic. /Electrical characteristics
2. Speed and armature current (N Vs Ia) characteristic.
3. Speed and torque (N Vs T) characteristic. / Mechanical characteristics

These are explained below for each type of DC motor. These characteristics are determined by keeping the following two relations in mind.

$\mathbf{T_a \propto \phi . I_a}$ and $\mathbf{N \propto E_b/\phi}$

Characteristics Of DC Shunt Motors

A) <u>Torque versus Armature curent</u>: The theoretical torque/ armature current can be derived from the expression a T ∝ φ.I for a shunt-wound motor, the field winding is connected in parallel with the armature circuit and thus the applied voltage gives a constant field current, i.e. a shunt-wound motor is a constant flux machine. Since (φ) is constant, it follows that T ∝ Ia

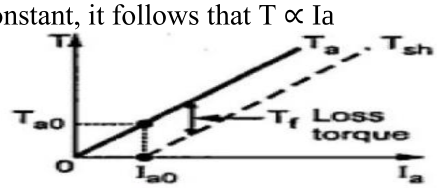


Fig. 1.34 Torque Vs Armature Current

B) <u>Speed Vs. Armature Current (N-Ia)</u>:

As N α $\frac{Eb}{\phi}$ and, $\phi = constant$ so, N α E_b

and, N α $\frac{V - IaRa}{\phi}$ α $\frac{V - IaRa}{constant}$

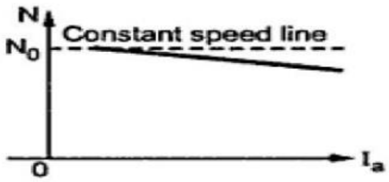


Fig. 1.35 Speed Vs Armature Current

So as load increases >> The armature current increases and hence drop IaRa also increases.
Hence for constant supply voltage $V - IaRa$ decreases and hence speed reduces. But as Ra is very small, and for change Ia in from no load to full load, drop IaRa is very small and hence drop in speed is also not significant from no load to full load.
In DC. shunt motor >> Speed regulation is an order of 5 to 10 % from no load to full load >> That's why DC. shunt motor is also called as a constant drive motor.

C) **<u>Speed versus Torque</u>**:

As, $N \alpha \frac{V - IaRa}{\phi} \alpha \frac{V - IaRa}{constant}$

And, $T \propto . Ia$

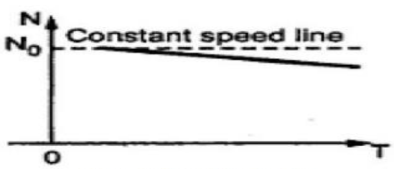


Fig. 1.36 Speed Vs Torque

So, from these 2 equations, we can conclude that Speed and Torque both has a linear relationship. This characteristic is similar to speed – Armature current characteristics.
This curve shows that the speed almost remains constant through torque changes from no load to full load conditions.

Characteristics of DC Series Motor

A) Torque Vs. Armature Current (T_a-I_a)

In the case of a series motor, the series field winding is carrying the entire armature current. So, flux produced is proportional to the armature current.

As, $T \propto \varphi . I_a$ and $I_f \propto \varphi$. But, for series motor, $I_a = I_f$

So, $T \propto I_a^2$,

The torque proportional to the square of the armature current. This relation is parabolic in nature as shown in the figure.
After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to Ia only, $T \propto Ia$. Therefore, after magnetic saturation, Ta-Ia curve becomes a straight line.
The shaft torque (Tsh) is less than armature torque (Ta) due to stray losses. Hence, the curve Tsh vs Ia lies slightly lower.

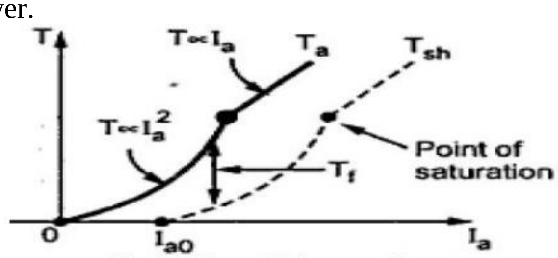


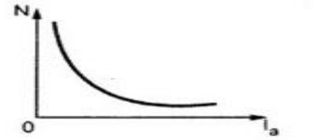
Fig. 1.37 Torque Vs Armature Current

B) <u>Speed Vs. Armature Current (N-Ia)</u>

$N \alpha \frac{Eb}{\phi} = \frac{V - IaRa - IaRse}{Ia}$

Now the values of R_a and R_{se} are so small that the effect of change in Ia on speed overrides the effect of change in $V - IaRa - IaRse$ on the speed. Hence in the speed equation, $E_b \approx V$ and can be assumed constant. So, speed equation reduces N α $\frac{Eb}{\phi}$ α $\frac{1}{Ia}$ $\frac{V-IaRa}{\phi}$ α $\frac{V}{\phi}$-(IaR/ ϕ) *so,* $\frac{V}{\phi}$*-k* = $\frac{V}{Ia}$*-k* *so, rectangular hyperbola with decreasing*

So, speed – armature current characteristics is rectangular hyperbola as shown in the figure.



17 N Vs I_a for series motor

C) <u>Speed Vs. Torque (N-Ta</u>

In case of series motors, T ∝ φ.Ia ∝ I_a^2

And, N α $\frac{Eb}{\phi}$ α

N α $\frac{1}{\sqrt{T}}$

Thus, as torque increases when load increases, the speed decreases. On no load, torque is very less and hence speed increases to dangerously high value. Thus, the nature of the speed-torque characteristics is similar to the nature of the speed – armature characteristics.

Fig. 1.39 Speed Vs Torque

Characteristics Of DC Compound Motor

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

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

(b) **Differential compound motor**: In a differential compound motor, as two fluxes oppose each other, the resultant flux decreases as load increases, thus the machine runs at a higher speed with an increase in load. This property is dangerous as on full load, the motor may try to run with dangerously high speed. So, the differential compound motor is generally not used in practice.

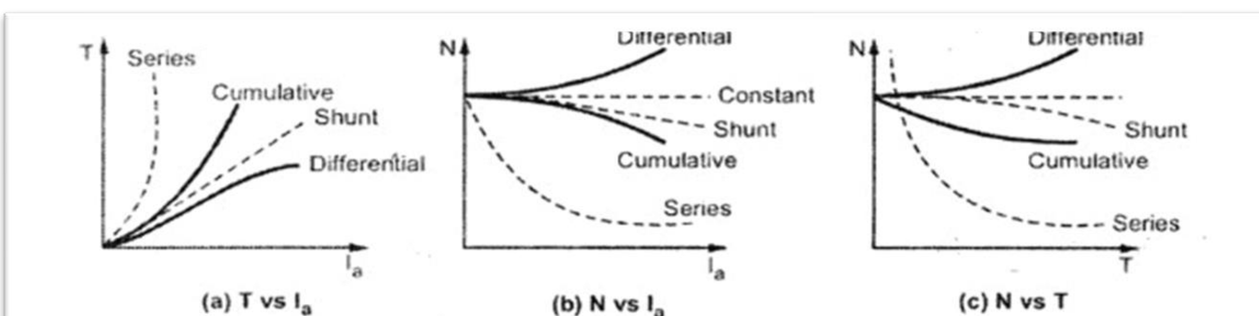


Fig. 2.19 Characteristics of compound motor

Q. **Why Series Motor Cannot Be Started on No-load?**

Ans: Series motor cannot be started without load because of high starting torque. Series motor are used in Trains, Crane etc.

Q. **Why The Field of a D.C Shunt Motor Should Not Be Open?**

Ans: The shunt motor will achieve dangerously high speed and may destroy itself.

Q. Why can we start a DC shunt motor without a load?

Since the field winding is connected parallel to supply, the field current is independent from load current. Once the supply is given the flux will be created immediately, which will be constant always. So this flux will prevent the motor from over speeding since, **flux is inversely proportional to speed.**

Note: In case of dc series motor the field is connected In series to load. If it is started without load the field current will be less, hence flux will be less and due to this motor speed will go infinite and damages itself.

This is the reason why series motor should not be started without load and shunt motor can be started without load.

Speed Control of D.C Motor

Speed control means intentional change of the drive speed to a value required for performing the specific work process. We know that the expression of speed control dc motor is given as,

$$N \alpha \frac{V - IaRa}{\phi}$$

So, speed can be varied by changing

(i) Terminal voltage of the armature V,

(ii) Armature circuit resistance R and

(iii) Flux per pole ϕ .

The first two cases involve change that affects armature circuit and the third one involves change in magnetic field. Therefore, speed control of dc motor is classified as

1) Armature control methods i.e. applicable to decrease base speed and

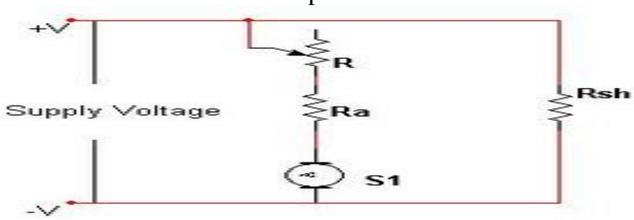
2) Field control methods. i.e applicable to increase base speed

1) Speed control of DC shunt motor

i) Armature Resistance Control Method: In this method, external resistance is added to the armature circuit. The field winding is directly connected with the supply. Hence, the field current will remain as same. And also, the flux will remain the same if the external resistance varies.

From the equation of speed, Speed of a dc motor is directly proportional to the back emf E_b and $E_b = V - I_aR_a$. That means, when supply voltage V and the armature resistance R_a are kept constant, then the speed is directly proportional to armature current I_a. Thus, if we add resistance in series with the armature, I_a decreases and, hence, the speed also decreases. Greater the resistance in series with the armature, greater the decrease in speed.

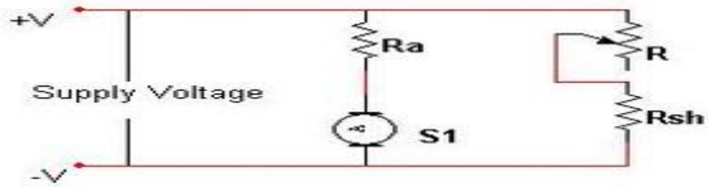
This method is used to control the speed below its normal value.



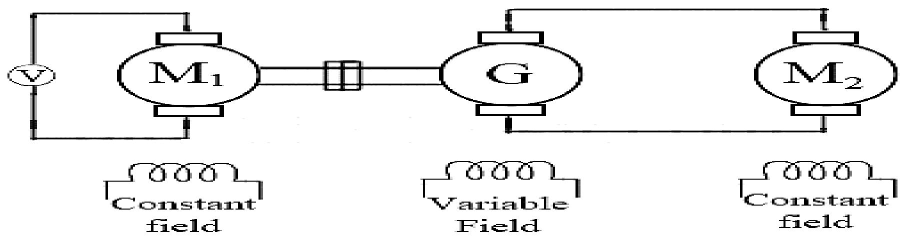
ii) Flux Control Method: Speed of a dc motor is inversely proportional to the flux per pole. Thus, by decreasing the flux, speed can be increased and vice versa.

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux. Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of field flux beyond a limit will adversely affect the commutation.

So, this method is suitable for speed control above the rated speed.

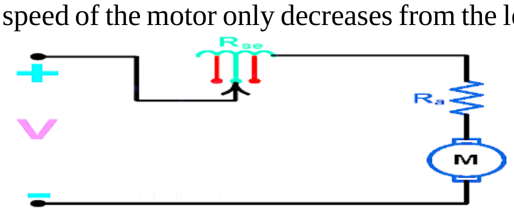


iii) **Armature Voltage control**:
This system is used where very sensitive speed control of motor is required (e.g., electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right.
M_2 is the motor to which speed control is required.
M_1 may be any AC motor or DC motor with constant speed.
G is a generator directly coupled to M_1.
In this method, the output from generator G is fed to the armature of the motor M_2 whose speed is to be controlled. The output voltage of generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M_2 is varied very smoothly. Hence, very smooth speed control of the dc motor can be obtained by this method.



2) Speed Control of DC Series Motor

i) **Armature Resistance control method**
In this method, a variable resistor or rheostat connected in series with armature resistor. in series motor, armature winding is connected in series with the field winding. Therefore, armature current and field current are the same.
By varying the armature resistance, the armature current and voltage vary. If the value of external resistance increases, the voltage across the armature and current from the armature winding is reduced. And the speed will be decreased.
By this method speed of the motor only decreases from the level of speed when external resistance is not connected.



ii) **Flux Control Method**
• **Field diverter**: A variable resistance is connected parallel to the series field as shown in fig (a). This variable resistor is called as a diverter, as the desired amount of current can be diverted through this resistor and, hence, current through field coil can be decreased. Thus, flux can be decreased to the desired amount and speed can be increased.
• **Armature diverter:** Diverter is connected across the armature as shown in fig(b). For a given constant load torque, if armature current is reduced then the flux must increase, as Ta ∝ Ø Ia This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the motor will decrease.

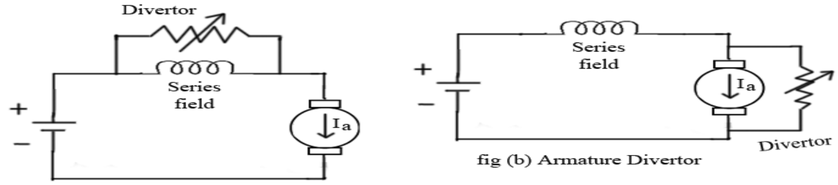
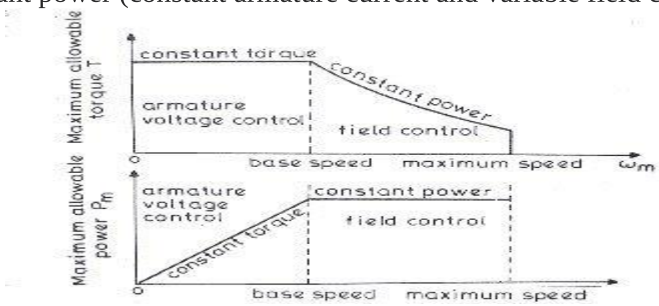


fig (a) Field Divertor
fig (b) Armature Divertor

Q. **Why is armature control being superior to field control scheme in the case of a dc shunt motor?**

Q. Why is the armature control method employed only below the rated speed in shunt DC motors?
In a shunt motor one may control the torque withe by varying the armature current or field current or both.
In order to simply the control and make the dynamics linear it is best to only vary one and keep the other constant. Generally, and as the field time constant is very much larger than the armature time constant is best to keep the field current constant and vary the armature current.
This may only be done below rated speed where the armature current is variable and field current constant, where's above rated speed the armature current must be held constant (constant power mode) in which case the field current is reduced (field weakening). Hence the constant torque (constant field current, variable armature current) and constant power (constant armature current and variable field current modes of operation.

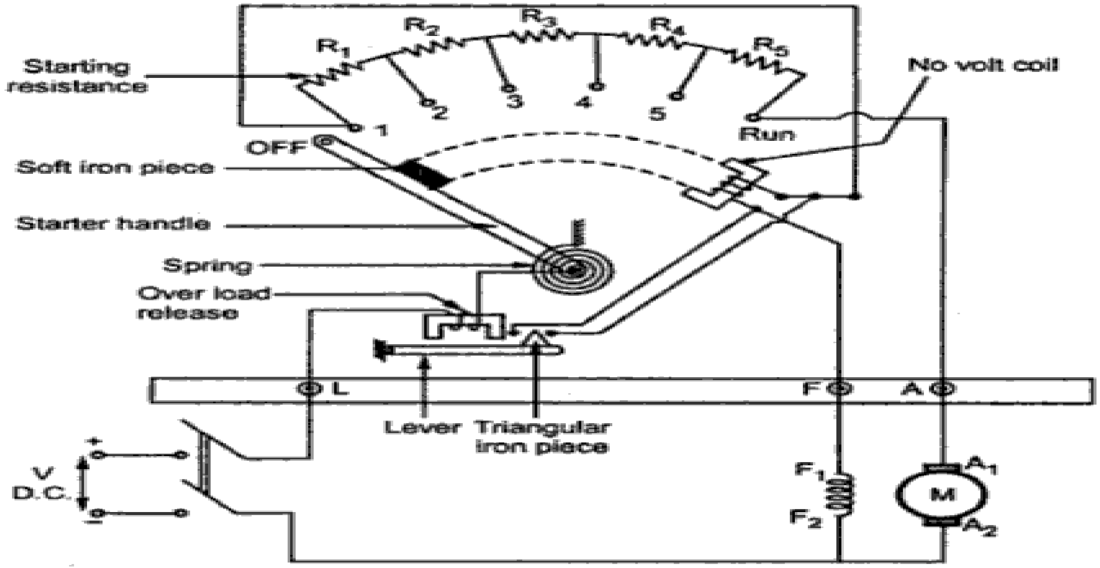


Q. **Is it possible obtain the speed higher than the rated speed by armature control method?**
No, you can't get speeds above rated speed using armature voltage control method, because applied voltage can't go beyond rating, otherwise it will damage machine insulation, which are designed for rated voltage, if voltage goes beyond rating, dielectric of the insulator will face huge electric stress and can break down. So, we go for flux weakening method, in constant power mode, to increase speed beyond rating.
Q. **How do you obtain the speed of motor above and below rated speed by field control method?**
For a particular field winding rated for a current value it is not advisable to reduce the field resistance because it will allow for a higher current to flow through the field winding and this could damage the field winding, usually the field resistance is increased, and this would cause a lower field. current to flow and flux reduces, the reduction in the flux causes the speed to increase above its rated value…usually the field control approach is used to control speeds greater than the base speed of the motor.

D.C Motor Starter

- At starting N=0, so E_b=0. thus, Ia = $\frac{V}{Ra}$, In practical DC machines, armature resistance is basically very low, generally about 0.5 Ω. Therefore, a large current flow through the armature during starting. This current is large enough to damage the armature circuit if not restricted to some limited value. This limitation to the starting current of dc motor is brought about by means of the starter. Thus, the distinguishing fact about the starting methods of dc motor is that it is facilitated by means of a starter.
- There are various types of dc motor starters, such as 3-point starter, 4-point starter, no-load release coil starter, thyristor controller starter etc.
  The basic concept behind every DC motor starter is adding external resistance to the armature winding during starting.
  From the followings, 3-point starters and 4-point starters are used for starting shunt wound motors and compound wound motors.

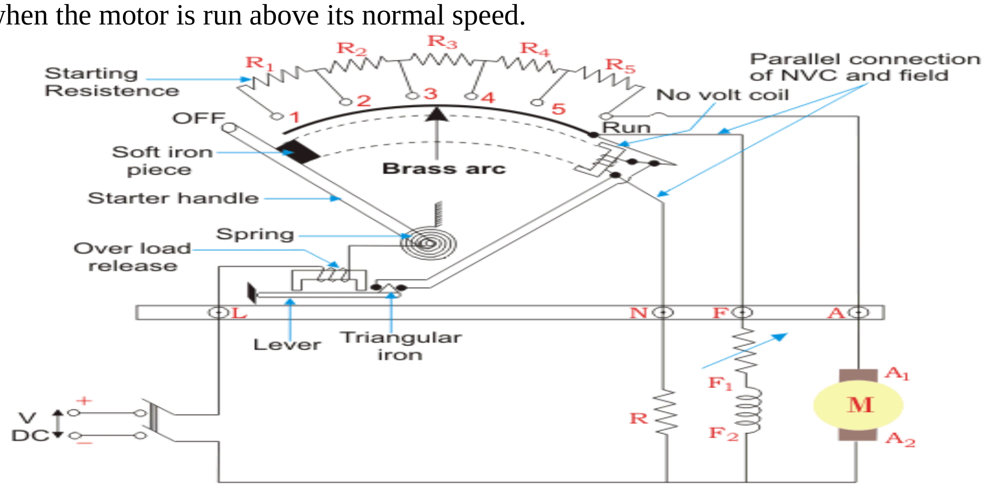
3 Point Starter
Mainly there are three main points or terminals in 3-point starter of DC motor. They are as follows
L is known as Line terminal, which is connected to the positive supply.
A is known as the armature terminal and is connected to the armature windings.
F is known as the field terminal and is connected to the field terminal windings.



- The primary purpose of a DC motor starter is to provide resistance proportional to the amount of generated CEMF. Three-point starters accomplish this by providing variable resistance at five studs along the path of the starter handle.
- In order to start the motor, the spring-loaded starter handle is moved from OFF to the first stud position. At this point, the first resistor (R1 above) provides high starting resistance, as CEMF has not yet developed. As the handle is slowly moved toward the RUN position, series resistance decreases as the motor gains speed and CEMF increases. When the handle reaches the RUN position, resistance is eliminated
- The handle remains in the RUN position against the force of the spring because the no voltage coil (NVC) shown above is magnetized when current flows through the starter. The NVC also acts as a safeguard during motor operation. If the motor's voltage supply is cut for any reason, the NVC demagnetizes and the handle spring returns the handle to the OFF position, effectively cutting the motor.
- The fact that the no voltage coil is magnetized by the field current represents the drawback of three-point starters. A motor's speed is controlled by current changes effected by the field rheostat; because the NVC relies on the constant supply of field current, speed changes may result in the demagnetization of the NVC, the release of the starter handle, and the unintentional cutting of the motor. Four-point starters overcome this problem by adding an additional terminal.

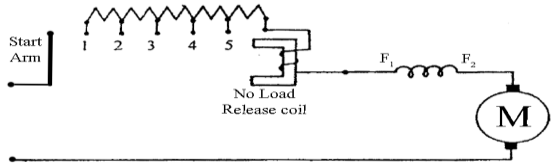
<u>4 Point Starter</u>

- Four-point starters are virtually identical to 3-point starters, but they have an additional terminal, labeled the “N” terminal, which links the supply to the no voltage coil of the starter. This protects against unnecessary tripping when the motor is run above its normal speed.



- **In a 4-point starter** is that the *no voltage coil* (electromagnet E) is not connected in series with the field coil. The field winding gets directly connected to the supply, as the lever moves touching the brass arc (the arc below the resistance studs). The no voltage coil (or Hold-on coil) is connected with a current limiting resistance Rh. This arrangement ensures that any change of current in the shunt field does not affect the current through hold-on coil at all. This means, electromagnetic pull of the hold-on coil will always be sufficient so that the spring does not unnecessarily restore the lever to the off position. A 4-point starter is used where field current is to be adjusted by means of a field rheostat for the purpose of operating the motor above rated speed by reducing the field current.

DC Series Motor Starter/2 point starter



- They involve two terminals: the line (L) connecting the supply positive and the starting handle, and the field/armature connection to the motor itself. These devices are sometimes called two-point starters for this reason. Series starters are identical to three- and four-point types in operation: the handle is simply moved from OFF to RUN, at which point it remains there using the magnetized NVC.

Application of DC motors

1) **Series Motor**: The series motors are used in the application where high starting torque is necessary and speed variation is possible. Example- Vacuum cleaner, Air Compressor, Cranes, Traction system, sewing machine, lifts, winching system, cheap toys and automotive, and in speed regulation application, power tools, Sewing machine, Electric footing etc.

2) **Shunt Motor**: The shunt motor is used in the application where starting torque is not needed more and running on the constant speed application from no load to full load. Example- conveyer, Lift, Fans, Lathe machine, spinning machine, centrifugal pump, Blowers, Weaving Machine, Wiper, Automatic windscreen, Drills, Boring mills, Shapers, weighing machine etc.

3) **Cumulative Compound Motor**: The Cumulative compound Motor is used in the application where high starting torque and fairly constant speed is required. Also, it has good speed regulation at high speed. Examples- Presses, Shears, Conveyors, Elevators, rolling mills, Heavy planners, stamping machine, Reciprocating machine, Electric shovels etc.

4) **Differential Compound Motors**: Differential compound motors are rarely used because of its poor torque characteristics as speed increases as load increases. So used in practical or laboratory application.