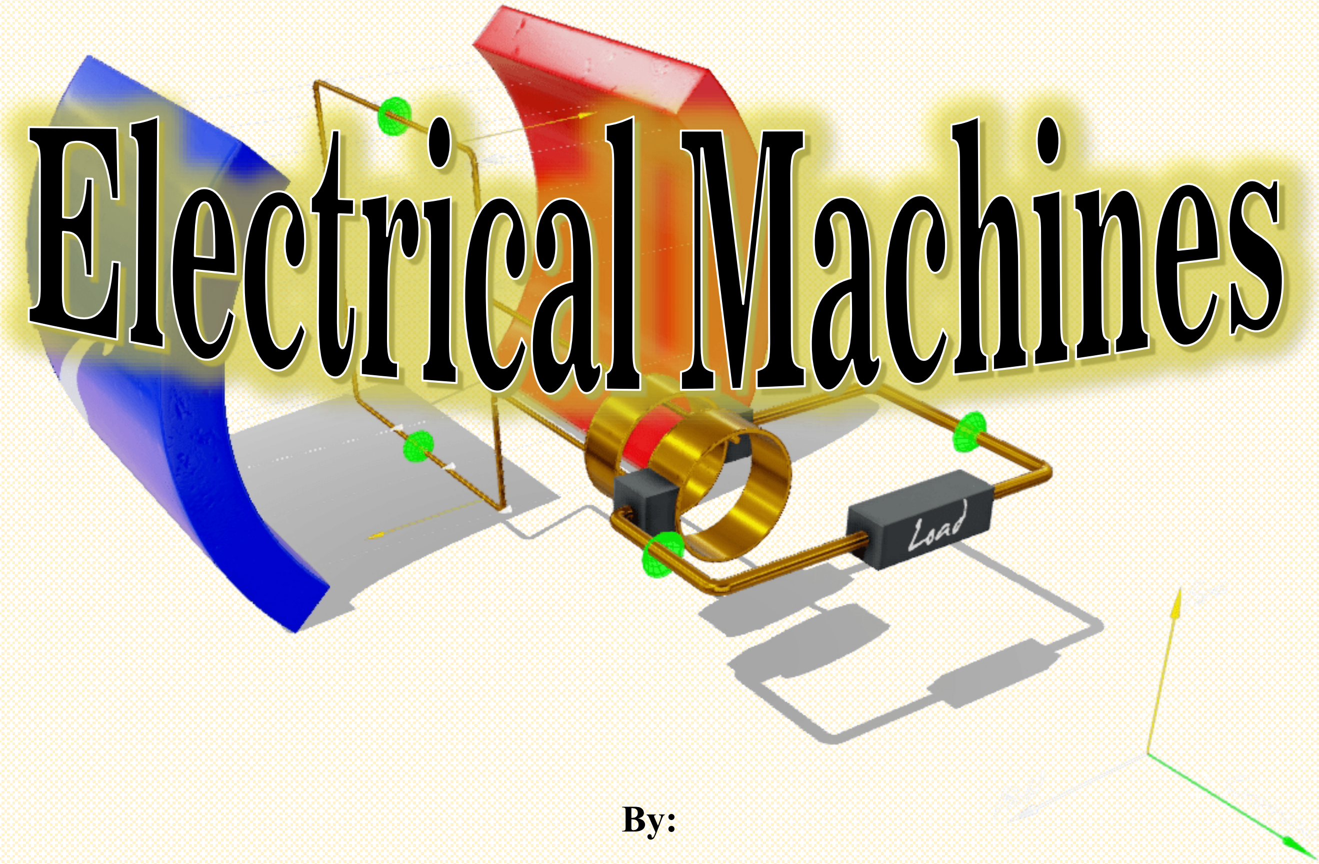
Ministry Of Higher Education

Tikrit University

Petroleum Processes Engineering College

Dept. Of Petroleum System Control Eng.

Electrical Machines



By:

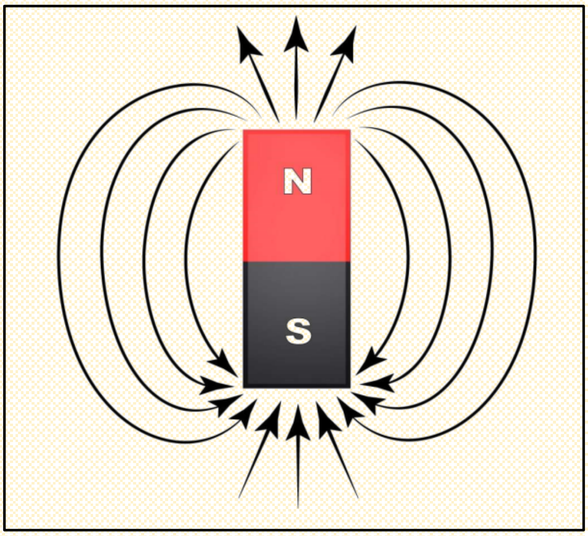
Assist. Lect. Mohammed H. Ibrahim

2024

1. Magnetism and Electromagnetism

1.1. Important Definitions

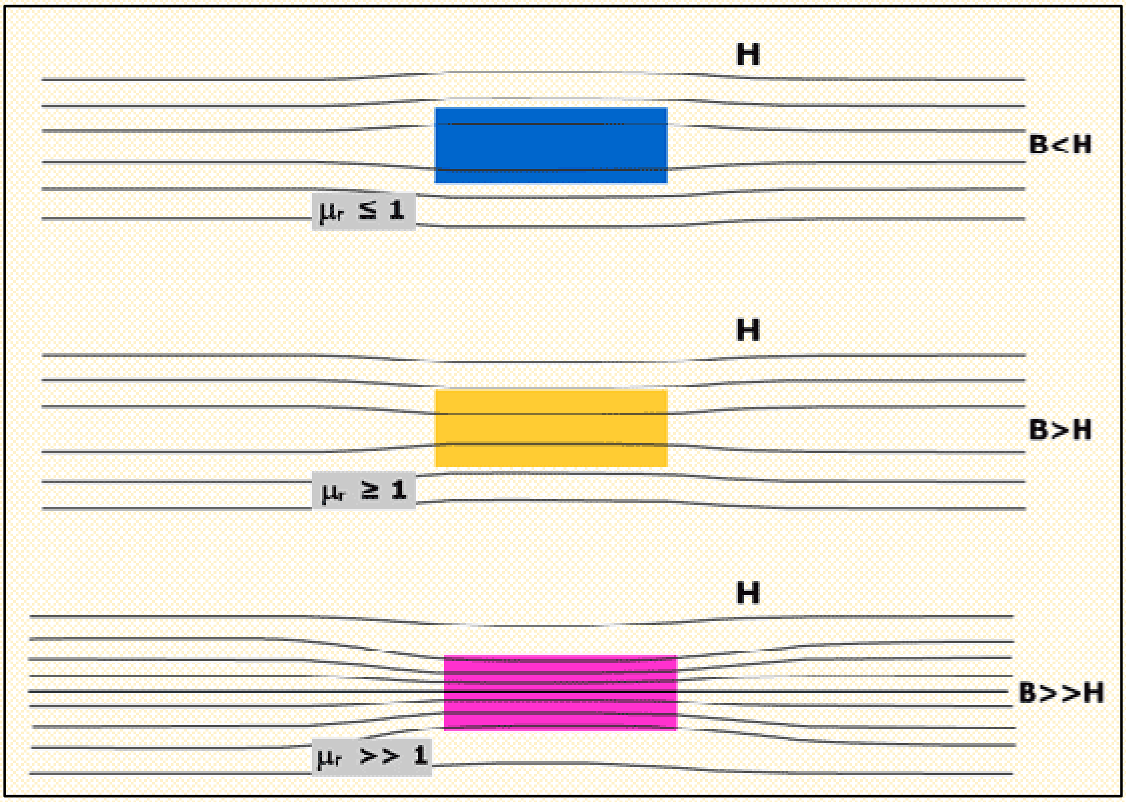
i. *The magnetic field:* It is the area surrounding the magnet and in which various effects appear, to which the objects affected by the magnet respond



ii. *Permeability (electromagnetism)* μ: It is a value that expresses the extent to which magnetic field lines can flow in a medium

$$\mu = \mu_o \mu_r \qquad \mu_o = 4\pi * 10^{-7} \quad \text{H/m} \qquad (1)$$

$\mu_{r:}$ relative Permeability, for free space=1



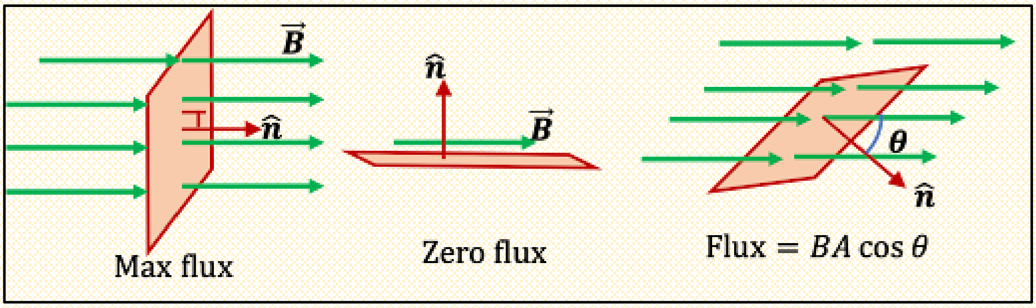
iii. *Magnetic flux Φ (wb):* is the number of total lines in the magnetic field. Flux corresponds to the electric current.

iv. *Magnetic flux density B (wb/m2):* It expresses the density of magnetic field lines that cross a unit area and are perpendicular to it.

$$B = \frac{\Phi}{A} \qquad \text{wb/m}^2, \text{T} \qquad (2)$$

v. *Magnetic flux intensity H:* the ratio of the MMF needed to create a certain Flux Density (B) within a particular material per unit length of that material.

$$H = \frac{B}{\mu} \qquad \text{A/m}$$
$$= \frac{N.I}{l} \qquad (3)$$



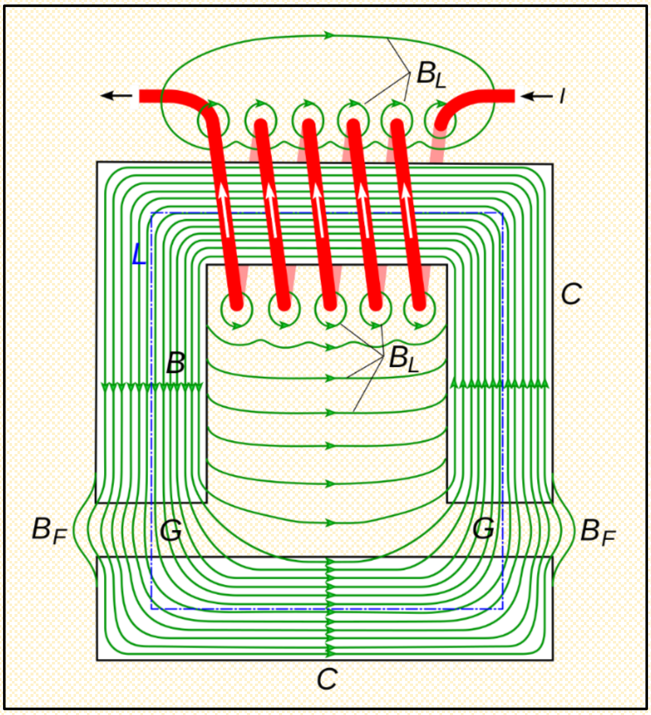
vi. *Magneto-motive-force mmf:* Magnetic pressure that drives magnetic flux in a magnetic circuit. Its value depends on the value of the electric current passing through the coil and the number of turns, and its units are the ampere (ampere.turn).

$$m.m.f = N.I \qquad \text{A.T} \qquad (4)$$

vii. *Magnetic reluctance (Rmag):* When passing through a magnetic circuit, magnetic flux encounters reluctance, which is defined as the ratio between the magnetic driving force and the magnetic flux.

$$R_{mag} = \frac{\text{m.m.f}}{\Phi} = \frac{\text{N.I}}{\Phi} \qquad \text{AT/wb}$$

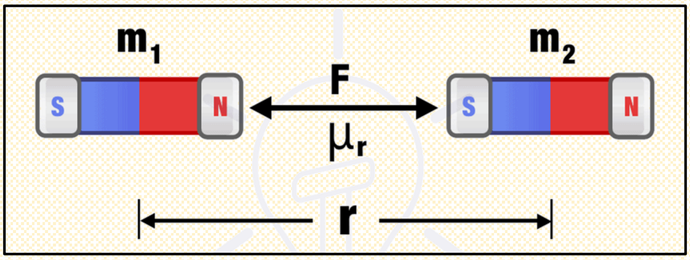
Or $$R_{mag} = \frac{L}{\mu A}$$



L: Path length of magnetic flux, A: Area

1.2. Magnetic Force (Coulomb laws):

State that the force between two magnetic poles placed in a medium is:



i. Directly proportional to their pole strengths.

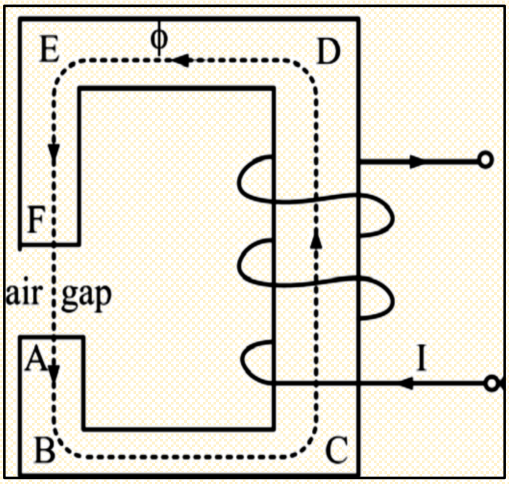
ii. Inversely proportional to the square of the distance between them

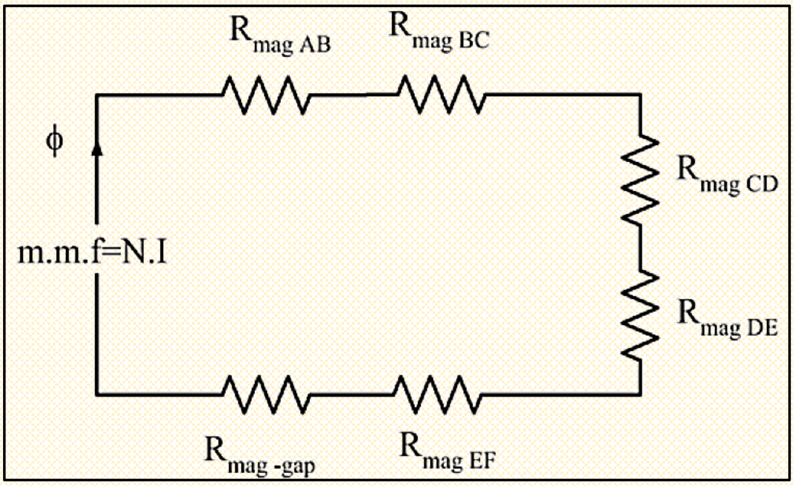
iii. Inversely proportional to the absolute permeability of the surrounding medium.

$$F = \frac{m_1 m_2}{4\pi\mu r^2}$$ F : magnetic force. m: the magnetic flux of the pole,

1.3. Electric circuit and magnetic circuit

The electrical circuit equivalent to the aforementioned magnetic series circuit can be found and Figure below





$$R_{mag-t} = \frac{L_{AB}}{\mu_{AB}A_{AB}} + \frac{L_{BC}}{\mu_{BC}A_{BC}} + \frac{L_{CD}}{\mu_{CD}A_{CD}} + \frac{L_{DE}}{\mu_{DE}A_{DE}} + \frac{L_{EF}}{\mu_{EF}A_{EF}} + \frac{L_{gap}}{\mu_o A_{gap}}$$

$$\Phi = \frac{N.I}{\frac{L_{AB}}{\mu_{AB}A_{AB}} + \frac{L_{BC}}{\mu_{BC}A_{BC}} + \frac{L_{CD}}{\mu_{CD}A_{CD}} + \frac{L_{DE}}{\mu_{DE}A_{DE}} + \frac{L_{EF}}{\mu_{EF}A_{EF}} + \frac{L_{gap}}{\mu_o A_{gap}}}$$

Magnetic circuit	Electric circuit
Magneto-motive-force mmf:	Electro-motive force e.m.f
$R_{mag} = \frac{L}{\mu A}$	$R = \frac{\rho l}{A}$
$\Phi = \frac{mmf}{R_{mag}}$	$I = \frac{E}{R}$

1.4. Relation between magnetism and electricity

It is known that a current passing through a conductor generates a magnetic field around it, and vice versa, a change in the magnetic field around a wire generates an electric current passing through the wire. This is the working principle of electrical machines.

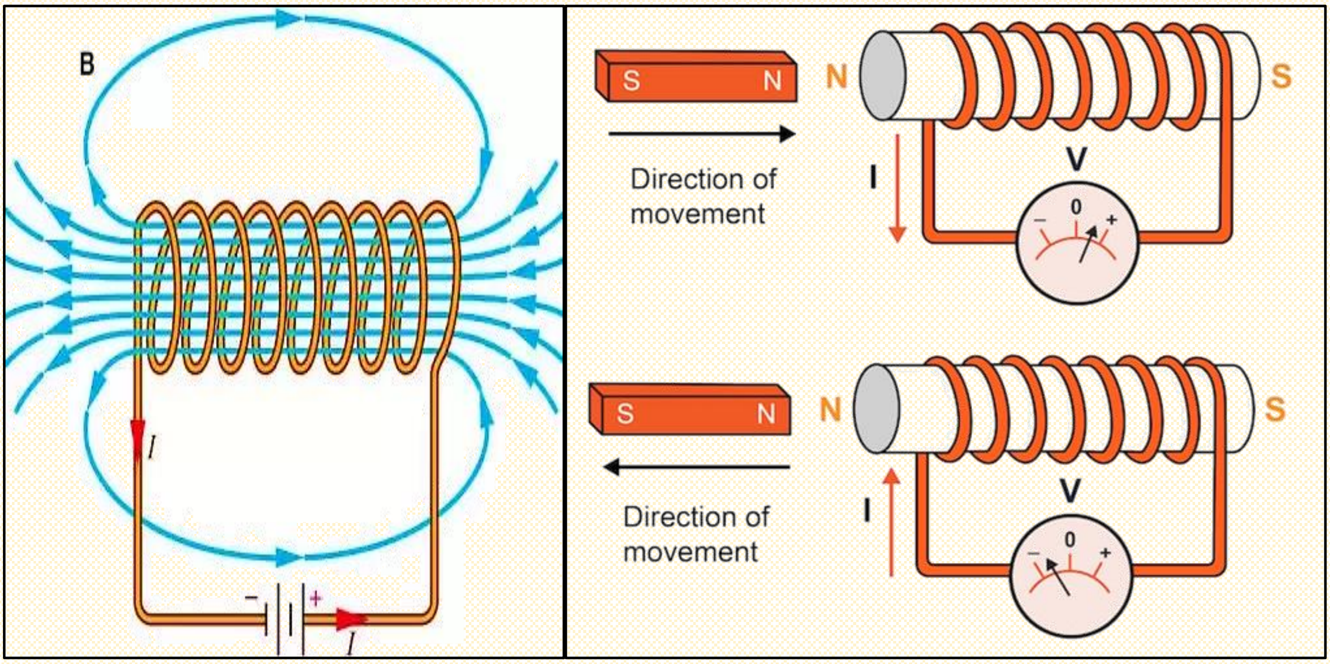
1.5. Faraday's Laws:

Faraday's laws can be summarized in the below:

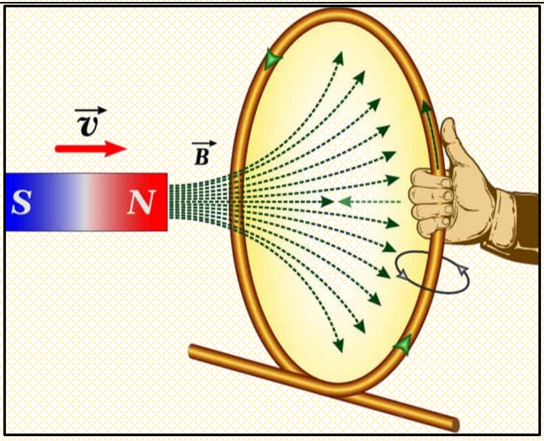
First Law: states that whenever a conductor cuts magnetic flux, an e.m.f. is induced in that conductor.

Second Law: states that the magnitude of the induced e.m.f. is equal to the rate of change of flux-linkages.

$$e = N(d\text{Ø}/dt) \quad \text{volts} \qquad 10$$



1.6. Lenz's Law



The current produced by the emf tends to oppose the flux change

$$e = -N(d\text{Ø}/dt) \quad \text{volts} \qquad 11$$

1.7. Induced e.m.f.

Induced e.m.f. can be summarized as below

i. dynamically : usually the field is stationary and conductors cut across it (as in d.c. generators).

ii. statically: usually the conductors or the coil remains stationary and flux linked with it is changed by simply increasing or decreasing the current producing this flux (as in transformers).

Self-Induced e.m.f: Is the e.m.f. induced in a coil due to the change of flux. If current through the coil is changed, then the flux on its turns will also change, which will produce in it that is called self-induced e.m.f.

Coefficient of Self-induction (L):

i. The Coefficient of Self-induction of a coil is defined as the weber-turns per ampere in coil

$$L = \frac{N\Phi}{I} \qquad \text{Henry(H)} \qquad 12$$

ii. It gives the value of self-induction in terms of the dimension of the solenoid

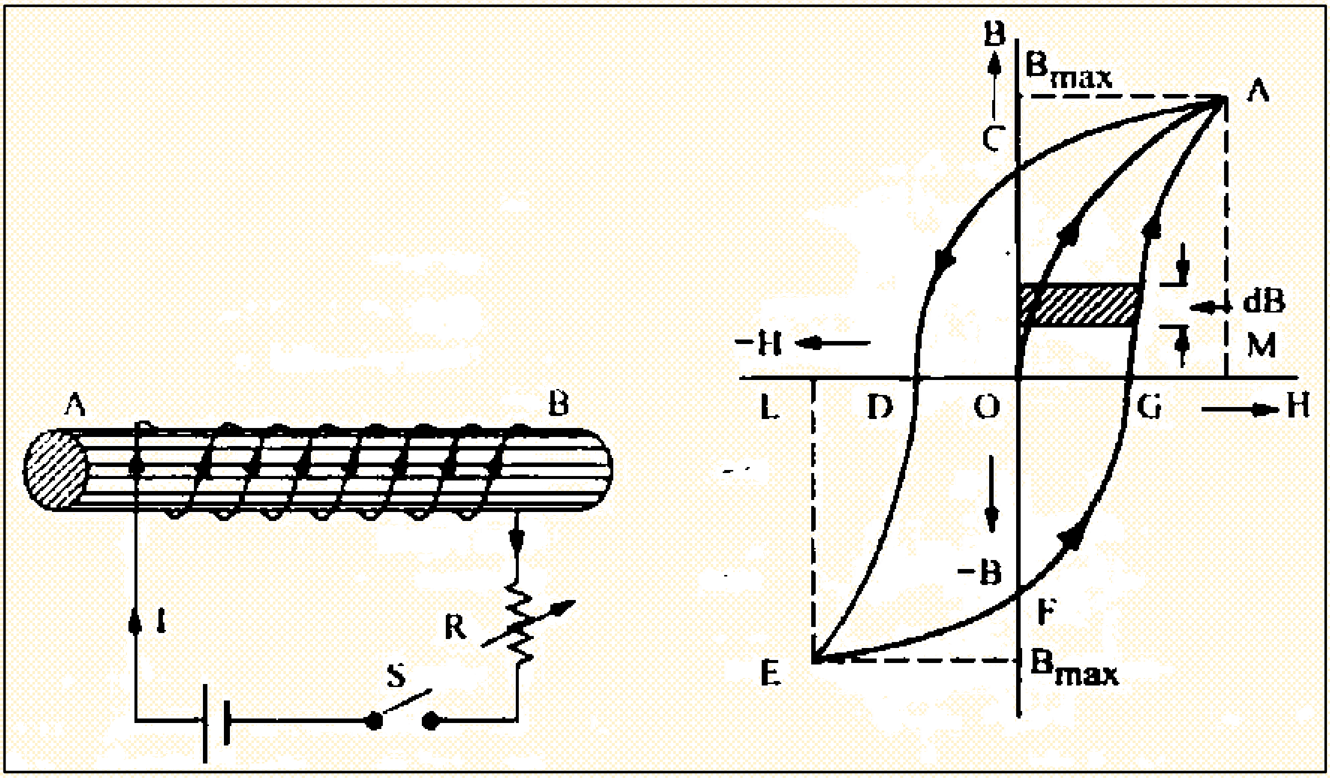
$$L = \frac{\mu A N^2}{l} \qquad \text{Henry(H)} \qquad 13$$

Hence, a coil has a self-inductance of one henry if one volt is induced in it when current through it changes at the rate of one ampere/second.

1.8. Magnetic Hysteresis

It may be defined as the lagging of magnetization of induction flux density (B) behind the magnetizing force (H). Alternatively, it may be defined as that quality of a magnetic substance, due to which energy is dissipated in it, on the reversal of its magnetism.

It is seen that B always lag behind H. the two never attain zero value simultaneously. This lagging of B behind H is given the name (hystereis), the close loop BCDEFGB which is obtained when iron bar is taken through one complete cycle of magnetisation is known as (hypothesis loop).



Example 1: A magnetic field of 8.9 T passes perpendicular to a disc with a radius of 5 cm. Find the magnetic fluxof the disc.

Solution:

B = 8.9 T, r = 5 cm = 5 × 10^{-5} m, A = $\pi(5 \times 10^{-2})^2$

By applying the formula,

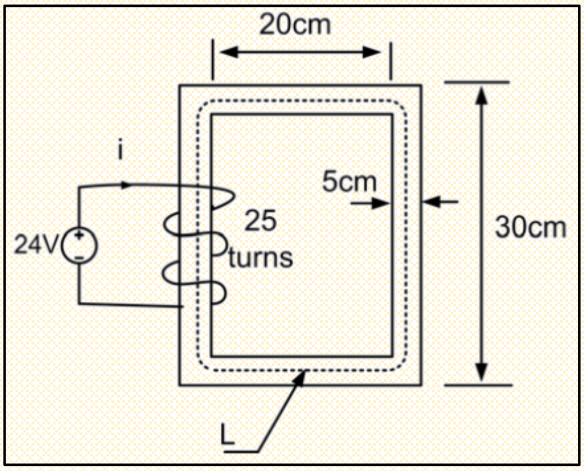
$$\Phi = B*A = 8.9 * \pi(5 \times 10^{-2})^2$$

$$= 139.7 \times 10^{-4} \text{ Wb.}$$

Example 2: An iron frame in the shape of a rectangle, its dimensions are 30*20 cm, and its cross-sectional area is in the form of a square with a side length of 5 cm. It is wrapped on one side of the frame with a coil with a number of turns of 25 and a resistance of 2 ohms, and it is fed from a constant voltage source of 24 volts. If the magnetic flux density in the frame is 0.008 Tesla, calculate: the current in the coil, Magnetic field intensity, magnetic flux.

Solution:

The magnetic circuit can be drawn as shown



Flux line length for the long side =30-5 =25 cm

Flux line length for the short side =20-5 =15 cm

Flux length (L) = 2 *(25+15) = 80 cm = 0.8 m

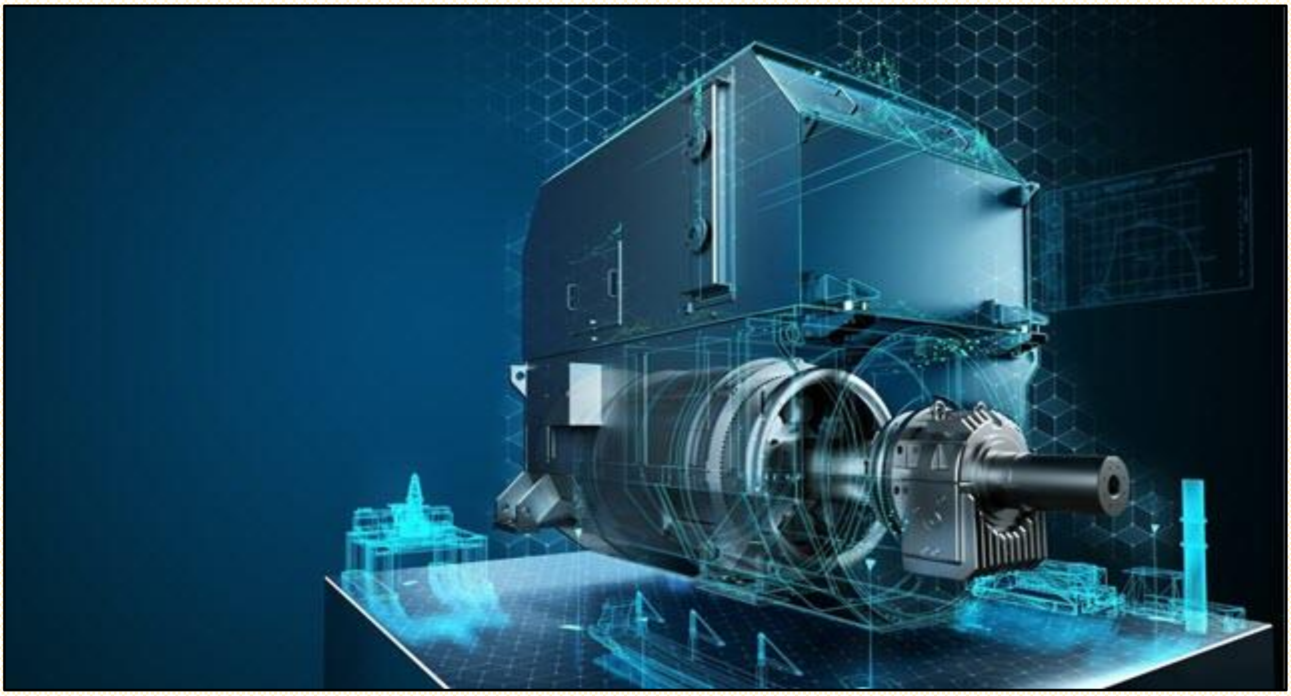
N=25 turns, R=2 Ω, V=24v, B=0.008 T , A=$(0.05)^2$=0.0025 m

I=V/R=24/2= 12 A

$$H = \frac{NI}{l} = \frac{25*12}{0.8} = 375 \text{ A/m}$$

$$B = \frac{\Phi}{A} \Rightarrow \Phi = B.A = 0.008 * 0.0025 = 2*10^{-5} \quad \text{wb}$$

2. D.C. Generator



2.1. Introduction

A direct-current (DC) generator is a rotating machine that supplies an electrical output with unidirectional voltage and current

The essential components of a generator are:

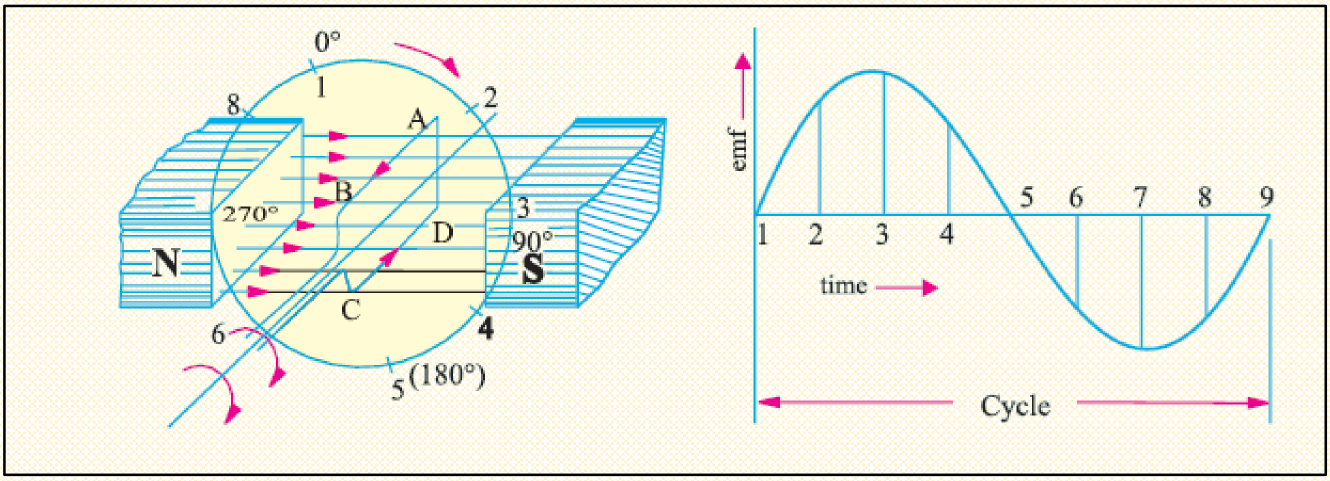
i. Magnetic field

ii. Conductor or a group of conductors

iii. Motion of conductor w.r.t. magnetic field

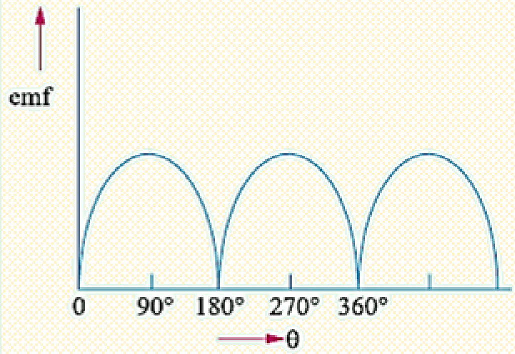
2.2. Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed .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.



Note that e.m.f. generated in the loop is alternating one, 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.* We then have the a.c. generator in fact.

Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes (by Commutator). This is not a steady direct voltage but has a *pulsating character*. It is because the voltage appearing across the brushes varies from zero to maximum value and back to zero twice for each revolution of the loop.



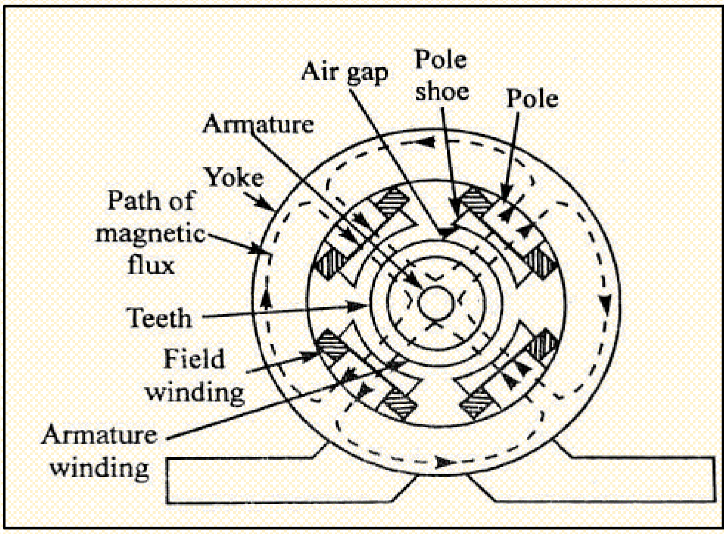
If we require is the *steady direct voltage*. This can be achieved by using a large number of coils connected in series. The resulting arrangement is known as *armature winding.*

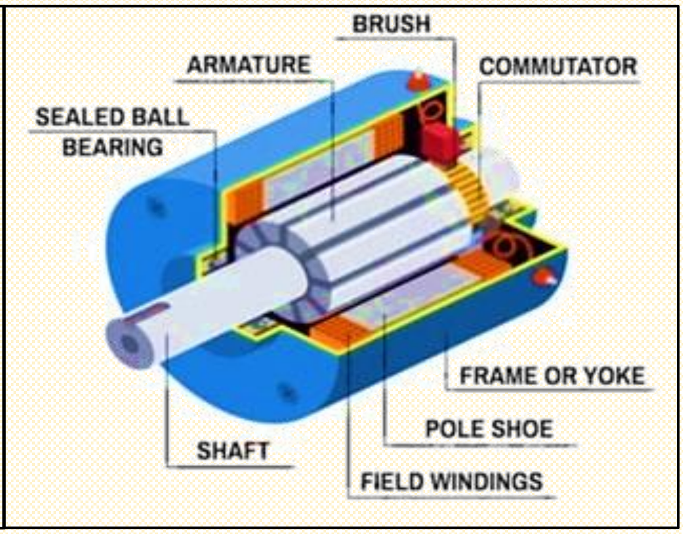
2.3. Construction of DC Generator

All d.c. machines have six principal components viz..

- i. Yoke
- ii. Field Poles (Pole shoe & Pole Core)
- iii. Field winding
- iv. Armature core & Armature winding
- v. Commutator
- vi. Brushes

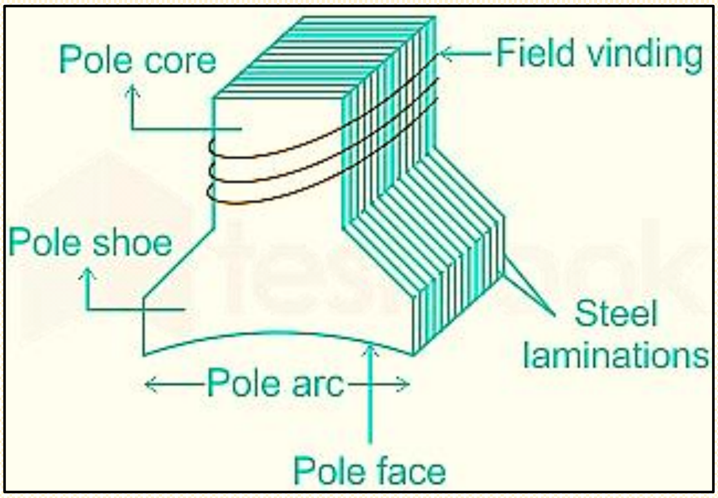
(i–iii: Field system)





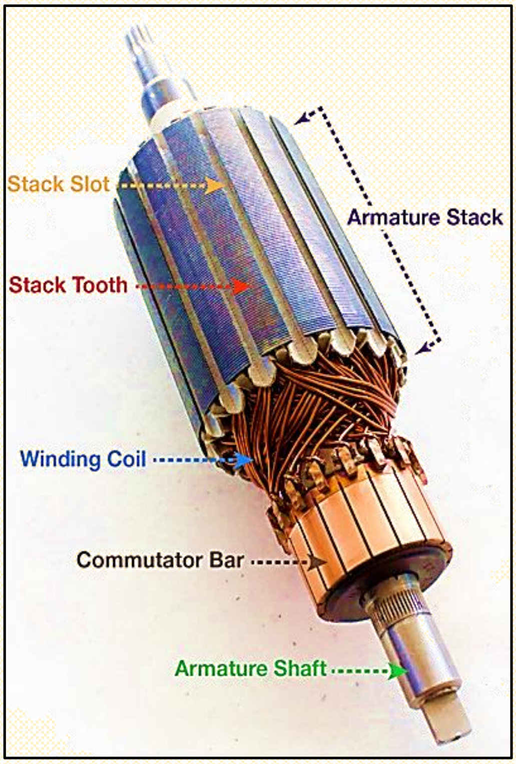
2.3.1. Field system

- Consists of a number of salient poles (of course, even number)
- The yoke is made up of cast iron or steel
- Field coils are mounted on the poles and carry the d.c. exciting current
- The air gaps ranging from 0.5 mm to 1.5 mm.
- *Yoke of DC generator serves two purposes*; It holds the magnetic pole cores of the generator and acts as cover of the generator. It carries the magnetic field flux.



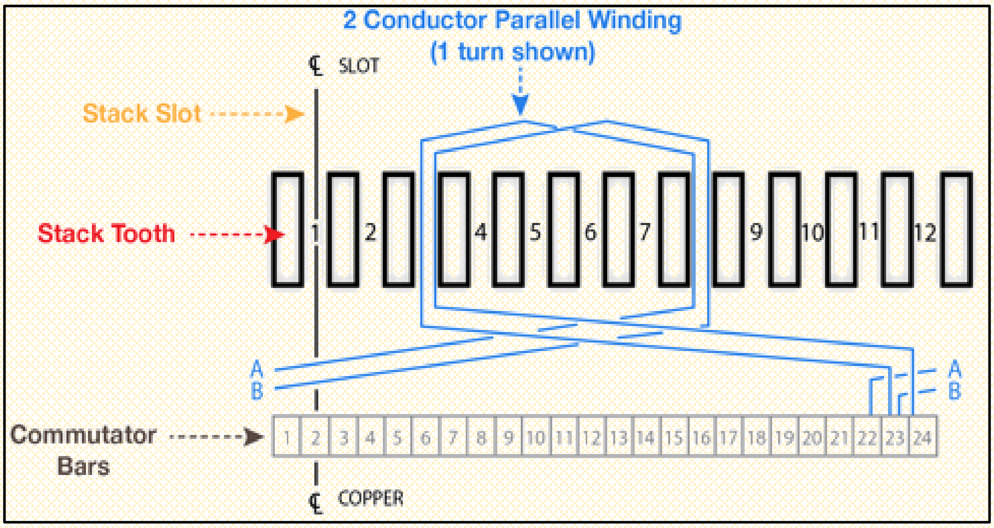
2.3.2. Armature core

- Armature core is the rotor of a dc machine
- It is cylindrical in shape with slots to carry armature winding.
- Built up of thin laminated circular steel disks for reducing eddy current losses.



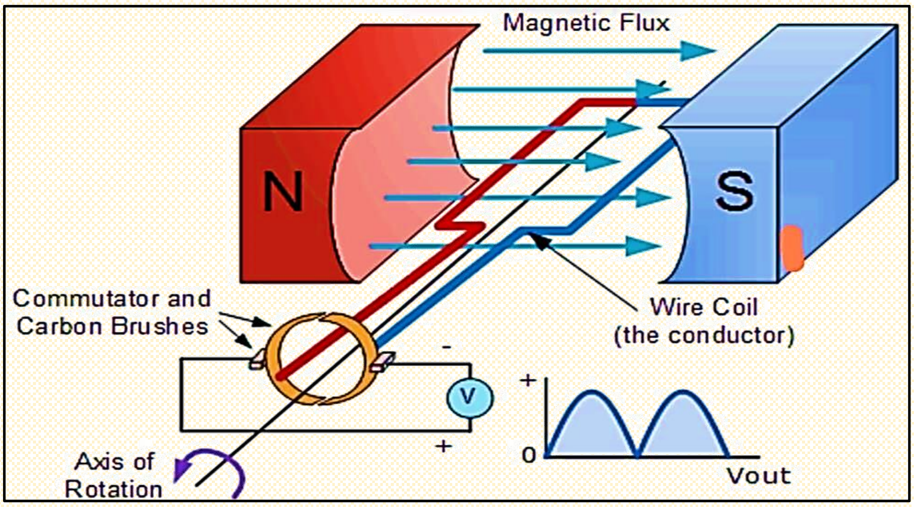
2.3.3. Armature winding:

- Usually a former wound copper coil rests in armature slots.
- The armature conductors are insulated from each other and from the armature core.
- One of the two methods; lap winding or wave winding can wind armature winding.



2.3.4. Commutator

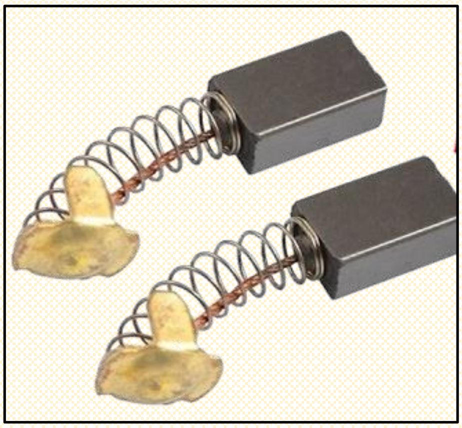
- A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes
- Physical connection to the armature winding made through a commutator-brush arrangement.
- The function of a commutator, is to collect the current generated in armature conductors.
- A commutator consists of a set of copper segments which are insulated from each other.
- The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil



- *No. of commutator segments = No. of slots = No. of coils*

2.3.5. Brushes

- Usually made from carbon or graphite.
- They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

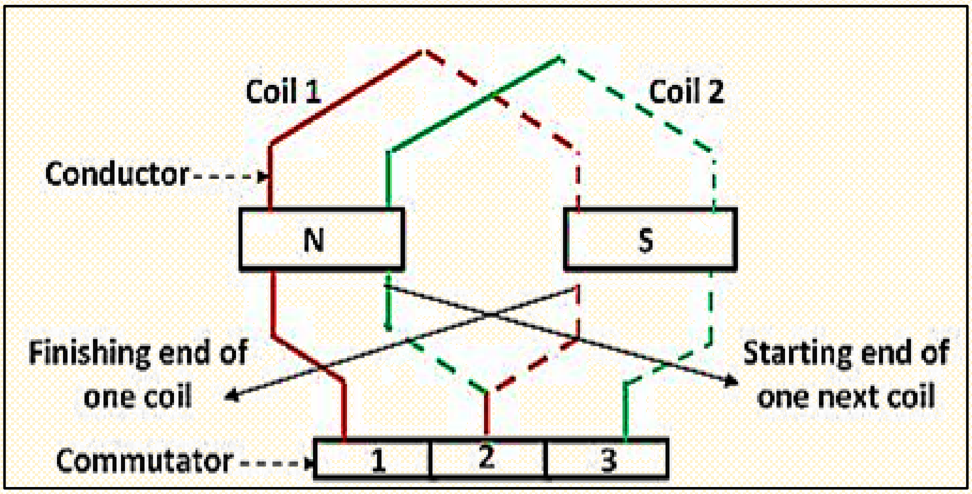


2.4. Types of D.C. Armature Windings

Two basic methods of making back connection and front connection (must be connected in series) end connections are:

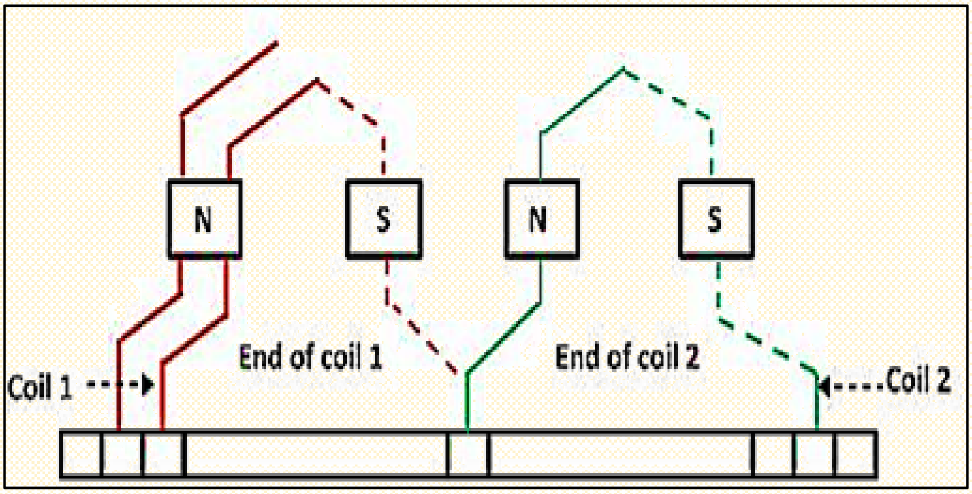
2.4.1. Lap Winding (Parallel) Winding

- In lap winding, the consecutive coils overlap each other.
- The conductors are connected in such a way that the number of parallel paths equals to the number of poles
- 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.



2.4.2. Wave Winding (Series Winding):

- The one end of the coil is connected to the starting end of the other coil.
- The coils are connected in the wave shape and hence it is called the wave winding.
- The conductor of the wave winding are 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.



LAP WINDING	WAVE WINDING
The number of parallel path in lap winding is equal to the number of poles.	The number of parallel path is always equal to 2.
The number of carbon brush in lap winding is equal to the number of poles.	The number of carbon brush in wave winding is 2.
Lap winding are used for low voltage and high current rating machines.	Wave connected winding is required for high voltage but low current rating machines
emf generated in lap winding is independent of number of poles.	the emf generated depends on the number of poles.
It is more costly due to requirement of equalizer ring and more carbon brushes.	It is comparatively cheap.

Note: In general, a high-current armature is lap-wound to provide a large number of parallel paths and a low-current armature is wave-wound to provide a small number of parallel paths.

2.5. Armature Resistance (Ra)

- The resistance offered by the armature circuit is known as armature resistance (Ra) and includes: (i) Resistance of armature winding (ii) Resistance of brushes
- The armature resistance depends upon the construction of machine. Except for small machines, its value is generally less than 1Ω. The armature resistance can be found as under:

Let ℓ = length of each conductor,

a = cross-sectional area

A = number of parallel paths = P (for simplex lap winding),

A=2 (for wave winding)

Z = number of armature conductors

P = number of poles

$$R_a = \frac{P * l * Z}{a * A^2}$$

2.6. EMF Equation For DC Generator

Let us suppose there are Z total numbers of conductor in a generator, and arranged in such a manner that all parallel paths are always in series.

$$E_g = \Phi Z \frac{N}{60} * \frac{P}{A}$$

Φ = Flux produced by each pole in Weber (wb) and

P = number of poles in the DC generator.

N = speed of the armature conductor in rpm.

Z/A = number of conductors connected in series

2.7. Solved Example

E.1. A6 pole lap wound DC generator has 720 conductors and a flux of 80 mili Weber per pole is driven at 1000 RPM. Find the generated EMF?

Solution:

P=6 , A=P=6 (Lap wound generator) , Z= 720 , φ = 80 mWb =0.080 Wb

N=1000rpm

$$E_g = \Phi Z \frac{N}{60} * \frac{P}{A} = 0.08 * 720 * \frac{1000}{60} * \frac{6}{6} = 960 \text{ V}$$

E.2. A 4 pole DC generator has 51 slots and each contains 20 conductors. Flux per pole is 7 mili Weber and runs at 1500 RPM. Find the produced EMF of the machine if its armature is wave wounded.

Solution:

P= 4 , φ = 0.007 Weber's , N= 1500 rpm , A=2 (wave windings)

Armature core slots are = 51

No. of conductors in one slot = 20

Total no. of conductors (Z) = 51*20 =1020

$$E_g = \Phi Z \frac{N}{60} * \frac{P}{A} = 0.007 * 1020 * \frac{1500}{60} * \frac{4}{2} = 357 \text{ V}$$

E.3. A 6 pole machine has an armature with 90 slots and 8 conductors per slot and runs at 1000 RPM. Flux per pole is 0.05wb. Determine the Induced EMF if winding is lap and wave.

Solution:

P =6

No. of slots=90 Conductors per slot =8

Total no. Of conductors(Z) =90*8=720

N=1000rpm

φ = 0.05 wb

i) LAP winding (A=P) Eg= (φ ZN/60) (P/A) = 600V

ii) WAVE winding (A=2) Eg= (φ ZN/60) (P/A) =1800V

2.8. Tutorial Problems

P.1. A lap wound DC shunt generator having 80 slots with 10 conductors per slot generates no load EMF of 400 V when running at 1000 RPM. At what speed should It be rotated to generate a voltage of 220 V on open circuit. [N=550 r.p.m]

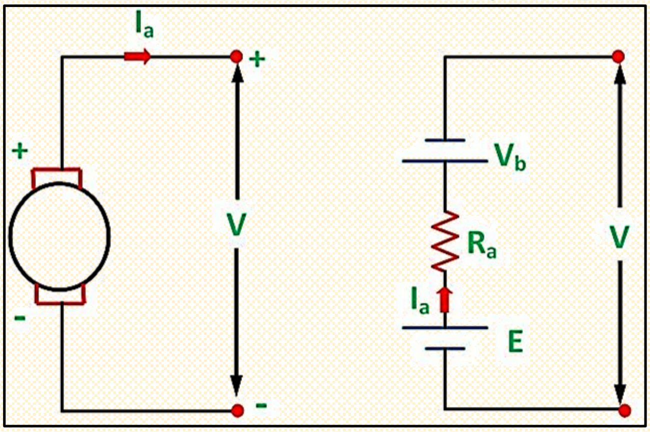
P.2. An 8 Pole DC generator has 500 armature conductors and has a useful flux per Pole of 0.065 wb. What will be the EMF generated if it is lap connected and runs at 1000 RPM. What must be the speed at which it is to be driven to produce the same EMF if it is wave wound? [Eg=541.67 V , N=250 r.p.m]

P.3. A four pole generator having wave-wound armature winding has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the machine when driven at 1500 rpm assuming the flux per pole to be 7.0 mWb ? [Eg=178.5 V]

3. Types of DC generators

Equivalent Circuit Of A DC Machine Armature

- The armature of a DC generator can be represented by an equivalent electrical circuit. It can be represented by three series-connected elements E, R_a and V_b.
- The element E in the equivalent circuit diagrams is the generated voltage, R_a is the armature resistance, and V_b is the brush contact voltage drop.

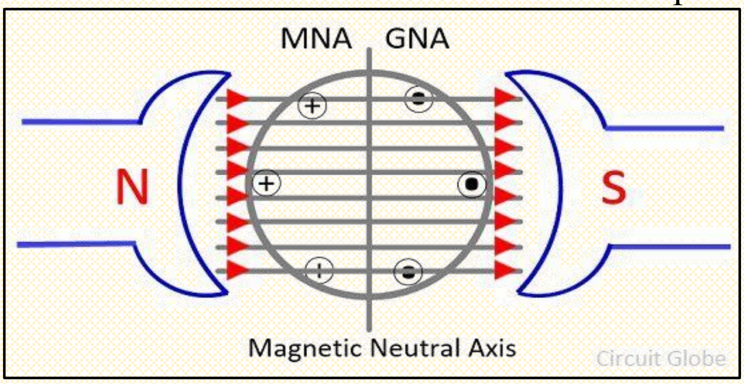


Armature Reaction

The armature reaction simply shows the effect of armature field on the main field. In other words, the armature reaction represents the impact of the armature flux on the main field flux. The armature field is produced by the armature conductors when current flows through them. And the main field is produced by the magnetic poles.

- The armature flux causes two effects on the main field flux.
- The armature reaction distorted the main field flux.
- It reduces the magnitude of the main field flux.

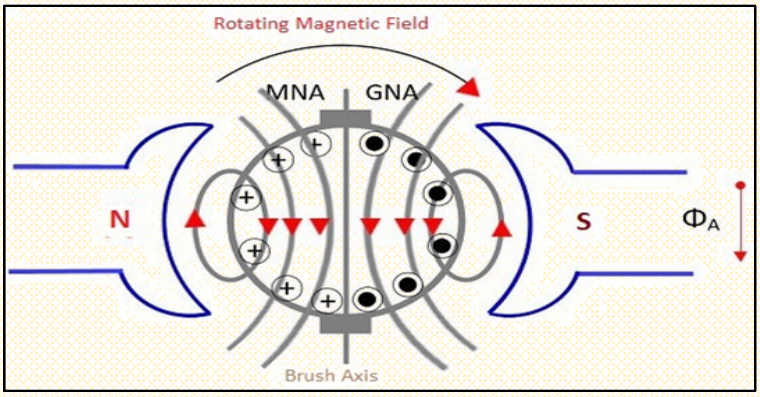
Consider the figure below shows the two poles dc generator. When no load connected to the generator, the armature current becomes zero. In this condition, only the MMF of the main poles exists in the generator. The MMF flux is uniformly distributed along the magnetic axis. The magnetic axis means the center line between the north and south pole. The arrow in the below-given image shows the direction of the magnetic flux ΦM. The magnetic neutral axis or plane is perpendicular to the axis of the magnetic flux.



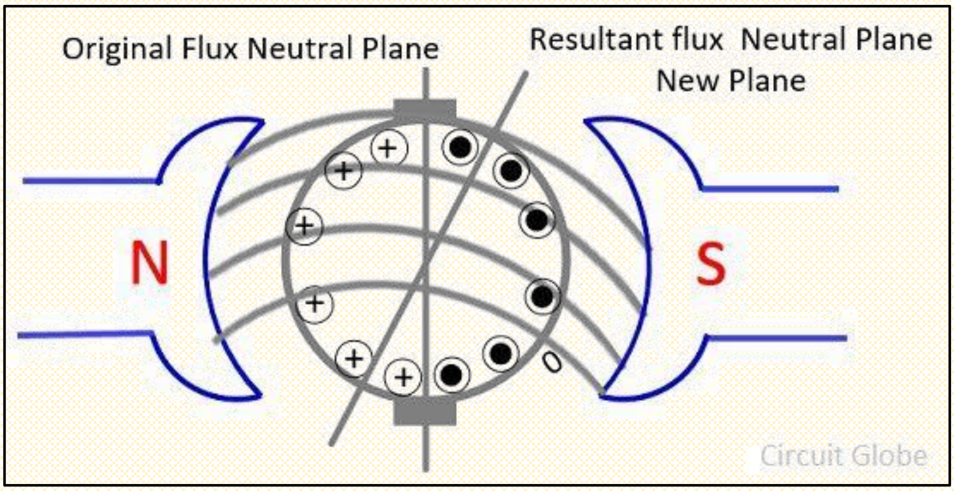
The MNA coincides with the geometrical neutral axis (GNA). The brushes of the DC machines are always placed in this axis, and hence this axis is called the axis of commutation.

Consider the condition in which only the armature conductors carrying current and no current flows through their main poles. The direction of the current remains the same in all the conductors lying under one pole. The direction of current induces in the conductor is given by the Fleming right-hand rule. And the direction of flux generates in the conductors is given by the corkscrew rule.The direction of current on the left sides of the armature conductor goes into the paper (represented by the cross inside the circle). The armature conductors combine their MMF for generating the fluxes through the armature in the downward direction.

Similarly, the right-hand side conductors carry current, and their direction goes out of the paper (shown by dots inside the circle). The conductor on the right-hand sides is also combining their MMF for producing the flux in the downwards direction. Hence, the conductor on both sides combines their MMF in such a way so that their flux goes downward direction. The flux induces in the armature conductor ΦA is given by the arrow shown behind.



The figure below shows the condition in which the field current and the armature current are simultaneously acting on the conductor.



The effects of Armature Reaction are as follows-:

- Because of the armature reaction the flux density of over one-half of the pole increases and over the other half decreases. The total flux produces by each pole is slightly less due to which the magnitude of the terminal voltage reduces. The effect due to which the armature reaction reduces the total flux is known as the demagnetizing effect.
- The resultant flux is distorted. The direction of the magnetic neutral axis is shifted with the direction of resultant flux in the case of the generator, and it is opposite to the direction of the resultant flux in the case of the motor.

Excitation System

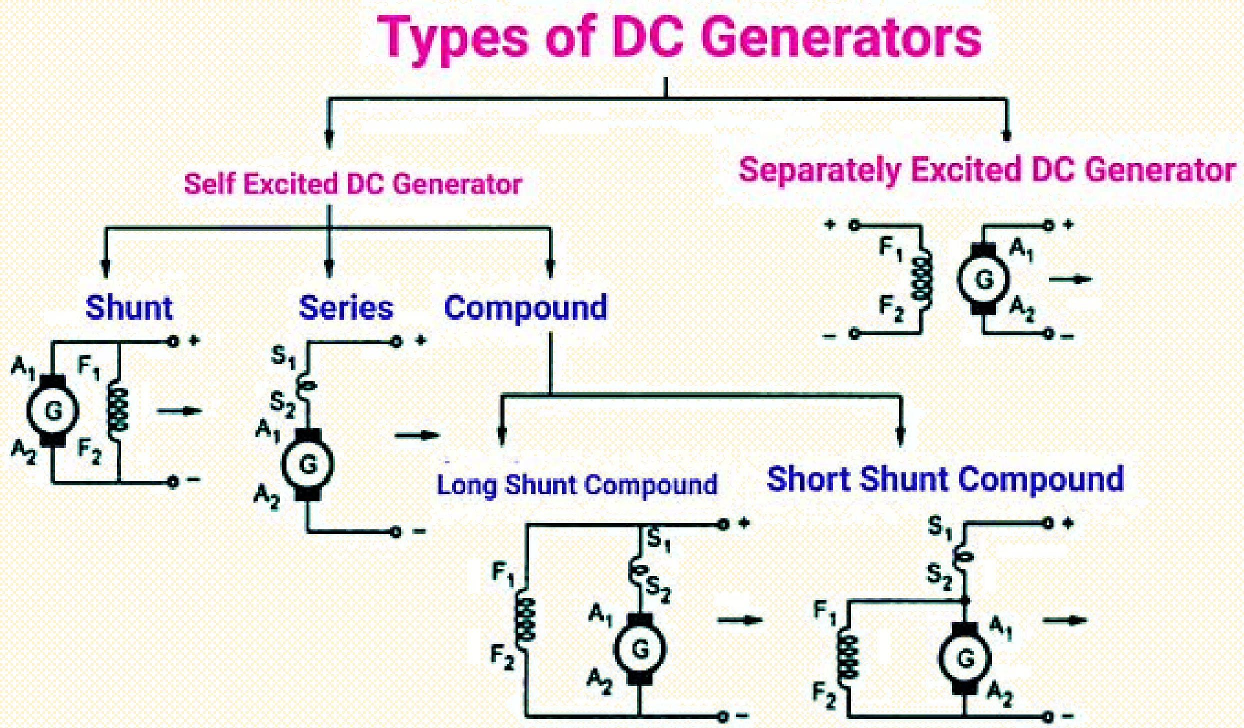
- Defined as the System which is used for the production of the flux by passing current in the field winding.
- The amount of excitation required depends on the load current, load power factor and speed of the machine.
- The magnetic field required for the operation of a d.c. generator is produced by an electromagnet.
- This electromagnet carries a field winding which produces required magnetic flux when current is passed through it.
- The field winding is also called exiting winding and current carried by the field winding is called an exciting current.

Methods of excitation

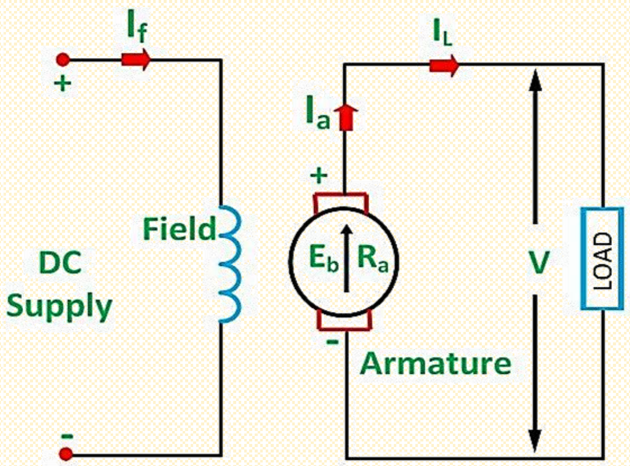
Depending on the methods of excitation used, the d.c. generators are classified as,

1. Separately excited generator
2. Self excited generator

Thus supplying current to the field winding is called excitation and the way of supplying the exciting current is called method of excitation.



3.1. Separately Excited Generator:



- A field winding or coil is energized by a separate or external dc source.
- $I_a = I_L$

  I_a : armature current

  I_L : line current.
- Terminal voltage is given as :

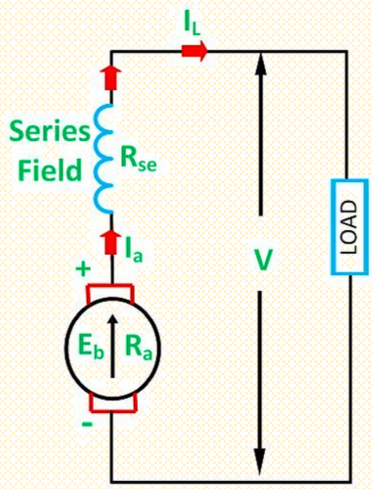
  $V = E_g - I_a R_a$
- If the contact brush drop is known, then:

  $V = E_g - I_a R_a - 2V_b$
- *Power developed* $= E_g I_a$
- *Power output* $= V I_L = V I_a$

3.2. Self-Excited Generator

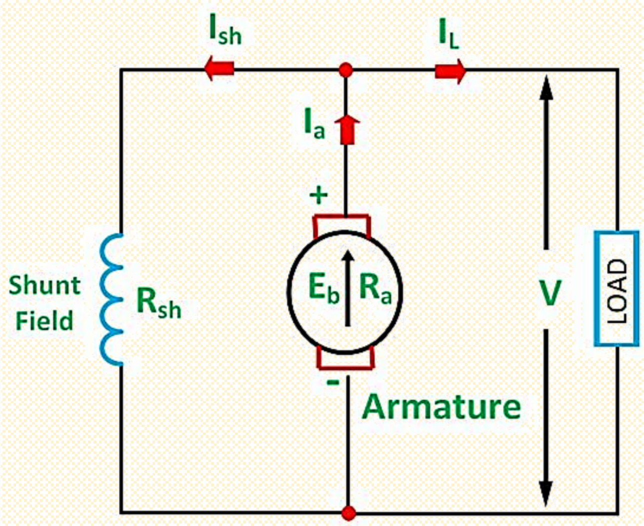
A d.c. generators are normally of self-excited type, whose field magnet winding is supplied current from the output of the generator itself. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

3.2.1. Series Excited Generator



- The field winding and armature winding is connected in series.
- This is different from shunt motor due to field winding is directly connected to the electric applications (load).
- Therefore, field winding conductor must be sized enough to carry the load current consumption and the basic circuit as illustrated below.
- $I_a = I_L = I_{se}$;
- $V_t = V = E_g - I_a.R_a - 2V_b$
- ***Power output*** $= V I_a = V I_L$

3.2.2.Shunt Excited Generator

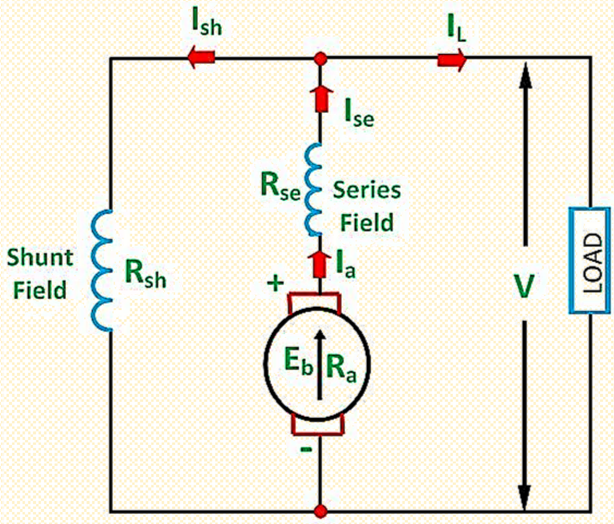


- The field winding is connected in parallel with the armature winding, so that terminal voltage of the generator is applied across it.
- Shunt field current, $I_{sh} = V/R_{sh}$
- Armature current, $I_a = I_L + I_{sh}$
- Terminal voltage, $V = E_g - I_a R_a$
- ***Power developed in armature*** $= E_g I_a$
- ***Power delivered to load*** $= V I_L$

3.2.3. Compound Generator

- The generator, which has both shunt and a series field.
- It is connected in two ways. One is a long shunt compound generator, and another is a short shunt compound generator.

3.2.3.1. Long Shunt Compound Wound Generator



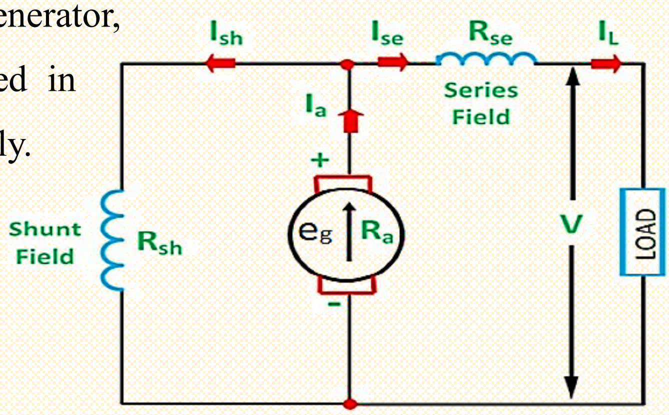
- The shunt field winding is parallel with both armature and series field winding.
- The shunt field current is: $I_{sh} = V/R_{sh}$

  Series field current is: $I_{se}= I_a=I_L+I_{sh}$
- Terminal voltage is :

  $$V=E_g-I_a R_a - I_{se} R_{se} = E_g - I (R_a+R_{se})$$
- If the brush contact drop is included, the terminal voltage equation is

  $$V=E_g - I(R_a+R_{se})-2V_b$$
- ***Power developed in armature*** $=E_g I_a$
- ***Power delivered to load*** $=VI_L$

3.2.3.2. Short Shunt Compound Wound Generator



- In a Short Shunt Compound Wound Generator, the shunt field winding is connected in parallel with the armature winding only.
- The shunt field current is given as

  $$I_{sh}= (V+I_L R_{se})/ R_{sh} = (E_g-I_a R_a)/R_{sh}$$
- Armature current; $I_a= I_L + I_{sh}$
- Series field current: $I_{se}= I_L$
- Terminal voltage $V=E_g-I_a R_a - I_L R_{se}$
- If the brush contact drop is included: $V=E_g- I R_a - I_L R_{se} -2V_b$
- ***Power developed in armature*** $=E_g I_a$
- ***Power delivered to load*** $=VI_L$

3.3. Solved Example Problems:

E.1. A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50 Ω and 0.03 Ω respectively. Calculate the generated e.m.f?

Solution: I_{sh} =230/50 =4.6 A , I_L =450A

Armature current I_a=I + I_{sh} =450+4.6

=454.6 A

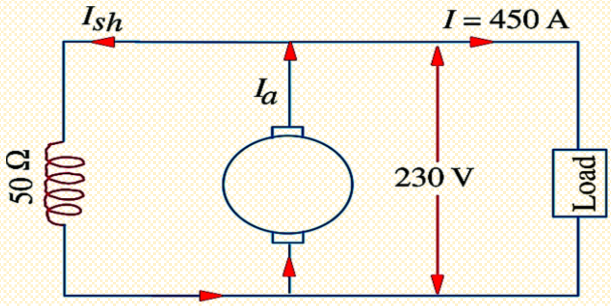
Armature voltage drop = I_a*R_a

=454.6*0.03

=13.6V

Generated EMF , Eg =V + Ia*Ra

=230 +13.6 =243.6V



E.2. A 4 Pole lap connected shunt generator has 300 armature conductors and a flux/pole of 0.1 Wb. It runs at 1000 rpm. The armature and field resistances are 0.2Ω and 125 Ω respectively. Calculate the terminal voltage when it is loaded to take a load current of 90A.

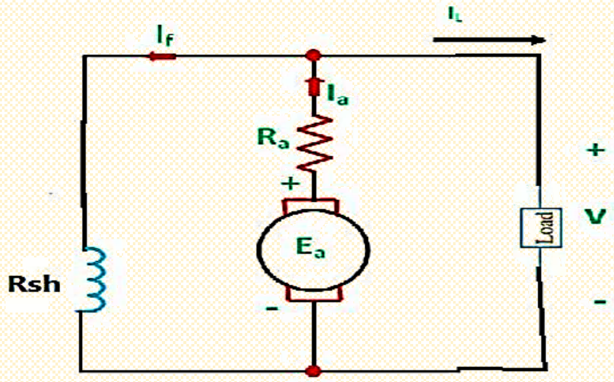
Solution: P=4, Z=300, φ=0.1 Wb, N=1000 rpm ; R_a=0.2Ω , R_{sh}=125Ω , I_L=90A

$$E_g = \Phi Z \frac{N}{60} * \frac{P}{A} = 0.1*300\frac{1000}{60}*\frac{4}{4} = 500V$$

$I_{sh} = E_g/R_{sh}$= 500/125 =4A

$I_a=I_{sh}+I_L$ =4+90=94A

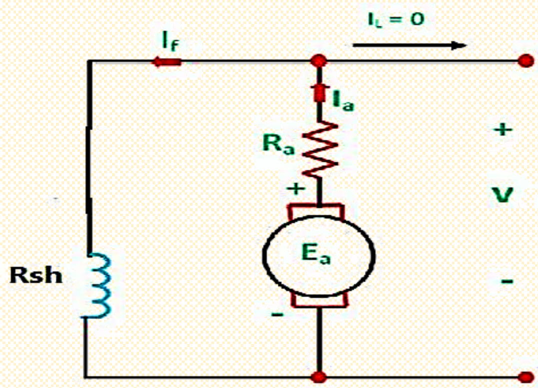
$V=E_g-I_aR_a$ = 500 - (94*0.2) =481.2V



ON LOAD

Ia=If+IL

V=Eg+IaRa =If.Rsh

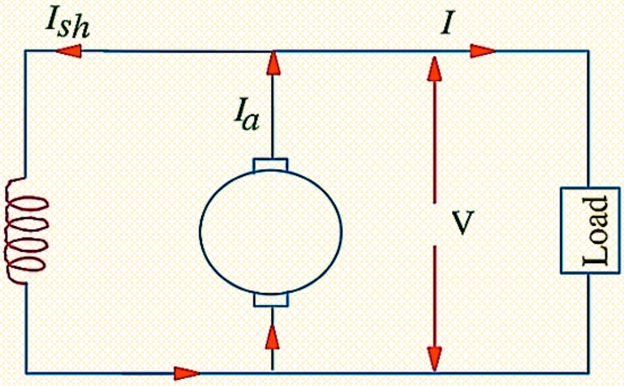


NO LOAD

If=Ia; (If*Ra) Drop neglected

V=Ea=Eg=Eo

E.3. A 30KW,300V Dc shunt generator has armature and field resistances of 0.05 Ω and 100 Ω respectively. Calculate the total power developed in the armature when it delivers full load.



Solution:

Power Output (P) =30KW

Terminal voltage V=300 volts

Ra = 0.05 Ω , R_{Sh}=100 Ω

load current, $I_L = P/V = 30000/300 = 100A$

$I_{sh} = V/R_{sh} = 300/100 = 3A$

$I_a = I_{sh} + I_L = 3 + 100 = 103A$

$V = E_g - I_a R_a \rightarrow E_g = V + I_a R_a = 300 + 103x0.05$

$= 305.15V$

Power at armature = $E_g * I_a = 305.15*103 = 31430.45 = 31.43KW$

3.4. Tutorial Problems

P.1. A DC shunt generator has an induced voltage on open circuit of 127V.When the machine is on load, the terminal voltage is 120V. Find the load current if the field circuit resistance is 15Ω and the armature resistance is 0.02Ω

P.2. A 4 pole dc shunt generator with lap connected armature has field and armature resistances of 50 Ω and 0.1 Ω respectively. It supplies power to sixty numbers of 100V, 40W lamps. Calculate the armature current and the generated emf. Allow a contact drop of 1V/brush and interpole and compensating winding drops of 1V/pole and 0.25V/pole respectively.

P.3. A short shunt compound wound dc generator delivers 100A to a load at 250V. The generator has shunt field, series field and armature resistances of 130Ω,0.1 Ω and 0.1 Ω respectively. Calculate the voltage generated in the armature winding. Assume 1V voltage drop per brush.

4. Characteristics and Losses of DC Machine

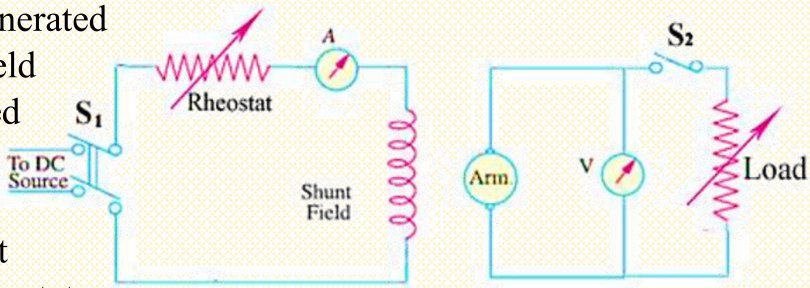
4.1. Characteristics of DC Machine

1. Open Circuit Characteristic (O.C.C.) (E_o/I_f): also known as magnetic characteristic or no-load saturation curve, This curve shows the relation between the generated e.m.f. at no-load (Eo) and the field current (If) at constant speed.
   Note: Its shape is practically the same for all generators whether separately-excited or self-excited.
2. Internal or Total characteristic (E_g/I_a): This curve shows the relation between the generated e.m.f. on load (Eg) and the armature current (Ia), The e.m.f. Eg is less than E_0 due to the armature reaction. Therefore, this curve will lie below the open circuit characteristic (O.C.C.).
3. External characteristic (V_t/I_L): This curve shows the relation between the terminal voltage (V or Vt) and load current (I_L). The terminal voltage V < Eg due to voltage drop in the armature circuit. Therefore, this curve will lie below the internal characteristic

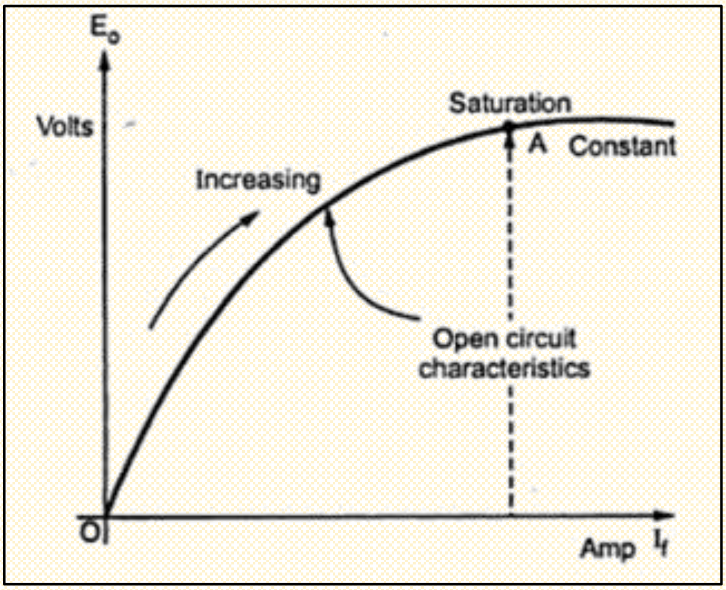
4.2. Characteristic of Separately Excited DC Generator

4.2.1. Open Circuit Characteristic of Separately Excited DC Generator

1. We can see the variation of generated emf on no load with field current for different fixed speeds of the armature.
2. In this curve speed is constant and the field current controlled by an external Rheostat connected in a series with field coil as shown in figure behind



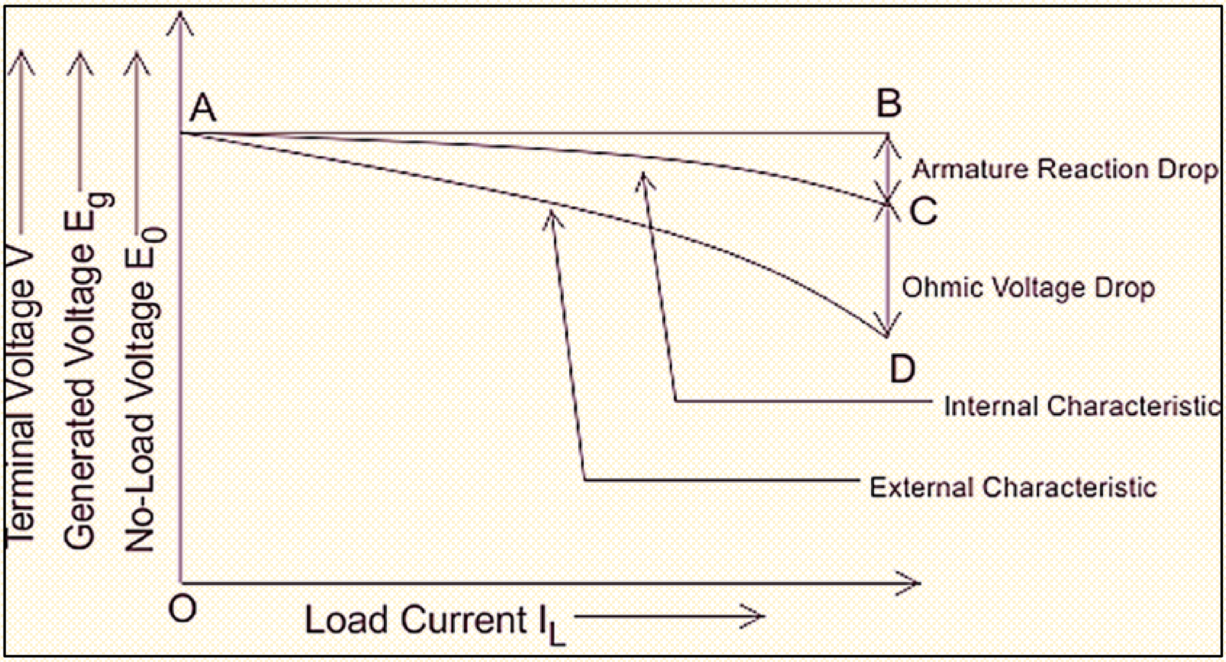
It is obvious that when (I_f) is increased from its initial small value, the flux Φ and hence generated e.m.f. E_g increase directly as current so long as the poles are unsaturated. Until reaching the saturation point, at this point any increasing in field current will not increase in E.



4.2.2. Internal and External Characteristics

i. The internal characteristic of the separately excited DC generator is obtained by subtracting the drops due to armature reaction from no load voltage, This curve of actually generated voltage (Eg) will be slightly dropping. Here, AC line in the diagram indicating the actually generated voltage (Eg) with respect to load current.

ii. The external characteristic of the separately excited DC generator is obtained by subtracting the drops due to ohmic loss (Ia Ra) in the armature from generated voltage (Eg). Terminal voltage(V) = Eg – Ia Ra, This curve gives the relation between the terminal voltage (V) and load current. The external characteristic curve lies below the internal characteristic curve.



Conclusion: It can operate in stable condition with any field excitation and gives wide range of output voltage. The main disadvantage of these kinds of generators is that it is very expensive of providing a separate excitation source.

4.3. Characteristics of a Self-excited Generator

It is the most commonly used and prevalent DC generator due to its need for an external source to supply excitation current, as well as providing stable voltage under normal loads.

But there are conditions for building voltage in this type, which are as follows

1. Residual magnetism: There must be residual magnetism remaining in the main poles with a value of (2-3)% of the rated flux.
2. The field resistance (R_f) must be less than the critical resistance (R_c), where the critical resistance is defined as the total field circuit resistance, which if exceeded by the field resistance, voltage build-up process does not occur.
3. The generator speed must be higher than the critical speed, which is the speed below which the generator speed, if decreased, will prevent the voltage build-up process.
4. The direction of rotation of the generator must be in the direction that assists residual magnetism and not counteract it.

If the speed or the excitation current or the voltage in the generator changes, the following law can be used to find the new voltage, speed, or excitation current.

$$\frac{N_2}{N_1} = \frac{E_2}{E_1}\frac{I_{f1}}{I_{f2}}$$

E.1. DC gen. has EMF=100 v when the speed N=1000 r.p.m, whats the speed when the EMF increase to 250 v, if no variation in field current

Solution:

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

$$\frac{N_2}{1000} = \frac{250}{100}$$

$$N_2 = 2500\, r.p.m$$

In above if the field current increased 50% from the first field current then,

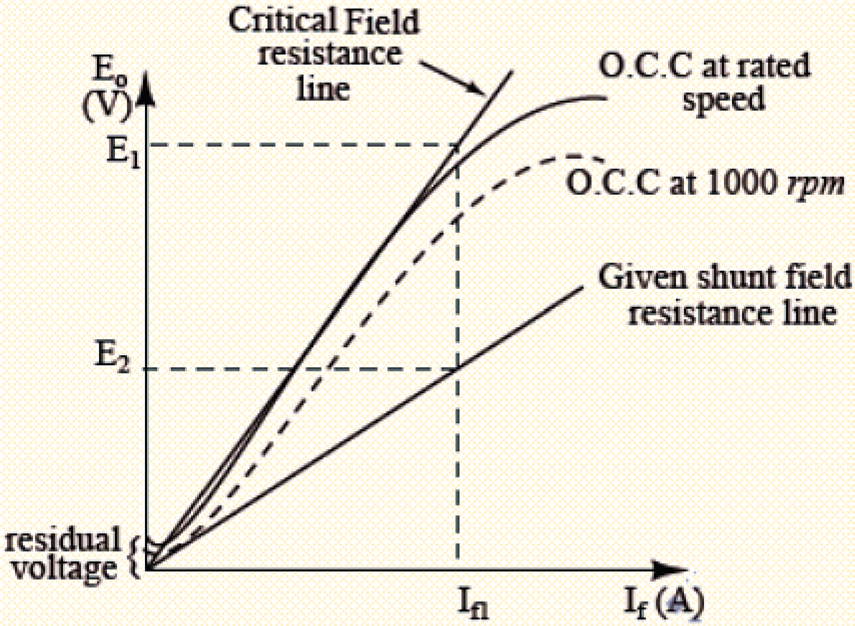
$$\frac{N_2}{N_1} = \frac{E_2}{E_1}\frac{I_{f1}}{I_{f2}}$$

$$\frac{N_2}{1000} = \frac{250}{100} * \frac{I_{f1}}{1.5 I_{f1}}$$

$$N_2 = 1666\, r.p.m$$

4.4. Critical Field Resistance And Critical Speed

- The critical field resistance is 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. Critical field resistance line is a tangent to the open circuit characteristics of the generator at a given speed**.**
- 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
- ***Critical Resistance***- The resistance of the field winding above which the generator doesn't build up voltage.
- ***Critical Speed***- The speed of generator below which the generator doesn't build up the voltage.



$$R_c = E_1 / I_{f1}$$

$$N_c = (E_2 / E_1)\, N_1$$

E.2. The magnetization curve of a d.c. shunt generator at 1500 r.p.m. is.

I_f (A)	0	0.4	0.8	1.2	1.6	2	2.4	2.8	3
E_0 (v)	0	60	120	172.5	202.5	221	231	237	240

For this generator find (i) no load e.m.f. for a total shunt field resistance of 100 Ω (ii) the critical field resistance at 1500 r.p.m. and (iii) the magnetization curve at 1200 r.p.m. and therefrom the open-circuit voltage for a field resistance of 100 Ω

Solution:

N_1=1500 rpm (Curve I)

N_2=1200 rpm (Curve II)

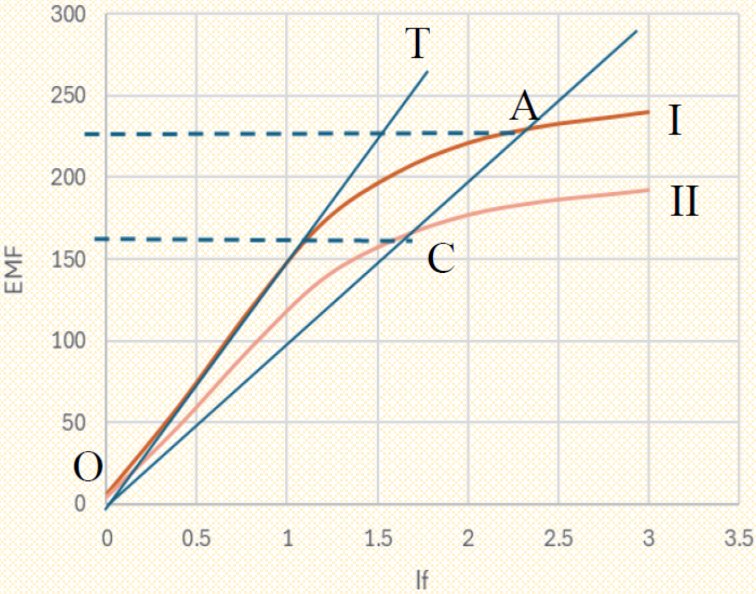
Point A (EMF , If) at full load

i. From figure Emf = 227.5 V

ii. Rc = 225/1.5=150 Ω at 1500 rpm

iii. N_2/N_1=1200/1500=**0 .8**

The values of these voltages are tabulated below



I_f (A)	0	0.4	0.8	1.2	1.6	2	2.4	2.8	3
E_0 (v)	4.8	48	96	138	162	176.8	184.8	189.6	192

Then emf = 166 V at R_f=100 Ω

Problem: The open-circuit characteristic of a separately-excited d.c. generator driven at 1000 r.p.m. is as follows :

I_f (A)	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
E_0 (v)	30	55	75	90	100	110	115	120

If the machine is connected as shunt generator and driven at 1,000 r.p.m. and has a field resistance of 100 Ω, find

(a) open-circuit voltage and exciting current

(b) the critical resistance and

(c) resistance to induce 115 volts on open circuit.

4.3.1. Characteristics of Series Generator

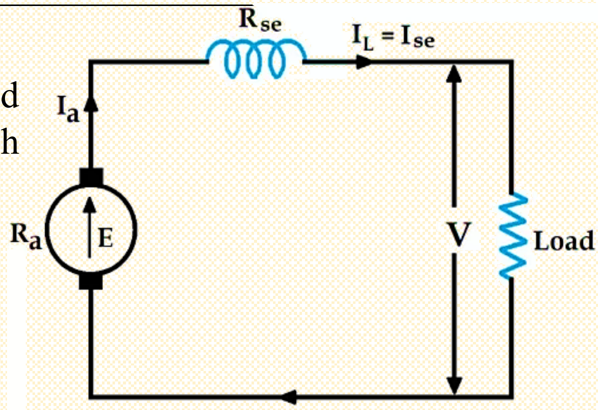


Fig. shows the connections of a series wound generator. Since there is only one current (that which flows through the whole machine), the load current is the same as the exciting current.

i. O.C.C.

Curve 1 shows the open circuit characteristic (O.C.C.) of a series generator. It can be obtained experimentally by disconnecting the field winding from the machine and exciting it from a separate d.c. source

ii. Internal characteristic

Curve 2 shows the total or internal characteristic of a series generator. It gives the relation between the generated e.m.f. E. on load and armature current. Due to armature reaction, the flux in the machine will be less than the flux at no load.

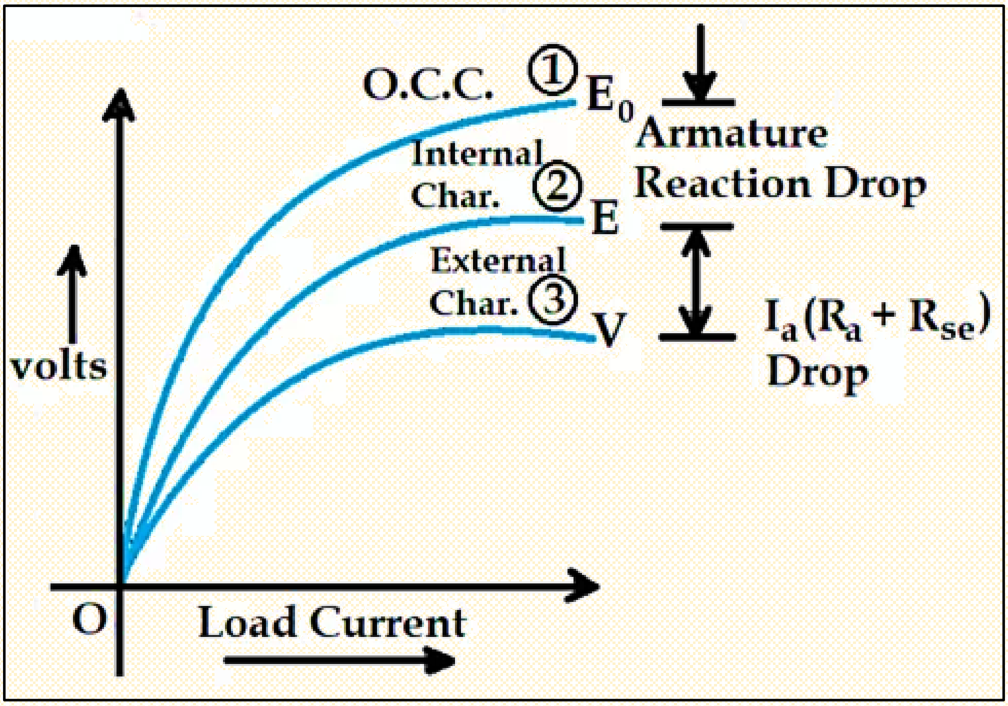
Hence, e.m.f. E generated under load conditions will be less than the e.m.f. E_0 generated under no load conditions. Consequently, internal characteristic curve lies below the O.C.C. curve; the difference between them representing the effect of armature reaction.

iii. External characteristic

Curve 3 shows the external characteristic of a series generator. It gives the relation between terminal voltage and load current I_L.:

$$V = E - Ia\ (Ra + Rse\ )$$

Therefore, external characteristic curve will lie below internal characteristic curve by an amount equal to ohmic drop [i.e., Ia(Ra + Rse)] in the machine as shown in Fig. above



4.3.2. Characteristics of a Shunt Generator

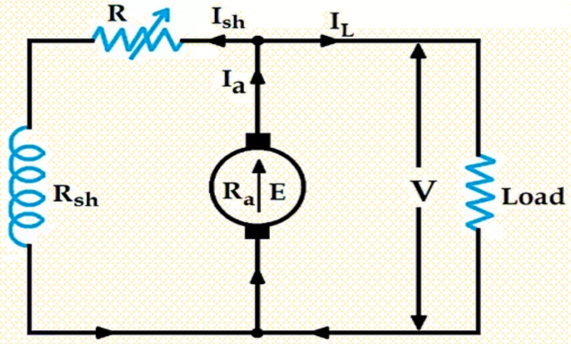


Fig. shows the connections of a shunt wound generator. The armature current Ia splits up into two parts; a small fraction Ish flowing through shunt field winding while the major part IL goes to the external load.

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. 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/Ia) drops down slightly as shown in Fig.

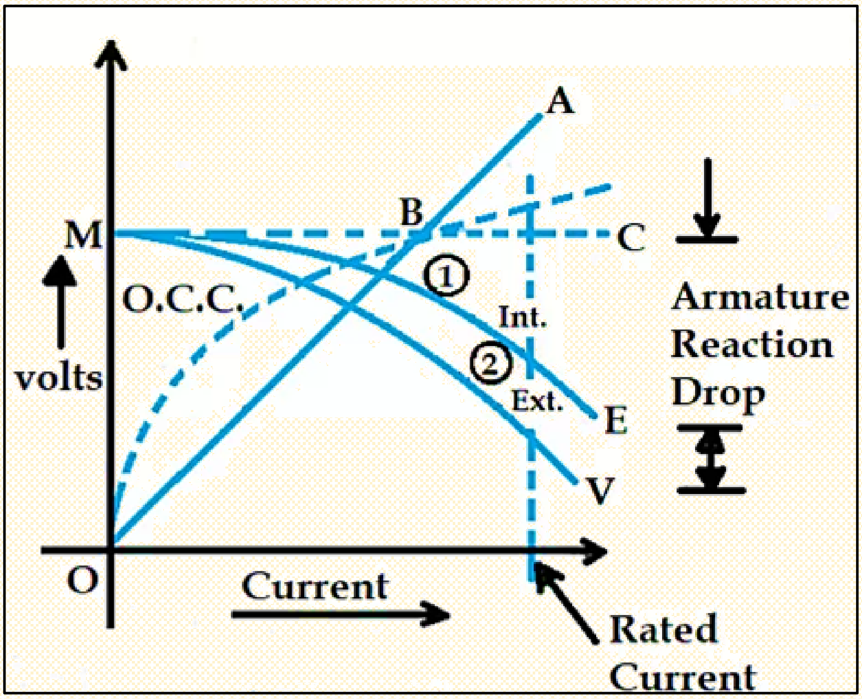
iii. *External characteristic*

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

$$V = E - IaRa = E - (I_L + I_{sh})\ Ra$$

Therefore, external characteristic curve will lie below the internal characteristic curve by an amount equal to drop in the armature circuit [i.e., (IL + Ish)Ra] as shown in Fig.

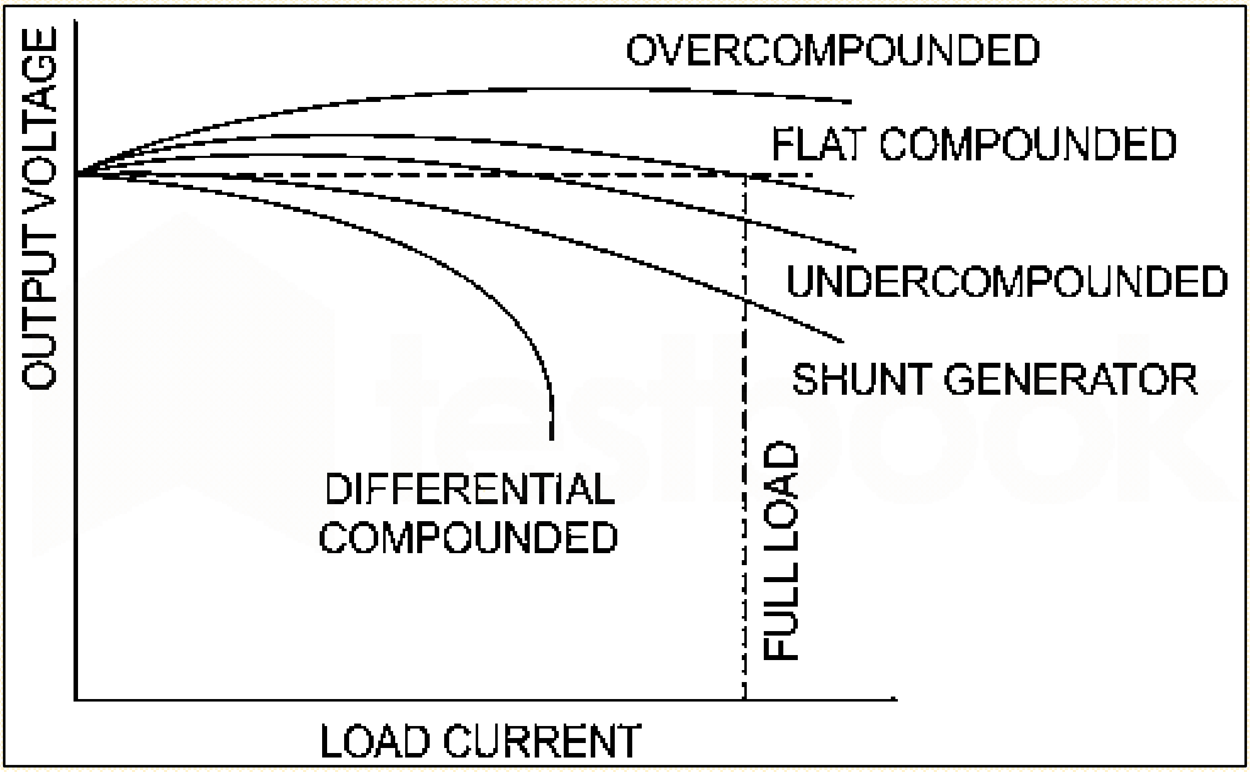
Note. It may be seen from the external characteristic that change in terminal voltage from no-load to full load is small. The terminal voltage can always be maintained constant by adjusting the field rheostat R automatically



4.3.3. Compound Generator Characteristics

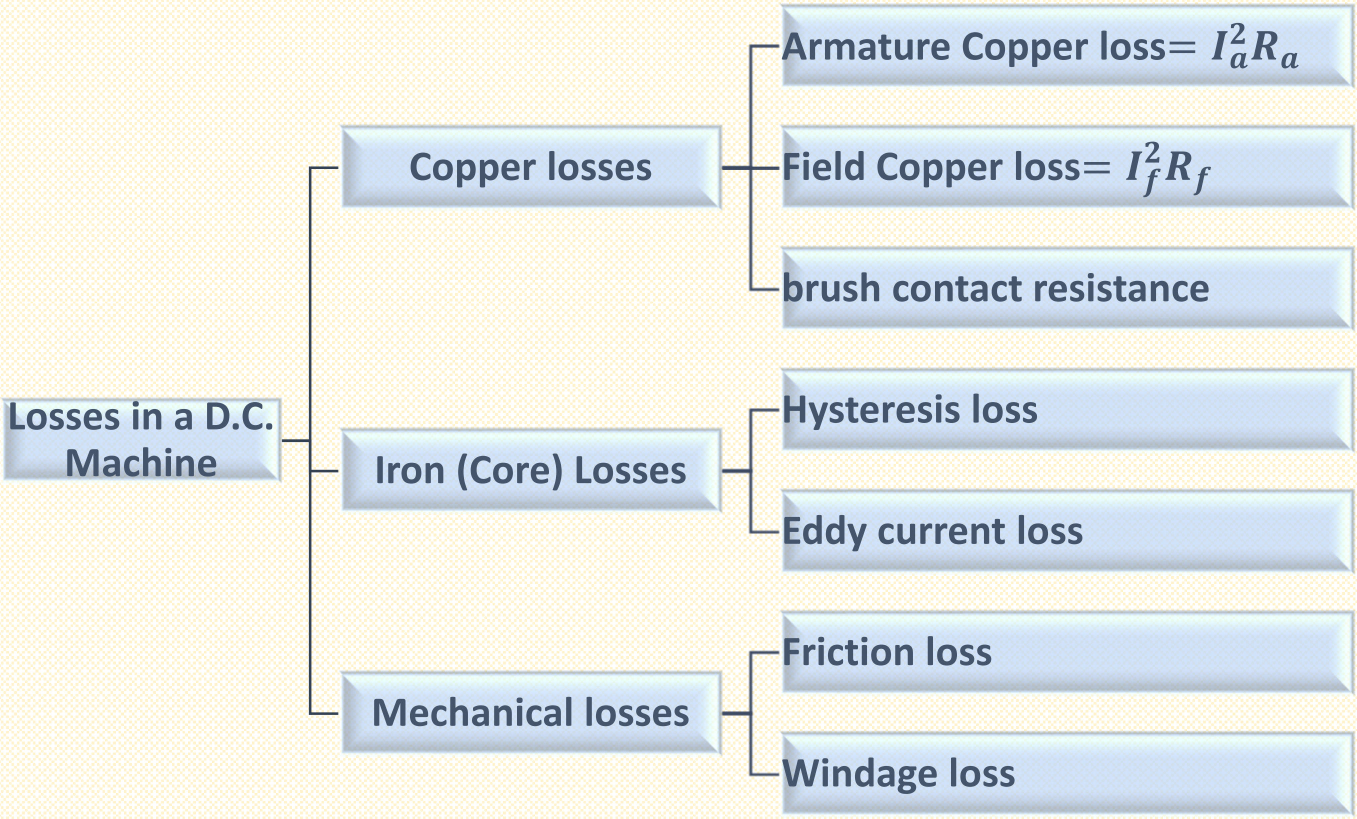
The external characteristic curve of the compound generator, whether long or short-shunt, varies depending on the influence of the series coils relative to the shunt coils. From this perspective, there are three types of compound generators.

1. ***Cumulative compound***: The two winding are usually connected such that their ampere- turns act in the same direction. As such the generator is said to be Cumulative compounded *(used as voltage source of lighting purpose*).
   a. Under-compound: When shunt field excitation is more effective then series field, full load terminal voltage is less than no-load terminal voltage, the generator is said to be under compounded
   b. Flat compound : If the series excitation is increased by increasing the number of a series field turns to rise up terminal voltage when on no-load and full load condition, (terminal voltage is made nearly same value or equal) (Vt=Eo) (*used as exciting field of alternator*)
   c. Over-compound: If the number of series field turns is more than necessary to compensate of the reduced voltage , terminal voltage rises with increase in load and generator is said to be over compounded.
2. ***Differential compound***: If a reversing the polarity of the series field occur this cause to the relation between series field and shunt field, the field will oppose to each other more and more as the load current increase.
   Therefore terminal voltage will drop fastly, such generator is said to be a differentially compound (*used in welding purpose*).



4.5. Losses in a D.C. Machine

In a practical machine, whole of the input power cannot be converted into output power as some power is lost in the conversion process. This causes the efficiency of the machine to be reduced. Efficiency is the ratio of output power to the input power.



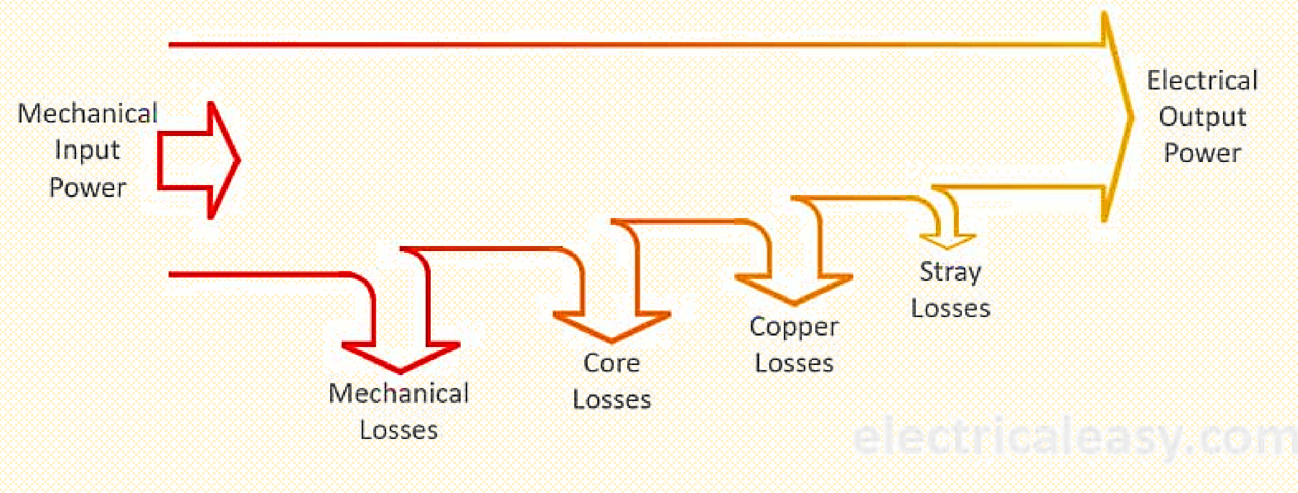
The losses of generators may be classified as:

4.5.1. *Copper losses*: The copper losses are present because of the resistance of the windings. Currents flowing through these windings create ohmic losses. The windings that may be present in addition to the armature winding are the field windings, inter-pole and compensate windings.

4.5.2. *Iron losses:* As the armature rotates in the magnetic field, the iron parts of the armature as well as the conductors cut the magnetic flux. Since iron is a good conductor of electricity, the EMF s induced in the iron parts courses to flow through these parts. These are the eddy currents. Another loss occurring in the iron is due to the Hysteresis loss is present in the armature core.

4.5.3. *Mechanical losses*: Other rotational losses consist of

- ► Bearing Friction Loss
- ► Friction of the Rushes Riding On The Commutator
- ► Windage Losses : are those associated with overcoming air friction in setting up circulation currents of air inside the machine for cooling purposes. These losses are usually very small.



Power flow diagram of a DC generator

The losses in a d.c. generator (or d.c. motor) may be sub-divided into:

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:
- iron losses
- mechanical losses
- 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:
- Copper loss in armature winding
- Copper loss in series field winding

Total losses = Constant losses + Variable losses

4.6. Efficiency of DC Generator

Efficiency is simply defined as the ratio of output power to the input power, In DC generator there are two type of efficiencies

i. Mechanical efficiency

$$\eta_m = \frac{E_g I_a}{Mechanical\ power\ input\ (\text{hp} * 746)}$$

ii. Electrical efficiency

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

iii. Commercial or overall efficiency

$$\eta_c = \frac{output\ P_o}{input\ P_i} = \frac{P_i - losses}{P_i} = \frac{V I_L}{Mechanical\ power\ input}$$

4.7. 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.

Generator output = V I_L

Generator input = Output + Losses

= V I_L + Variable losses + Constant losses

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

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

The shunt field current Ish is generally small as compared to IL and, therefore, can be neglected

$$generator\ input = VI_L + I_L^2 R_a + Wc$$

$$\eta = \frac{output}{input} = \frac{VI_L}{VI_L + I_L^2 R_a + Wc} = \frac{1}{1 + \left(\frac{I_L R_a}{V} + \frac{Wc}{V\,I_L}\right)}$$

The efficiency will be maximum when the denominator of Eq. is minimum i.e.,

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

$$or \quad \frac{R_a}{V} - \frac{Wc}{V\,I_L^2} = 0$$

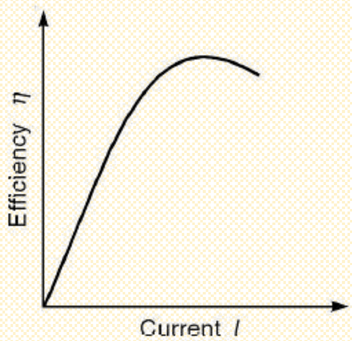
$$or \quad \frac{R_a}{V} = \frac{Wc}{V\,I_L^2}$$

$$or \quad I_L^2 R_a = Wc$$

$i.e.$ Variable loss = Constant loss ($I_L \cong I_a$)
The load current corresponding to maximum efficiency is given by:

$$\boldsymbol{I_L = \sqrt{\frac{Wc}{R_a}}}$$

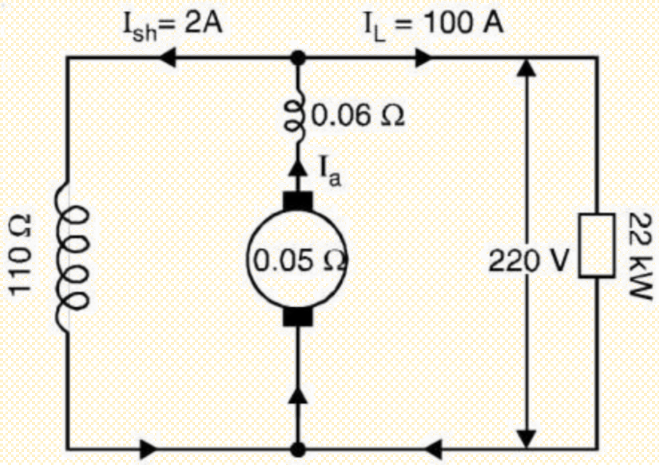
Hence, the efficiency of a d.c. generator will be maximum when the load current is such that variable loss is equal to the constant loss. Fig. shows the variation of h with load current.



E.3. A long-shunt compound generator running at 1000 rpm supplies 22 kW at a terminal voltage of 220 V. The resistances of the armature, shunt field and series field are 0.05Ω, 110Ω and 0.06Ω respectively. The overall efficiency of the above load is 88%. Find: (i) Cu losses (ii)Iron and friction losses

Solution:

$$I_L = \frac{22 * 10^3}{220} = 100\ A\ , I_{sh} = \frac{220}{110} = 2\ A$$



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

$$voltage\ drop\ in\ series\ field\ winding = I_a R_{se} = 102 * 0.06 = 6.12\ v$$

$$i)\ Armature\ Cu\ loss = I_a^2 R_a = (102)^2 * 0.05 = 520.2\ W$$

$$series\ field\ Cu\ loss = I_a^2 R_{se} = (102)^2 * 0.06 = 624.3\ W$$

$$shunt\ field\ Cu\ loss = VI_{sh} = 220 * 2 = 440\ W$$

$$Total\ Cu\ loss = 520.2 + 624.3 + 440 = 1584.5\ W$$

$$ii)\ output = 22\ kW\ , Input = \frac{22kW}{0.88} = 25\ kW$$

$$Total\ losses = input - output = 25kW - 22kW = 3\ kW$$

$$Iron\ and\ friction\ losses = total\ losses - total\ Cu\ losses$$

$$= 3000W - 1584.5\ W = 1415.5\ W$$

E.4. A shunt generator delivers 195 A at terminal voltage of 250 V. The armature resistance and shunt field resistance are 0.02 Ω and 50 Ω respectively. The iron and friction losses equal 950 W. Find

i. E.M.F. generated
ii. Cu losses
iii. output of the prime mover
iv. commercial, mechanical and electrical efficiencies.

Solution:

Ish = 250/50 = 5A

Ia = 195 + 5 = 200 A

i. $E_a = 250 + 200 \times 0.02 = 254$ V
ii. $P_{cu\ a} = 200^2 \times 0.02 = 800$ W

$P_{cu\,sh} = 5^2 \times 50 = 1250$ W

iii. Electromagnetic Power $P_{em} = E_a I_a = 254 \times 200 = 50800$ W
Mech. input power = output of prime mover = P_{em} + iron and friction losses
output of the prime mover = 50800 + 950 = 51750 W
Pout = 250×195 = 48750 W

iv. electrical Efficiency = P_{out} / P_{em} = 48750 / 50800 = 95.9647 %
mech. Efficiency = P_{em} / P_{mech} = 50800 / 51750 = 98.1643 %
overall (commercial) efficiency = 0.959647×0.981643×100 = 94.2031 %

E.5. A shunt generator has a F.L. current of 196 A at 220 V. The stray losses are 720 W and the shunt field coil resistance is 55 Ω. If it has a F.L. efficiency of 88%, find the armature resistance. Also, find the load current corresponding to maximum efficiency.

Solution:

Ish = 220/55 = 4A
$P_{cu\,sh} = 4^2 \times 55 = 880$ W
Ia = 196 + 4 = 200 A
Pout = 220×196 = 43120 W
P_{in} = 43120/0.88 = 49000 W
Total losses = 49000 – 43120 = 5880 W
$P_{cu\,a}$ = 5880 – 880 – 720 = 4280 W = $200^2 \times R_a$
Ra = 0.107 Ω
for maximum efficiency, the variable losses equal the constant losses.
Constant losses = stray loss + $P_{cu\,sh}$ = 720 + 880 = 1600 W
$I_a^2 \times 0.107 = 1600 \rightarrow I_a = 122.2836$ A

Tutorial problems

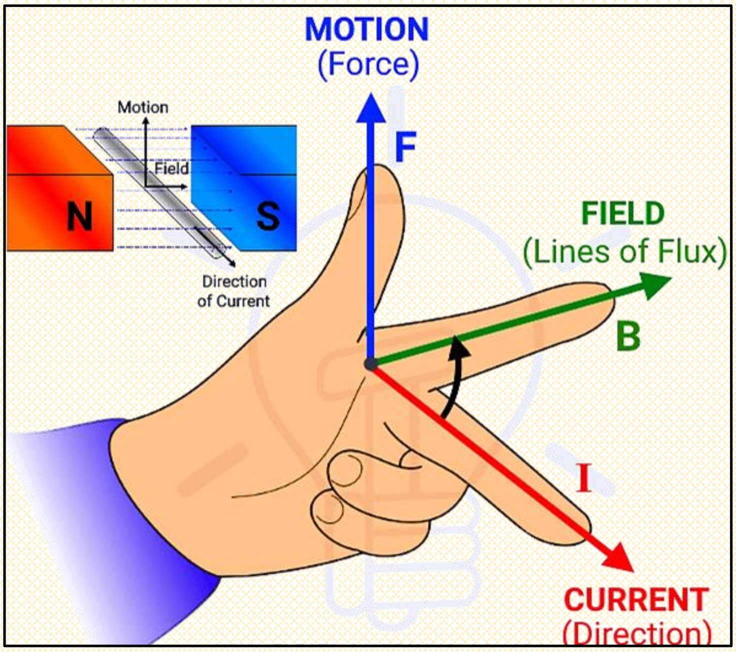
P.1 A long-shunt generator running at 1000 r.p.m. supplies 22 kW at a terminal voltage of 220 V. The resistances of armature, shunt field and the series field are 0.05, 110 and 0.06 Ω respectively. The overall efficiency at the above load is 88%. Find **(a)** Induced voltage E_a **(b)** Cu losses, iron and friction losses

P.2 A short compound generator gives 240 V at a full-load output current of 100 A. The resistances of various windings of the machine are: armature 0.01 Ω, series field 0.2 Ω, shunt field 100 Ω. The iron loss, windage and friction losses are 1200 W. Calculate: (a) The efficiency of the machine at full load,
(b) The efficiency of the machine at half load.

5. DC Motors, Types of DC Motors, Armature Torque of DC Motor

5.1 Introduction

The DC motor is the 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". And that force is called the Lorentz force. The Fleming left-hand rule gives the direction of the force.



Construction of dc motor is same as dc generator (see lecture 2)

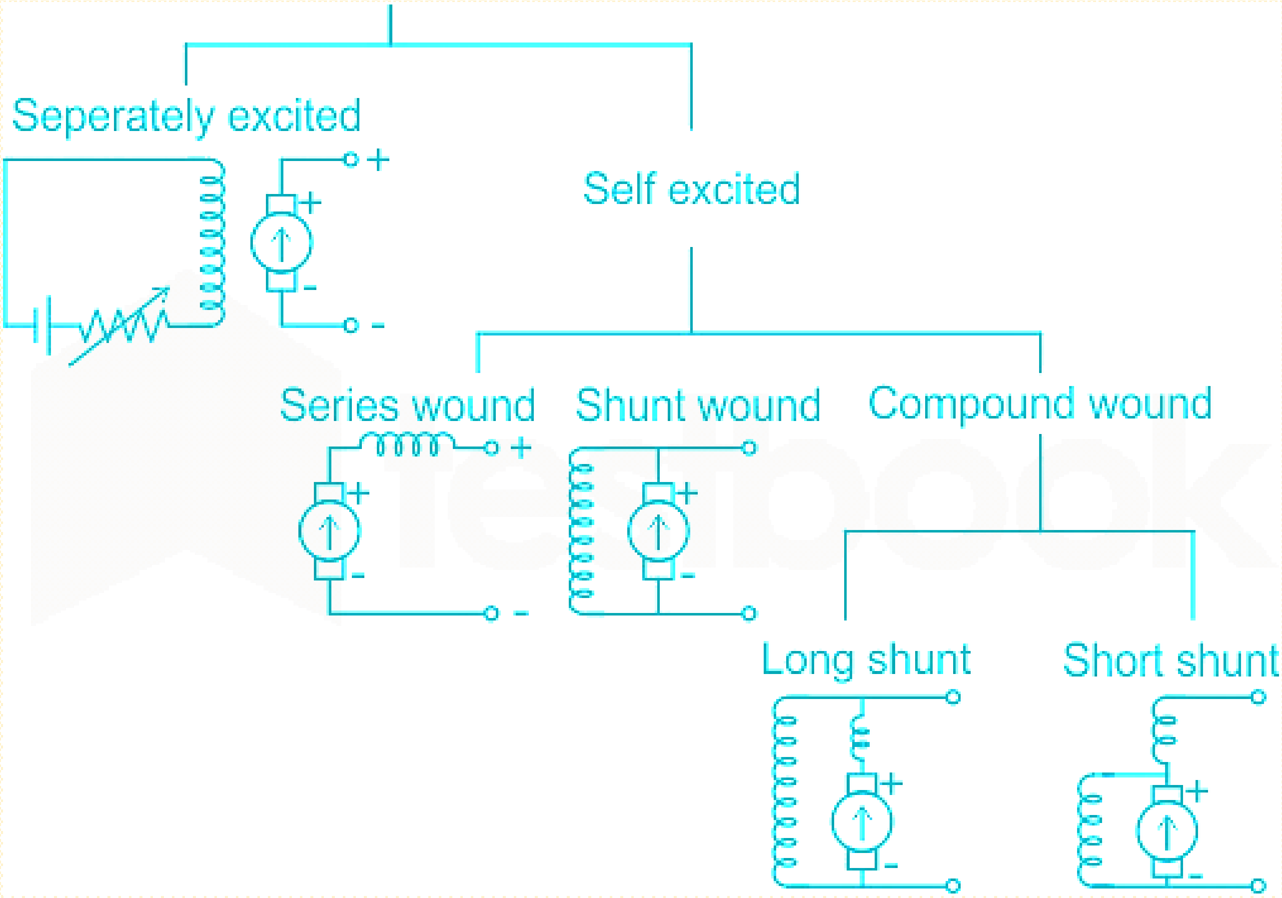
- Consider a two polar DC motor as shown in figure. When motor terminals are connected to DC mains, field gets excited and alternate N-pole and S-pole is created. Armature conductors under N-pole carry current in one direction while conductor carry current in opposite direction as shown in figure.
- By applying Flemings left hand rule, the armature conductors experience a force which tends to rotate armature in clockwise direction. These forces collectively produce a driving torque which sets armature rotating.
- When armature of dc motor rotates, the armature conductors move through the magnetic field, emf is induced in them. The induced emf acts in opposite direction to applied voltage. This voltage is known as **back emf equation**

$$E = \varphi Z \frac{N}{60} \frac{P}{A}$$

5. 2 Types of DC Motors

- Magnetic flux in DC machine is produced by field coils carrying current. This is called excitation.
- DC machines are classified based on type of excitation.

Classification of Motor



5.2. 1 Separately Excited DC Motor

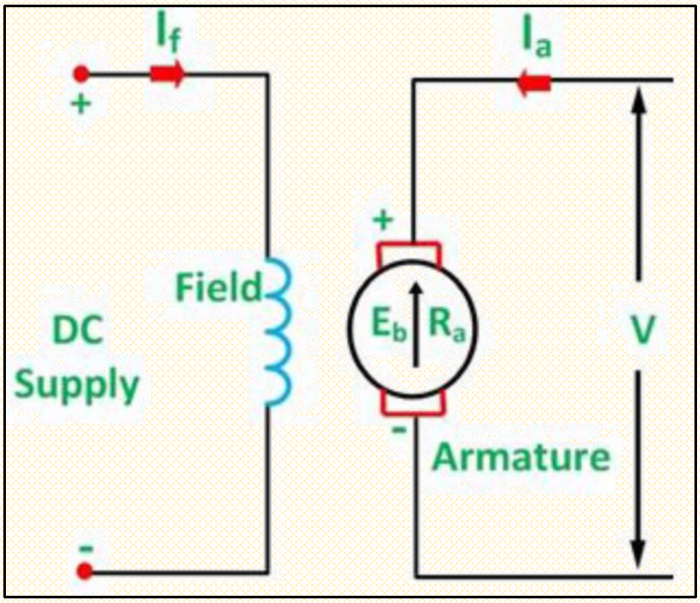
Field winding is supplied from an external source

Armature Current, $I_a = I_L$ (line current)

Terminal Voltage, $V = E_b + I_a R_a$

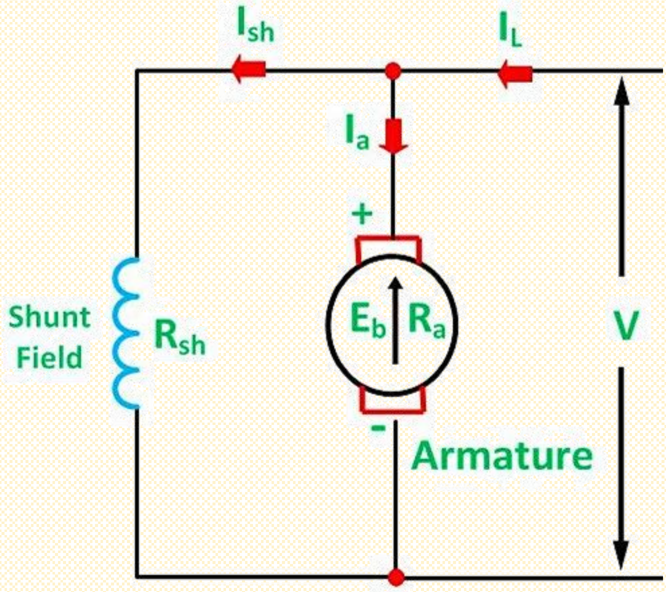
Electrical Power Developed $= E_b I_a$

Power Delivered to Load $= V I_L$



5.2. 2 Shunt Wound DC Motor

Field winding is connected in parallel with armature winding. Shunt field winding is generally made of large no. of turns of fine wire having high resistance.



Armature Current, Ia = I_L - I_{sh}

Field Current, $I_{sh} = V/R_{sh}$

Terminal Voltage, $V = E_b + I_a R_a$

Electrical Power Developed = $E_b I_a$

Power Delivered to Load = $V I_L$

5.2. 3 Series Wound DC Motor

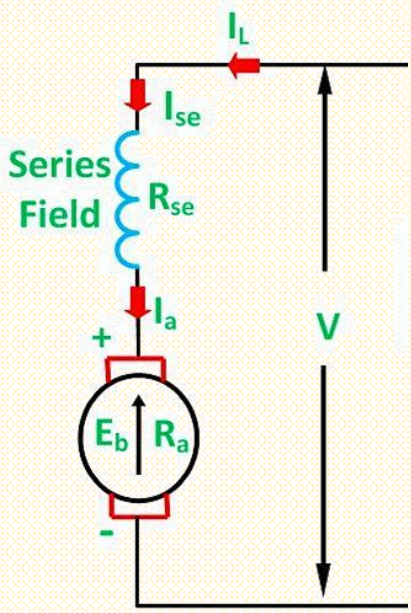
Field winding is connected in series with armature winding

Armature Current, $I_a = I_{se} = I_L$

Terminal Voltage, $V = E_b + I_a R_a + I_{se} R_{se}$

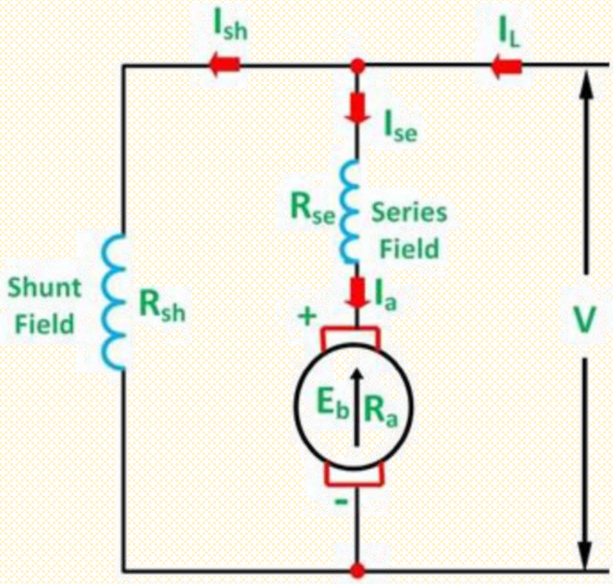
Electrical Power Developed = $E_b I_a$

Power Delivered to Load = $V I_L$



5.2. 4 Compound Wound DC Motor – Long Shunt

Shunt field winding is connected in parallel with series field winding and armature winding.



Armature Current, $Ia = I_L - I_{sh} = I_{se}$

Field Current, $I_{sh} = V/R_{sh}$

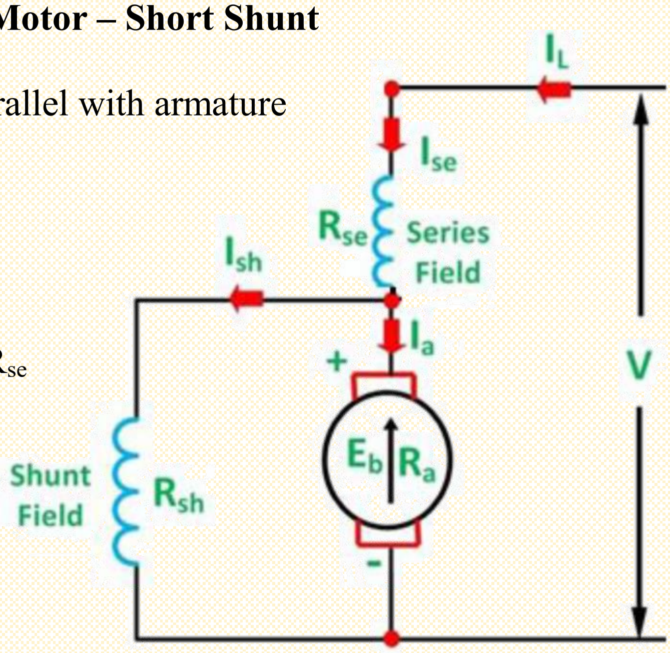
Terminal Voltage, $V = E_b + I_a R_a + I_{se} R_{se}$

Electrical Power Developed = $E_b I_a$

Power Delivered to Load = $V I_L$

5.2. 5 Compound Wound DC Motor – Short Shunt

Shunt field winding is connected in parallel with armature winding only.



Armature Current, $Ia = I_L - I_{sh}$

Field Current, $Ish = (V - I_{se} R_{se})/R_{sh}$

Terminal Voltage, $V = E_b + I_a R_a + I_{se} R_{se}$

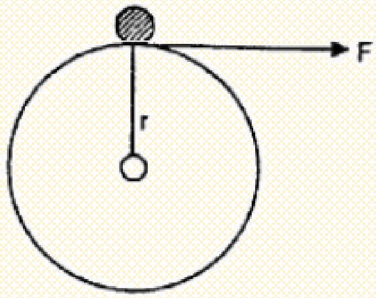
$= I_{sh} R_{sh}$

Electrical Power Developed = $E_b I_a$

Power Delivered to Load = $V I_L$

5. 3 Armature Torque of D.C. Motor

Motor Torque(T) is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e.



$$T = F \times r$$

In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature (Fig.). Therefore, each conductor exerts a torque, tending to rotate the armature. The sum of the torques due to all armature conductors is known as gross or armature torque (Ta).

Let in a d.c. motor

r = average radius of armature in m

L = effective length of each conductor in m

Z = total number of armature conductors

A = number of parallel paths

i = current in each conductor = Ia/A

B = average flux density in Wb/m^2, B = φ/a

φ = flux per pole in Wb

P = number of poles

Force on each conductor, F = B i L newtons

Torque due to one conductor = F × r newton- meter

Total armature torque, Ta = Z F r newton-meter

where a is the x-sectional area of flux path per pole at radius r.

Clearly, a = 2πr/P.

$$T_a = Z\left(\frac{\varphi}{2}\right)\left(\frac{I_a}{A}\right) * L * r \qquad N - m$$

$$= 0.159\, Z\, \varphi\, I_a \left(\frac{P}{A}\right) \qquad N - m$$

E.1 An 8-pole d.c. motor has a wave-wound armature with 900 conductors. The useful flux per pole is 25mWb. Determine the torque exerted when a current of 30A flows in each armature conductor.

Solution:

$$T_a = 0.159\, Z\, \varphi\, I_a \left(\frac{P}{A}\right)$$

$$= 0.159 * 900 * 0.025 * 30 * \frac{8}{2}$$

$$= 429.3 \quad N - m$$

E.2 A DC motor takes an armature current of 110 A at 480 V. The armature circuit resistance is 0.2 Ω. The machine has 6-poles and the armature is lap-connected with 864 conductors. The flux per pole is 0.05 Wb. Calculate (i), the speed in r.p.m and (ii) the gross torque developed by the armature.

solution

Ea = Vt – Ia Ra = 480 - 110×0.2 = 458 V

$$E = \varphi Z \frac{N}{60} \frac{P}{A}$$

$$458 = 0.05 * 864 \frac{N}{60} * \frac{6}{6}$$

$$N = \frac{60 * 458}{0.05 * 864}$$

$$= 636.11 \quad r.p.m$$

$$T_a = 0.159\, Z\, \varphi\, I_a \left(\frac{P}{A}\right)$$

$$= 0.159 * 864 * 0.05 * 110$$

$$= 755.56$$

Tutorial problems

P.1 A 4-pole d.c. motor has a wave-wound armature with 800 conductors. The useful flux per pole is 20mWb. Calculate the torque exerted when a current of 40A flows in each armature conductor [203.7 Nm]

6. Speed, Losses, Starting, Braking and Characteristic of DC Motors

6.1. Speed of a D.C. Motor

$$E_b = V - I_a R_a$$

$$but \quad E_b = \frac{P\,\varphi\,Z\,N}{60\,A}$$

$$\therefore \quad \frac{P\,\varphi\,Z\,N}{60\,A} = V - I_a R_a$$

$$or \quad N = \frac{(V - I_a R_a)}{\varphi}\,\frac{60\,A}{P\,Z}$$

$$let \quad \boldsymbol{K = \frac{60\,A}{P\,Z}}$$

$$\therefore \quad N = K\frac{(V - I_a R_a)}{\varphi}$$

$$but \quad V - I_a R_a = E_b$$

$$\therefore \quad \boldsymbol{N = \frac{60\,A}{P\,Z} . \frac{E_b}{\varphi} = K\frac{E_b}{\varphi}}$$

E.3 A 4-pole motor is fed at 440 V and takes an armature current of 50 A. The resistance of the armature circuit is 0.28 Ω. The armature winding is wave-connected with 888 conductors and useful flux per pole is 0.023 Wb. Calculate the speed of the motor.

solution

$E\,a = V\,t - I\,a\,R\,a$

$= 440 - 50 \times 0.28$

$= 426\ V$

$$K = \frac{60\,A}{P\,Z} = \frac{60 * 2}{4 * 888} = 0.0337$$

$$N = K\frac{E_b}{\varphi}$$

$$= 0.0337\frac{426}{0.023}$$

$$= 625.73 \quad rpm$$

E.4 An 8-pole d.c. motor has a wave-wound armature with 900 conductors. The useful flux per pole is 25mWb. Determine the torque exerted when a current of 30A flows in each armature conductor.

Solution:

$$T_a = 0.159\, Z\, \varphi\, I_a \left(\frac{P}{A}\right)$$

$$= 0.159 * 900 * 0.025 * 30 * \frac{8}{2}$$

$$= 429.3 \quad N - m$$

E.5 A six-pole lap-wound motor is connected to a 250V d.c. supply. The armature has 500 conductors and a resistance of 1Ω. The flux per pole is 20mWb. Calculate (a) the speed and (b) the torque developed when the armature current is 40A.

Solution: (a) Back e.m.f. E =V −IaRa =250−(40)(1)=210V

$$E = \varphi Z \frac{N}{60}\frac{P}{A} \rightarrow 210 = 0.02 * 500 \frac{N}{60} * \frac{6}{6}$$

$$\therefore N = 1260\, r.p.m$$

(b) $T_a = 0.159\, Z\, \varphi\, I_a \left(\frac{P}{A}\right) = 0.159 * 500 * 0.02 * 40 \left(\frac{6}{6}\right)$

$$= 63.6\, n - m$$

Tutorial problems

P.2 A DC motor takes an armature current of 110 A at 480 V. The armature circuit resistance is 0.2 Ω. The machine has 6-poles and the armature is lap-connected with 864 conductors. The flux per pole is 0.05 Wb. Calculate the speed in r.p.m

Hint [N=636.11 r.p.m]

P.3 A 4-pole d.c. motor has a wave-wound armature with 800 conductors. The useful flux per pole is 20mWb. Calculate the torque exerted when a current of 40A flows in each armature conductor [203.7 Nm]

P.4 An 8-pole lap-wound d.c. motor has a 200V supply. The armature has 800 conductors and a resistance of 0.8 Ω. If the useful flux per pole is 40mWb and the armature current is 30A, calculate (a) the speed and (b) the torque developed

[(a) 330 r.p.m (b) 152.8 Nm]

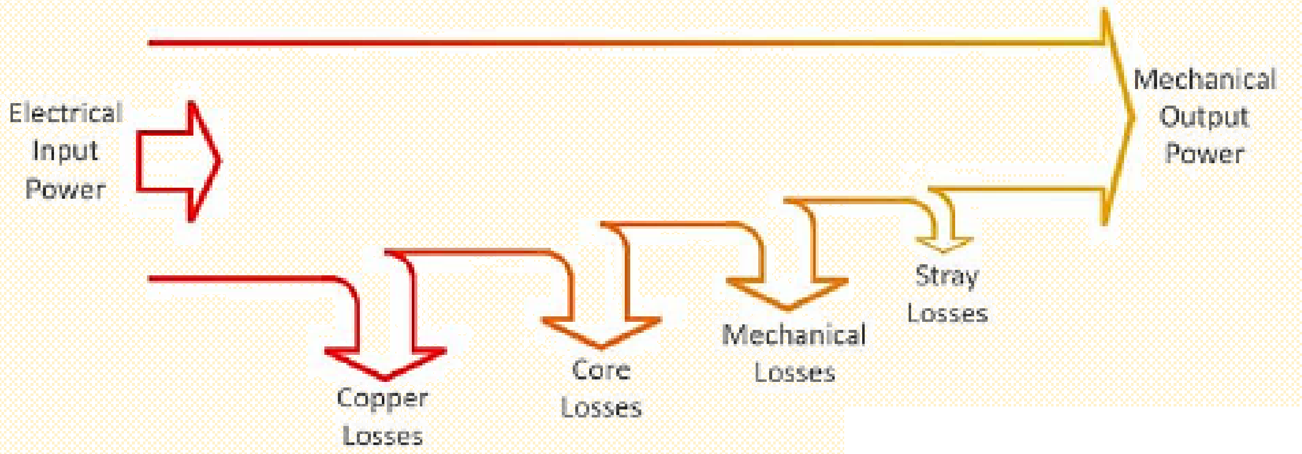
6.2. Losses in DC Motors

In DC machines (generator or motor), the losses may be classified into three categories namely,

- **i.** Copper losses
- **ii.** Iron or core losses
- **iii.** Mechanical losses

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

All these losses was explained briefly in the previous lecture.



Power flow diagram of a DC motor

6.3. Starting of DC Motors

At starting, when the motor is stationary, there is no back e.m.f. in the armature. Consequently, if the motor is directly switched on to the mains, the armature will draw a heavy current (Ia = V/Ra) because of small armature resistance. As an example, 5 H.P., 220 V shunt motor has a full-load current of 20 A and an armature resistance of about 0.5 W. If this motor is directly switched on to supply, it would take an armature current of 220/0.5 = 440 A which is 22 times the full-load current. ***This high starting current may result in:***

i. burning of armature due to excessive heating effect,

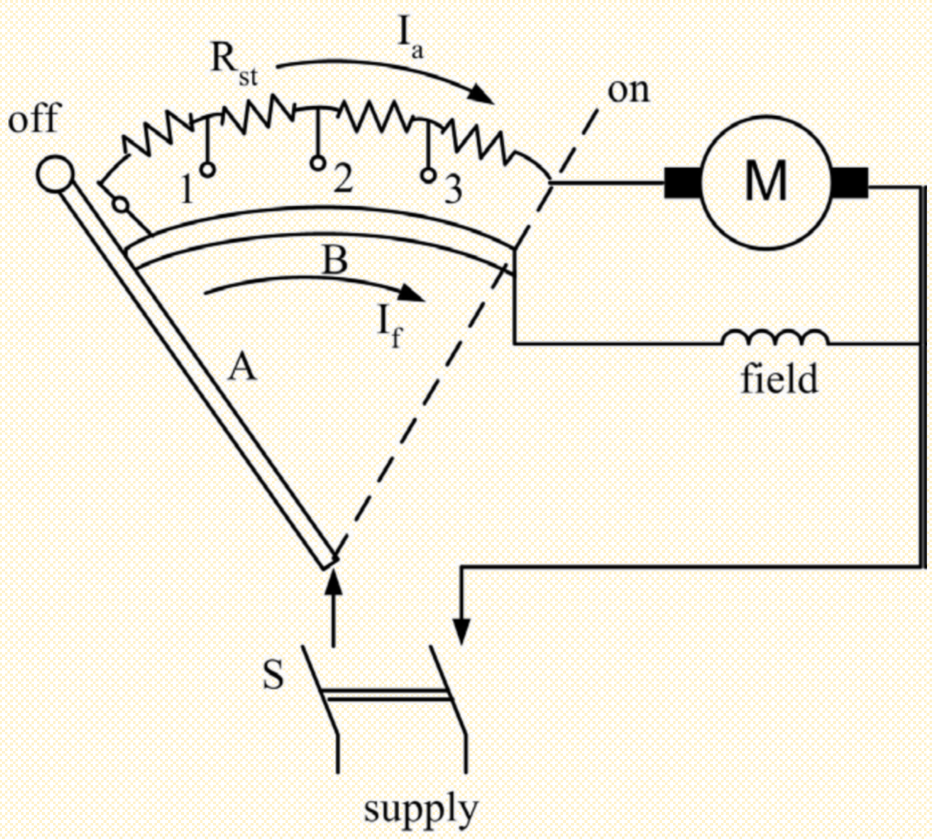
ii. damaging the commutator and brushes due to heavy sparking,

iii. excessive voltage drop in the line to which the motor is connected. The result is that the operation of other appliances connected to the line may be impaired and in particular cases, they may refuse to work.

In order to avoid excessive current at starting, a variable resistance (known as starting resistance) is inserted in series with the armature circuit. This resistance is gradually reduced as the motor gains speed (and hence Eb increases) and eventually it is cut out completely when the motor has attained full speed. The value of starting resistance is generally such that starting current is limited to 1.25 to 2 times the full-load current. The stalling operation of a d.c. motor consists in the insertion of external resistance into the armature circuit to limit the starting current taken by the motor and the removal of this resistance in steps as the motor accelerates.

6.3.1 Manual Starter

In small motors, a manual starter is used, which consists of a resistor made up of several parts connected in series with the product (motor). This resistor is gradually bypassed in stages until the motor reaches its final speed. Once all these resistors are completely bypassed, the motor is then directly connected to the voltage source. Figure illustrates this type of motor starter. In this setup, arm (A) makes contact with the junction point connected to the starting resistor (Rst) while simultaneously making contact with the copper arc (B), which supplies power to the parallel coils. Initially, at startup, the total resistance value is added to the product resistance, reducing the starting current. Then, we begin moving arm (A) to reach point 1, then 2, then 3 until reaching the "on" position, at which point the resistance is completely bypassed, and the voltage applied to the product is the source voltage. The motor rotates at the rated speed. However, one drawback of using a manual starter is that after turning off the main switch (S), disconnecting the voltage source from the motor to stop it, the arm remains in the "on" position. Consequently, when starting the motion again, the product is directly connected to the voltage source. Therefore, after stopping the motor, it is necessary to return the arm to the "off" position.



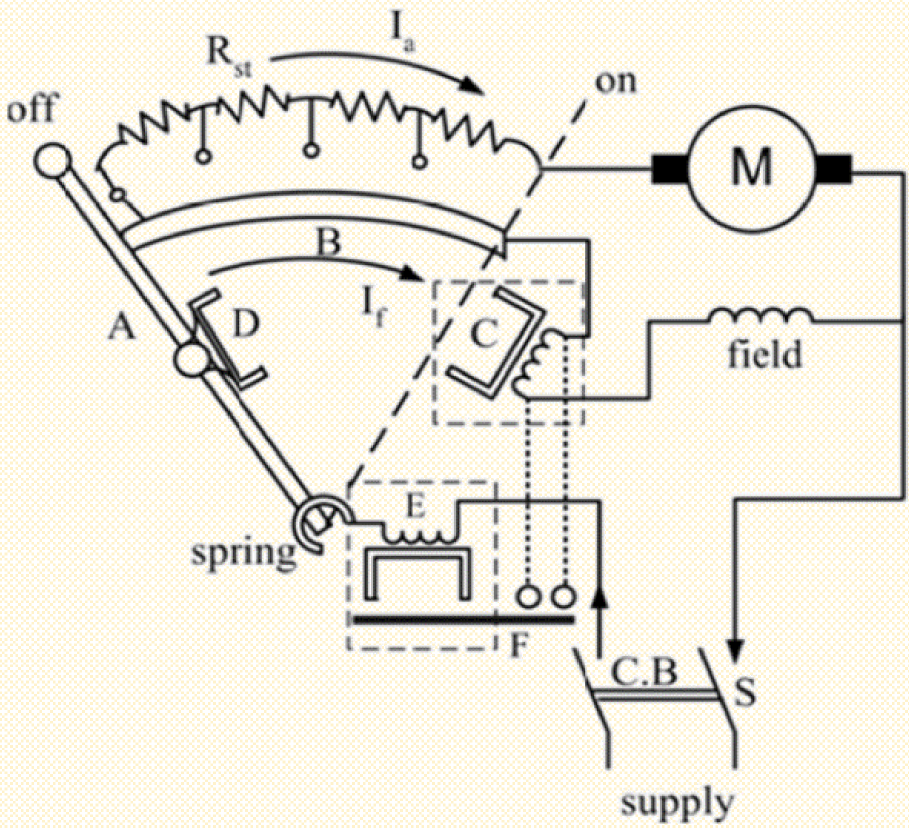
6.3.2 automatic starter

Used in DC motors with capacities exceeding 20 horsepower and is equipped with an overload coil that disconnects the motor from the power source when the load increases. Additionally, it includes an automatic circuit breaker to perform the function of the main switch (S) in case of a short circuit in the circuit. Figure illustrates a schematic of the arrangement for starting parallel and compound DC motors. Initially, arm A is in the off position. When the switch is connected, the voltage source is connected to the automatic circuit breaker, and current passes through the supplementary coil (E), then to arm A, then copper arc B, the attractor coil (C), and finally the field coils and product coils. At this point, the total starter resistance is connected in series with the product, reducing the starting current.

When current passes through the attractor coil (C), a magnetic field is generated, attracting the armature (D) towards the attractor coil (C), causing arm A to start moving towards attractor coil (C). Parts of the starter resistance (Rst) gradually begin to bypass until arm A reaches the "on" position, where the starter resistance is completely bypassed, and the source voltage is applied to the product.

When the main switch (S) is opened to stop the motor, the magnetic field generated by the current passing through the attractor coil (C) dissipates. As a result, the electromagnetic releases the armature (D), causing arm A to return from the "on" position to the "off" position due to the spring connected to arm A and the starter base.

Additionally, the automatic starter includes a supplementary coil (E) containing an electric magnet and an armature. The line current passes through the coil. When the load increases, the armature (F) is attracted to the electric magnet of the supplementary coil, and a piece of copper attached to the armature locks the connection path, causing a short circuit at the terminals of the attractor coil (C). Consequently, the electromagnetic dissipates, releasing the armature (D), and thus, arm A returns to the "off" position due to the spring, stopping the motor.



6.4. Characteristic of DC Motors

There are three principal types of d.c. motors viz., shunt motors, series motors and compound motors. Both shunt and series types have only one field winding wound on the core of each pole of the motor. The compound type has two separate field windings wound on the core of each pole. The performance of a d.c. motor can be judged from its characteristic curves known as motor characteristics, following are the three important characteristics of a d.c. motor

i. *Torque and Armature current characteristic (Ta/Ia):*. motor. It is also known as electrical characteristic of the motor.
ii. *Speed and armature current characteristic (N/Ia):* It is very important characteristic as it is often the deciding factor in the selection of the motor for a particular application.
iii. *Speed and armature torque characteristic (N/Ta):* It is also known as mechanical characteristic.

6.5.1 Characteristics of Shunt Motors

In d.c. shunt motor. The field current Ish is constant since the field winding is directly connected to the supply voltage V which is assumed to be constant. Hence, the flux in a shunt motor is approximately constant.

i. Ta/Ia Characteristic. We know that in a d.c. motor,

$$\text{Ta} \propto \varphi I_a$$

Since the motor is operating from a constant supply voltage, flux φ is constant (neglecting armature reaction).

$$\text{Ta} \propto I_a$$

Hence Ta/Ia characteristic is a straight line passing through the origin in (Fig. i)

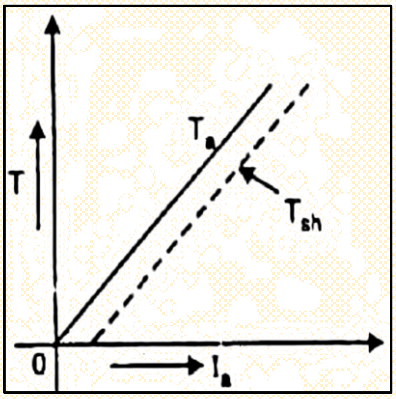
It is clear from the curve that a very large current is required to start a heavy load. Therefore, a shunt motor should not be started on heavy load.

ii. N/Ia Characteristic. The speed N of a. d.c. motor is given by;

$$\text{N} \propto \text{Eb}$$

The flux f and back e.m.f. Eb in a shunt motor are almost constant under normal conditions. Therefore, speed of a shunt motor will remain constant as the armature current varies (dotted line AB in Fig. ii). Strictly speaking, when load is increased, (Eb = V- IaRa) and f decrease due to the armature resistance drop and armature reaction respectively. However, Eb decreases slightly more than f so that the speed of the motor decreases slightly with load (line AC).

iii. N/Ta Characteristic. The curve is obtained by plotting the values of N and Ta for various armature currents (See Fig. iii). It may be seen that speed falls somewhat as the load torque increases.



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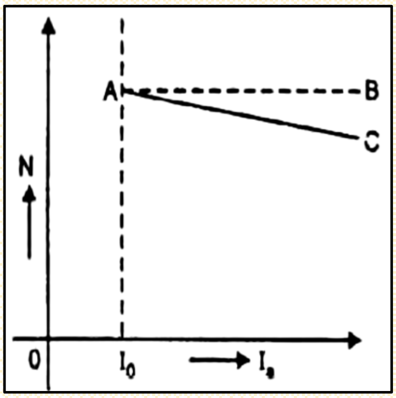

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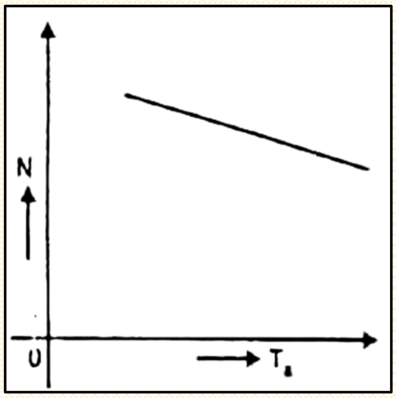


ii

Conclusions

Following two important conclusions are drawn from the above characteristics:

i. There is slight change in the speed of a shunt motor from no-load to full-load. Hence, it is essentially a constant-speed motor.

ii. The starting torque is not high because Ta ∝ Ia.

6.5.2 Characteristics of Series Motors

In a series motor. Note that current passing through the field winding is the same as that in the armature. If the mechanical load on the motor increases, the armature current also increases. Hence, the flux in a series motor increases with the increase in armature current and vice-versa

i. Ta/Ia Characteristic. We know that:

$$Ta \propto \varphi I_a$$

Upto magnetic saturation, $\varphi \propto I_a$ so that $Ta \propto Ia^2$

After magnetic saturation, f is constant so that $Ta \propto Ia$

Thus upto magnetic saturation, the armature torque is directly proportional to the square of armature current. If Ia is doubled, Ta is almost quadrupled. Therefore, Ta/Ia curve upto magnetic saturation is a parabola (portion OA of the curve in Fig i). However, after magnetic saturation, torque is directly proportional to the armature current. Therefore, Ta/Ia curve after magnetic saturation is a straight line (portion AB of the curve). It may be seen that in the initial portion of the curve (i.e. upto magnetic saturation), $Ta \propto Ia^2$. This means that starting torque of a d.c. series motor will be very high as compared to a shunt motor.

ii. N/Ia Characteristic. The speed N of a series motor is given by;

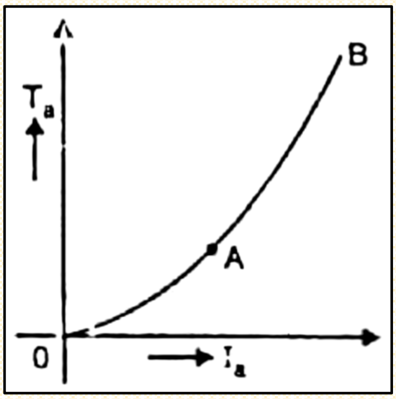
$N \propto \frac{E_b}{\varphi}$, where $E_b = V - Ia(Ra + Rse)$

When the armature current increases, the back e.m.f. Eb decreases due to Ia(Ra + Rse) drop while the flux f increases. However, Ia(Ra + Rse) drop is quite small under normal conditions and may be neglected.

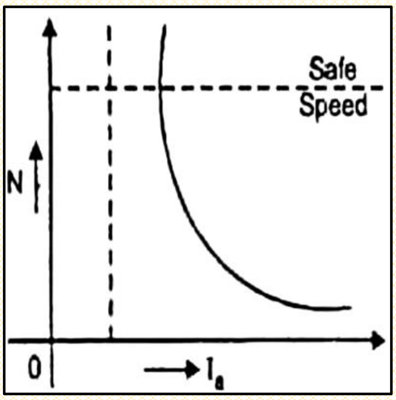
$$N \propto 1/\varphi$$
$$\propto 1/Ia \text{ upto magnetic saturation}$$

Thus, upto magnetic saturation, the N/Ia curve follows the hyperbolic path as shown in (Fig. ii) After saturation, the flux becomes constant and so does the speed

iii. N/Ta Characteristic. The N/Ta characteristic of a series motor is shown in (Fig. iii) It is clear that series motor develops high torque at low speed and vice-versa. It is because an increase in torque requires an increase in armature current, which is also the field current. The result is that flux is strengthened and hence the speed drops Reverse happens should the torque below.



i



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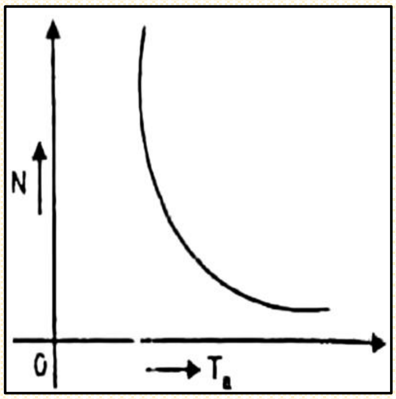


ii

Conclusions

Following three important conclusions are drawn from the above characteristics of series motors:

i. It has a high starting torque because initially $Ta \propto Ia^2$.

ii. It is a variable speed motor (See N/Ia curve) i.e., it automatically adjusts the speed as the load changes. Thus if the load decreases, its speed is automatically raised and vice-versa.

iii. At no-load, the armature current is very small and so is the flux. Hence, the speed rises to an excessive high value ($N \propto 1/\varphi$). This is dangerous for the machine which may be destroyed due to centrifugal forces set up in the rotating parts. Therefore, a series motor should never be started on no-load. However, to start a series motor, mechanical load is first put and then the motor is started.

6.5.3 Characteristics Compound Motors

A compound motor has both series field and shunt field. The shunt field is always stronger than the series field. Compound motors are of two types:

i. *Cumulative-compound motors* in which series field aids the shunt field.

ii. *Differential-compound motors* in which series field opposes the shunt field.

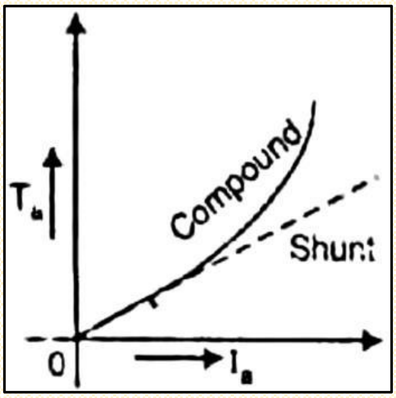
Differential compound motors are rarely used due to their poor torque characteristics at heavy loads.

Characteristics of Cumulative Compound Motors

i. **Ta/Ia Characteristic**. As the load increases, the series field increases but shunt field strength remains constant. Consequently, total flux is increased and hence the armature torque (Ta $\propto \varphi I_a$). It may be noted that torque of a cumulative-compound motor is greater than that of shunt motor for a given armature current due to series field [See Fig. i].

ii. **N/Ia Characteristic**. As explained above, as the lead increases, the flux per pole also increases. Consequently, the speed (N $\propto 1/\varphi$) of the motor tails as the load increases (See Fig. ii). It may be noted that as the load is added, the increased amount of flux causes the speed to decrease more than does the speed of a shunt motor. Thus the speed regulation of a cumulative compound motor is poorer than that of a shunt motor. ***Note:*** Due to shunt field, the motor has a definite no load speed and can be operated safely at no-load.

iii. **N/Ta Characteristic**. Fig. shows N/Ta characteristic of a cumulative compound motor. For a given armature current, the torque of a cumulative compound motor is more than that of a shunt motor but less than that of a series motor (see fig iii).



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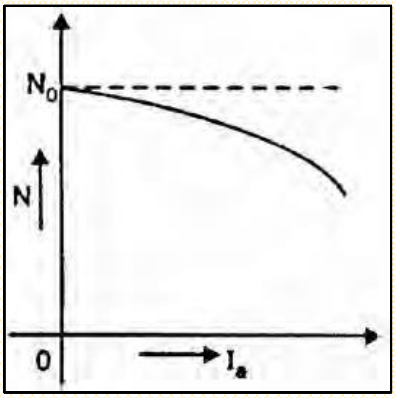

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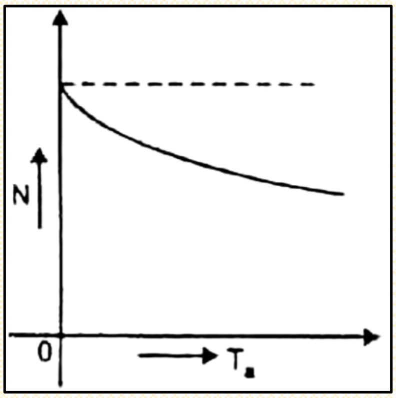


ii

Conclusions

A cumulative compound motor has characteristics intermediate between series and shunt motors.

i. Due to the presence of shunt field, the motor is prevented from running away at no-load.

ii. Due to the presence of series field, the starting torque is increased.

5. 4 Comparison of Three Types of Motors

i. The speed regulation of a shunt motor is better than that of a series motor. However, speed regulation of a cumulative compound motor lies between shunt and series motors (See Fig. a).

ii. For a given armature current, the starting torque of a series motor is more than that of a shunt motor. However, the starting torque of a cumulative compound motor lies between series and shunt motors (See Fig. b).

iii. Both shunt and cumulative compound motors have definite no-load speed. However, a series motor has dangerously high speed at no-load.

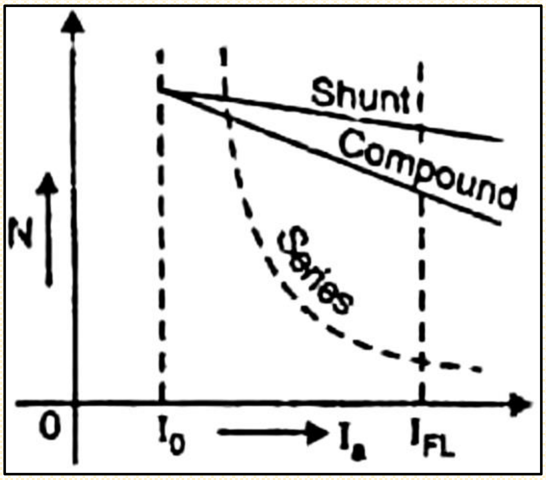


Figure a

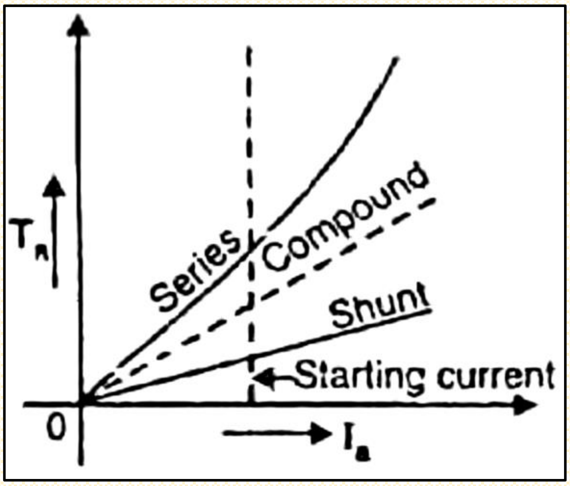


figure b

7. Speed Control of DC Motors, Electric Braking, DC Motor Characteristics

7.1. Speed Control of DC Motors

The speed of a d.c. motor is given by:

$$N \propto \frac{E_b}{\varphi}$$

$$or \qquad N = K\frac{(V - I_a R)}{\varphi} \quad r.p.m$$

$$where \qquad R = R_a \qquad (for\ shunt\ motor)$$

$$R = R_a + R_{se} \qquad (for\ series\ motor)$$

It is clear that there are three main methods of controlling the speed of a d.c. motor, namely:

i. By varying the flux per pole (φ). This is known as flux control method.

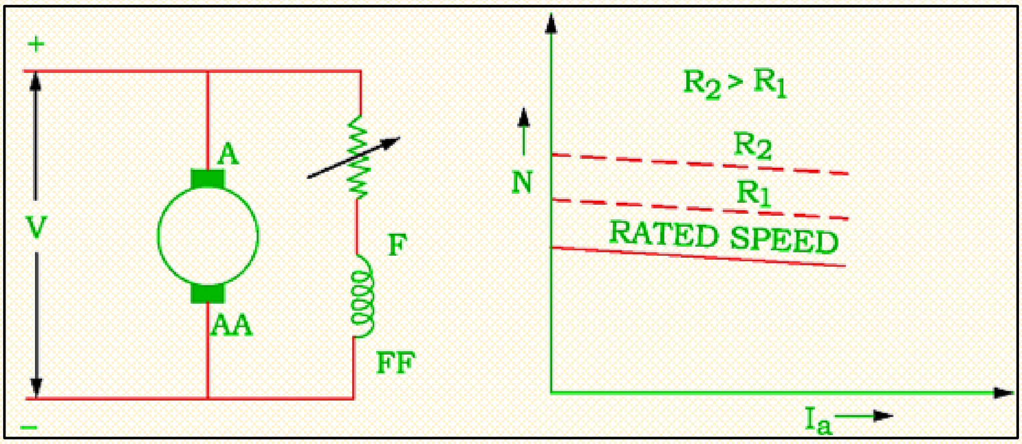
ii. By varying the resistance in the armature circuit. This is known as armature control method.

iii. By varying the applied voltage V. This is known as voltage control method.

7.2. Speed Control of D.C. Shunt Motors

7.2.1. Flux control method

It is based on the fact that by varying the flux φ, the motor speed($N \propto 1/\varphi$) can be changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding as shown in Fig.



The shunt field rheostat reduces the shunt field current Ish and hence the flux f. Therefore, we can only raise the speed of the motor above the normal speed (See Fig. above. Generally, this method permits to increase the speed in the ratio 3:1. Wider speed ranges tend to produce instability and poor commutation.

Advantages

i. This is an easy and convenient method.
ii. It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of Ish.
iii. The speed control exercised by this method is independent of load on the machine.

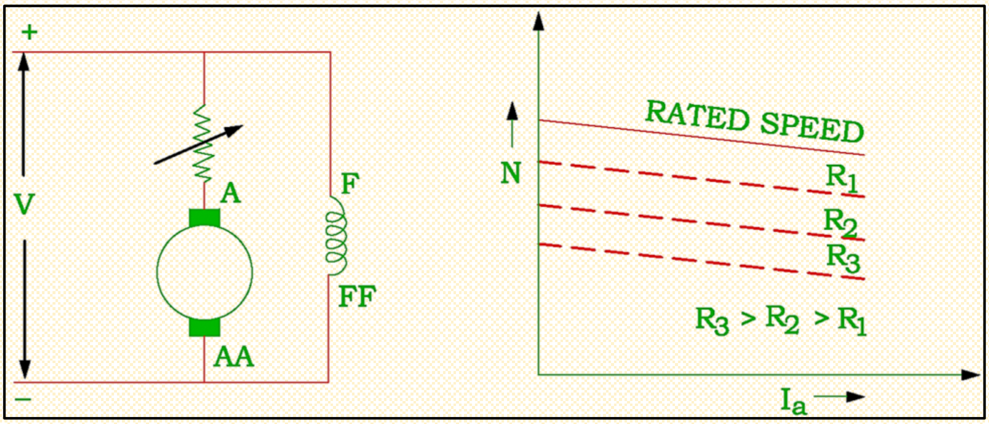
Disadvantages

i. Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below Rsh (the shunt field winding resistance).
ii. There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

Note. The field of a shunt motor in operation should never be opened because its speed will increase to an extremely high value.

7.2.2. Armature control method

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance Rc (known as controller resistance) in series with the armature as shown in Fig.



$N \propto V - Ia\,(Ra + R_C)$, where R_C = controller resistance

Due to voltage drop in the controller resistance, the back e.m.f. (Eb) is decreased. Since $N \propto Eb$, the speed of the motor is reduced. The highest speed obtainable is that corresponding to RC = 0 i.e., normal speed. Hence, this method can only provide speeds below the normal speed (See Fig. above).

Disadvantages

i. A large amount of power is wasted in the controller resistance since it carries full armature current Ia.

ii. The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.

iii. The output and efficiency of the motor are reduced.

iv. This method results in poor speed regulation.

Due to above disadvantages, this method is seldom used to control tie speed of shunt motors.

Note. The armature control method is a very common method for the speed control of d.c. series motors. The disadvantage of poor speed regulation is not important in a series motor which is used only where varying speed service is required.

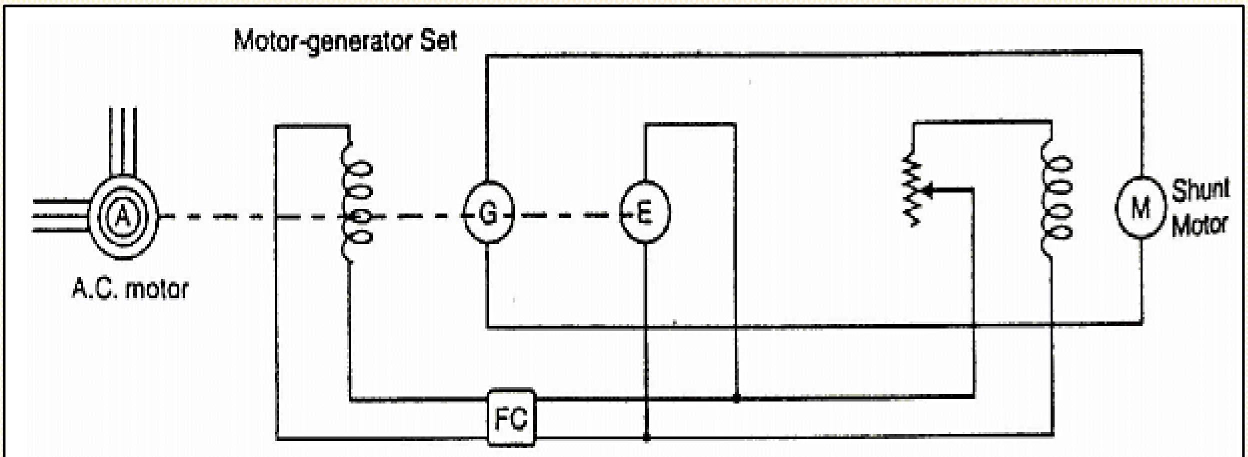
7.2.3. Voltage control method

In this method, the voltage source supplying the field current is different from that which supplies the armature. This method avoids the disadvantages of poor speed regulation and low efficiency as in armature control method. However, it is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance.

a. *Multiple voltage control*. In this method, the shunt field of the motor is connected permanently across a-fixed voltage source. The armature can be connected across several different voltages through a suitable switchgear.

   In this way, voltage applied across the armature can be changed. The speed will be approximately proportional to the voltage applied across the armature. Intermediate speeds can be obtained by means of a shunt field regulator.

b. *Ward-Leonard system*. In this method, the adjustable voltage for the armature is obtained from an adjustable-voltage generator while the field circuit is supplied from a separate source. This is illustrated in Fig below . The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A. The field of the shunt motor is supplied from a constant-voltage exciter E. The field of the generator G is also supplied from the exciter E. The voltage of the generator G can be varied by means of its field regulator. By reversing the field current of generator G by controller FC, the voltage applied to the motor may be reversed. Sometimes, a field regulator is included in the field circuit of shunt motor M for additional speed adjustment. With this method, the motor may be operated at any speed upto its maximum speed.



Ward-Leonard speed-control system.

Advantages

i. The speed of the motor can be adjusted through a wide range without resistance losses which results in high efficiency.
ii. The motor can be brought to a standstill quickly, simply by rapidly reducing the voltage of generator G. When the generator voltage is reduced below the back e.m.f. of the motor, this back e.m.f. sends current through the generator armature, establishing dynamic braking. While this takes place, the generator G operates as a motor driving motor A which returns power to the line.
iii. This method used for speed control of large motors when a d.c. supply not available.

The disadvantage of the method is that a special motor-generator set is required for each motor and the losses in this set are high if the motor is operating under light loads for long periods.

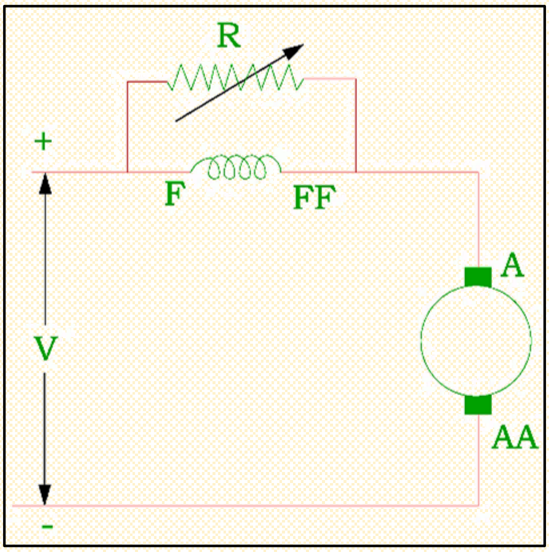
7.3. Speed Control of D.C. Series Motors

The speed control of d.c. series motors can be obtained by (i) flux control method (ii) armature-resistance control method. The latter method is mostly used

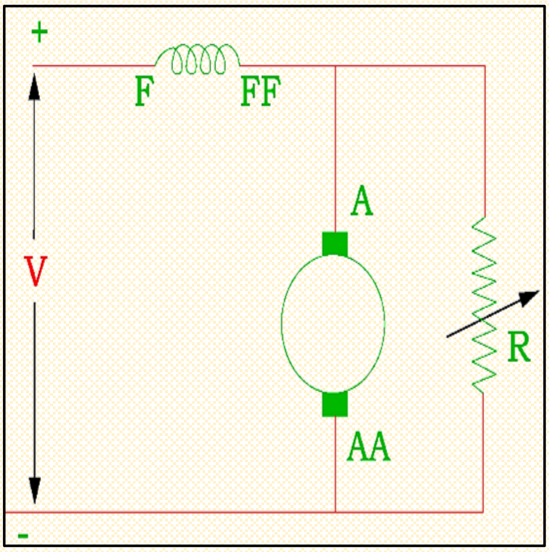
7.3.1. Flux control method

In this method, the flux produced by the series motor is varied and hence the speed. The variation of flux can be achieved in the following ways:

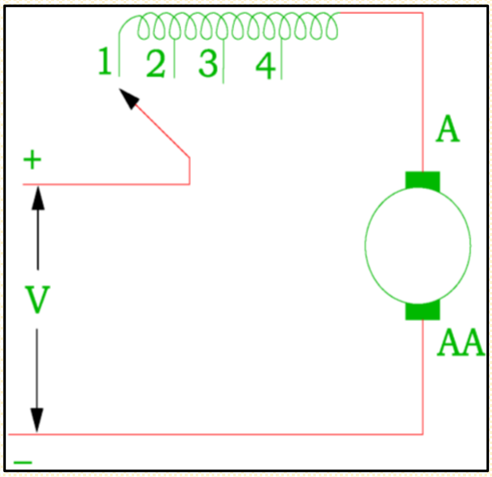
i. ***Field diverters***. *In this method*, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in Fig .Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the $N \propto \frac{1}{\varphi}$. The lowest speed obtainable is that corresponding to zero current in the diverter (i.e,. diverter is open). Obviously, the lowest speed obtainable is the normal speed of the motor. Consequently, this method can only provide speeds above the normal speed. The series field diverter method is often employed in traction work.



ii. ***Armature diverter***. In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature as shown in Fig. The diverter shunts some of the line current, thus reducing the armature current. Now for a given load, if Ia is decreased, the flux φ must increase ($T \propto \varphi I_a$). Since $N \propto \frac{1}{\varphi}$, the motor speed is decreased. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.



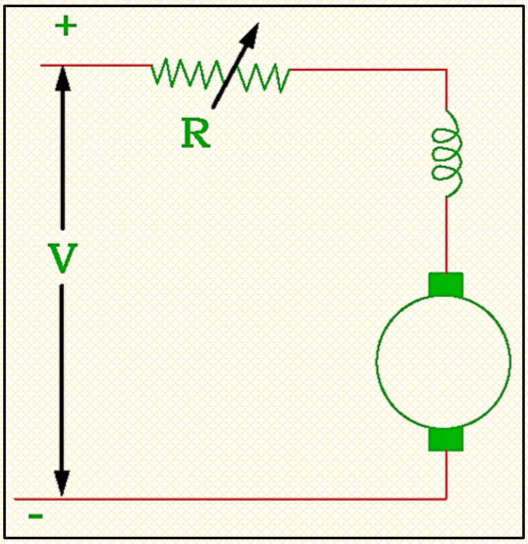
iii. *Tapped field control*. In this method, the flux is reduced (and hence speed is increased) by decreasing the number of turns of the series field winding as shown in Fig. The switch S can short circuit any part of the field winding, thus decreasing the flux and raising the speed. With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out, speeds higher than normal speed are achieved.



7.3.2. Armature-resistance control

In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in Fig. This reduces the voltage available across the armature and hence the speed falls.

By changing the value of variable resistance, any speed below the normal speed can be obtained. This is the most common method employed to control the speed of d.c. series motors. Although this method has poor speed regulation, this has no significance for series motors because they are used in varying speed applications. The loss of power in the series resistance for many applications of series motors is not too serious since in these applications, the control is utilized for a large portion of the time for reducing the speed under light-load conditions and is only used intermittently when the motor is carrying full-load.



Speed Control of Compound Motors

Speed control of compound motors may be obtained by any one of the methods described for shunt motors. Speed control cannot be obtained through adjustment of the series field since such adjustment would radically change the performance characteristics of the motor.

7.4. Electric Braking of a DC motor

Sometimes it is desirable to stop a d.c. motor quickly. This may be necessary in case of emergency or to save time if the motor is being used for frequently repeated operations. The motor and its load may be brought to rest by using either (i) mechanical (friction) braking or (ii) electric braking. In mechanical braking, the motor is stopped due to the friction between the moving parts of the motor and the brake shoe i.e. kinetic energy of the motor is dissipated as heat.

Mechanical braking has several disadvantages including non-smooth stop and greater stopping time.

In electric braking, the kinetic energy of the moving parts (i.e., motor) is converted into electrical energy which is dissipated in a resistance as heat or alternativley, it is returned to the supply source (Regenerative braking). For d.c. shunt as well as series motors, the following three methods of electric braking are used:

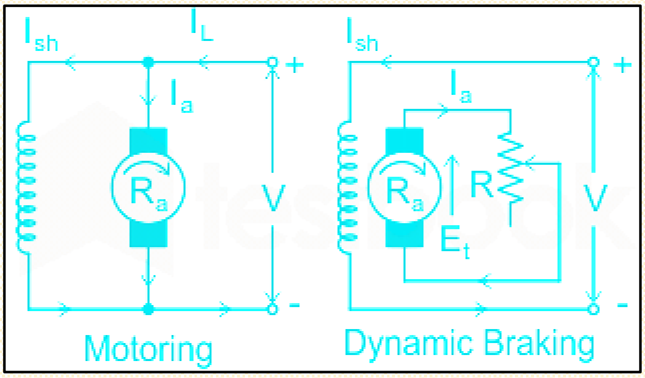
i. Rheostatic or Dynamic braking
ii. Plugging
iii. Regenerative braking

It may be noted that electric braking cannot hold the motor stationary and mechanical braking is necessary. However, the main advantage of using electric braking is that it reduces the wear and tear of mechanical brakes and cuts down the stopping time considerably due to high braking retardation.

7.4.1. Rheostatic or Dynamic braking

In this method, the armature of the running motor is disconnected from the supply and is connected across a variable resistance R. However, the field winding is left connected to the supply. The armature, while slowing down, rotates in a strong magnetic field and, therefore, operates as a generator, sending a large current through resistance R. This causes the energy possessed by the rotating armature to be dissipated quickly as heat in the resistance. As a result, the motor is brought to standstill quickly.

Fig. shows dynamic braking of a shunt motor. The braking torque can be controlled by varying the resistance R. If the value of R is decreased as the motor speed decreases, the braking torque may be maintained at a high value. At a low value of speed, the braking torque becomes small and the final stopping of the motor is due to friction. This type of braking is used extensively in connection with the control of elevators and hoists and in other applications in which motors must be started, stopped and reversed frequently.



We now investigate how braking torque depends upon the speed of the motor. Referring to Fig.

$$Armature\ current\ \ I_a = \frac{E_b}{R+R_a} = \frac{K_1 N\varphi}{R+R_a} \qquad (\because E_b \propto N\varphi)$$

$$Braking\ torque\ \ T_B = K_2 I_a \varphi \left(\frac{K_1 N\varphi}{R+R_a}\right) = K_3 N\varphi^2$$

where k2 and k3 are constants, For a shunt motor, $\varphi$is constant.

$$\therefore Braking\ torque,\ T_B \propto N$$

Therefore, braking torque decreases as the motor speed decreases.

7.4.2. Plugging

In this method, connections to the armature are reversed so that motor tends to rotate in the opposite direction, thus providing the necessary braking effect. When the motor comes to rest, the supply must be cut off otherwise the motor will start rotating in the opposite direction.

Fig. shows plugging of a d.c. shunt motor. Note that armature connections are reversed while the connections of the field winding are kept the same. As a result the current in the armature reverses. During the normal running of the motor [See Fig.], the back e.m.f. E_b opposes the applied voltage V. However, when armature connections are reversed, back e.m.f. E_b and V act in the same direction around the circuit. Therefore, a voltage equal to $V + E_b$ is impressed across the armature circuit. Since $E_b \approx V$, the impressed voltage is approximately 2V. In order 10 limit the current to safe value, a variable resistance R is inserted in the circuit at the time of changing armature connections.

We now investigate how braking torque depends upon the speed of the motor. Referring to Fig,

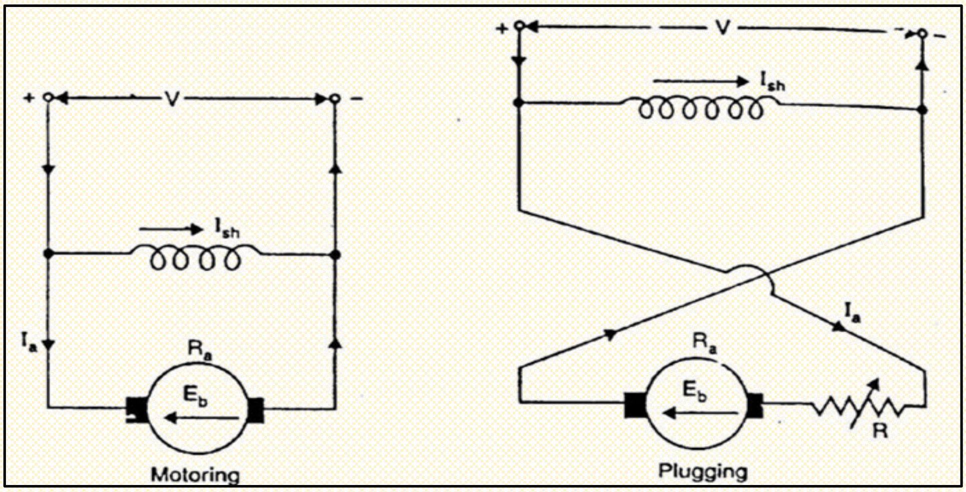
$$Armature\ current\ \ I_a = \frac{V + E_b}{R + R_a} = \frac{V}{R + R_a} + \frac{K_1 N\varphi}{R + R_a} \qquad (\because E_b \propto N\varphi)$$

$$Braking\ torque\ \ T_B = K_2 I_a \varphi \left(\frac{V}{R + R_a} + \frac{K_1 N\varphi}{R + R_a}\right) = K_3\varphi + K_4 N\varphi^2$$

For a shunt motor, φ is constant.

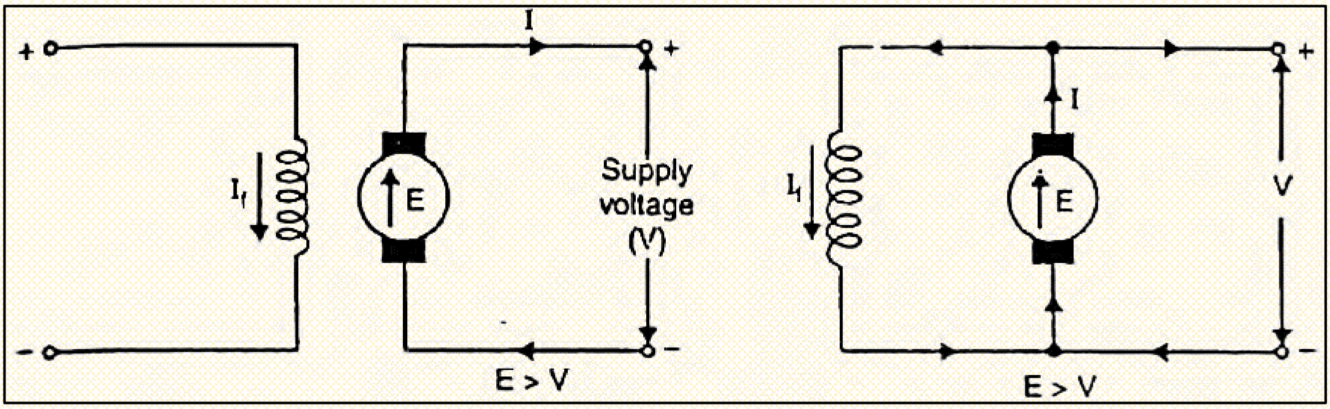
$$\therefore\ Braking\ torque,\ T_B = k_5 + k_6 N$$

Thus braking torque decreases as the motor slows down. Note that there is some braking torque ($T_B = k_5$) even when the motor speed is zero.



7.4.3. Regenerative braking

In the regenerative braking, the motor is run as a generator. As a result, the kinetic energy of the motor is converted into electrical energy and returned to the supply. Fig. shows two methods of regenerative braking for a shunt motor.



a. In one method, field winding is disconnected from the supply and field current is increased by exciting it from another source [See Fig]. As a result, induced e.m.f. E exceeds the supply voltage V and the machine feeds energy into the supply. Thus braking torque is provided upto the speed at which induced e.m.f. and supply voltage are equal. As the machine slows down, it is not possible to maintain induced e.m.f. at a higher value than the supply voltage. Therefore, this method is possible only for a limited range of speed.

b. In a second method, the field excitation does not change but the load causes the motor to run above the normal speed (e.g., descending load on a crane). As a result, the induced e.m.f. E becomes greater than the supply voltage V [See Fig]. The direction of armature current I, therefore, reverses but the direction of shunt field current I_f remains unaltered. Hence the torque is reversed and the speed falls until E becomes less than V.