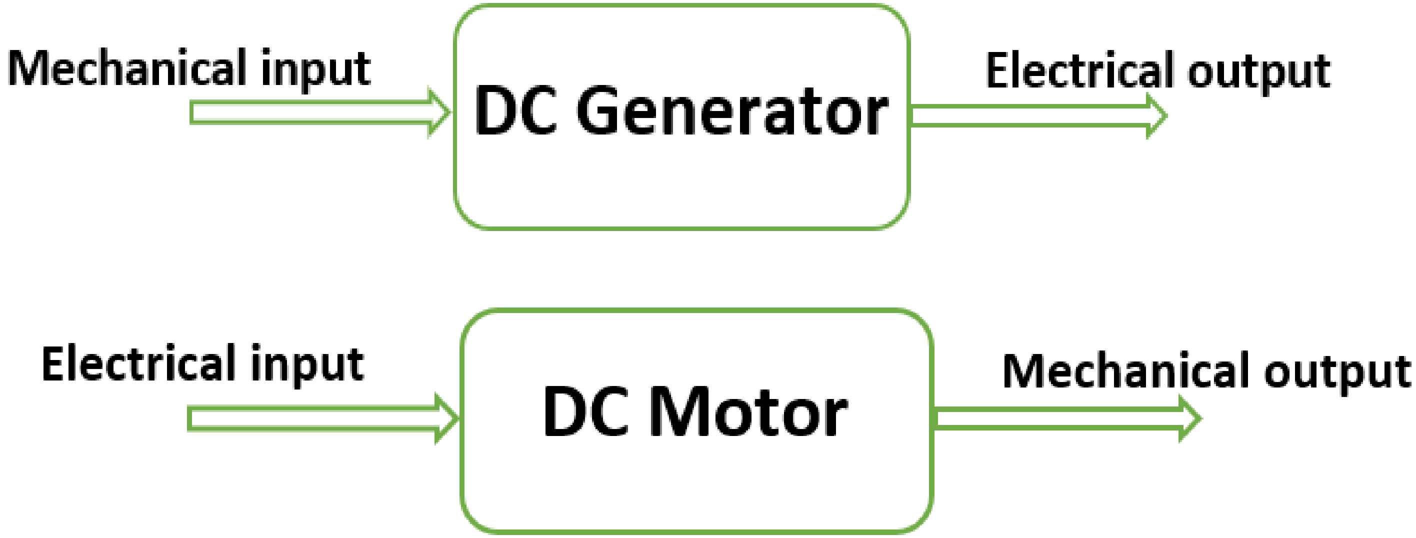
Basic Electrical Engineering

Chapter-5: Electric Machines

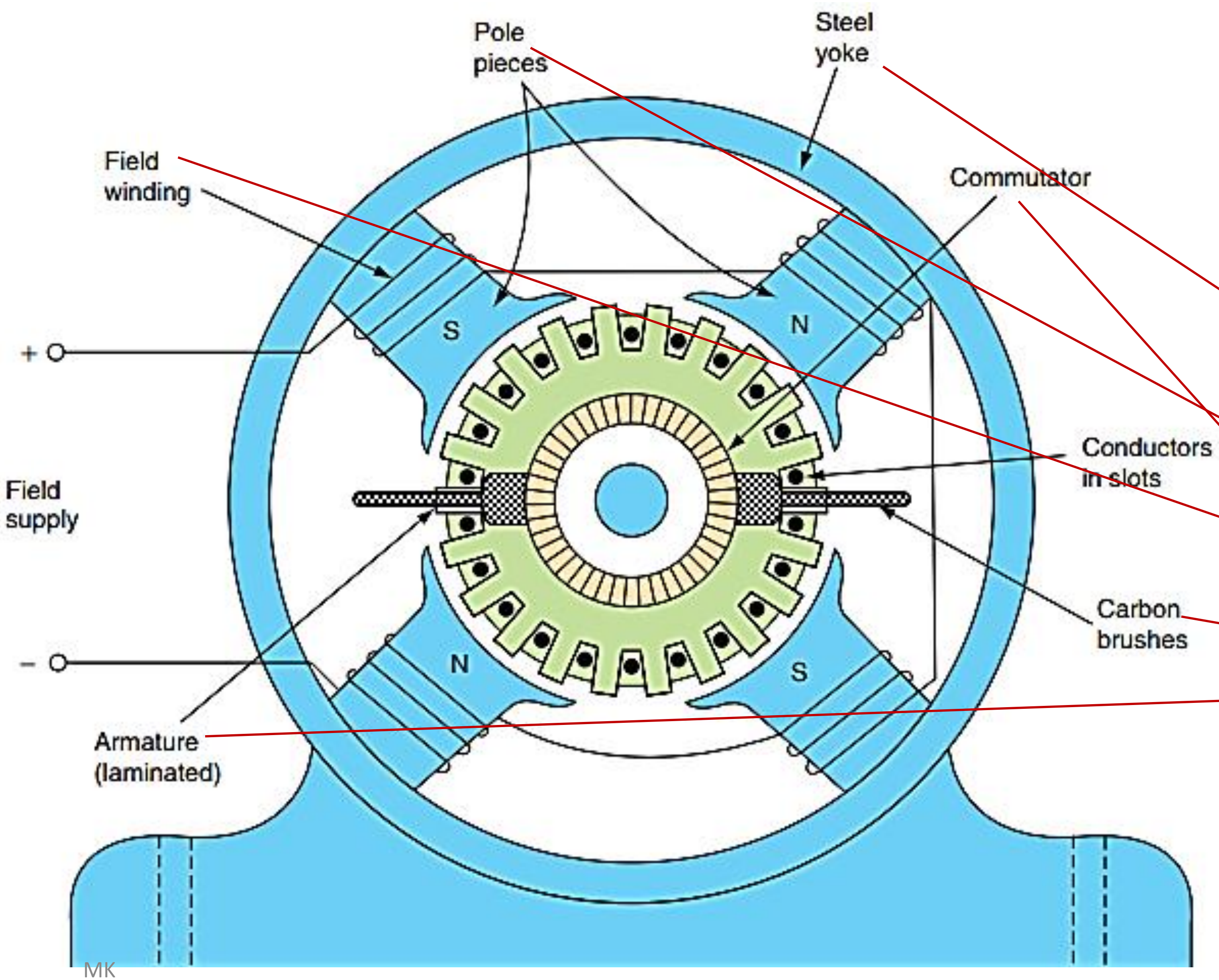
Asst. Prof. Menaka Karki

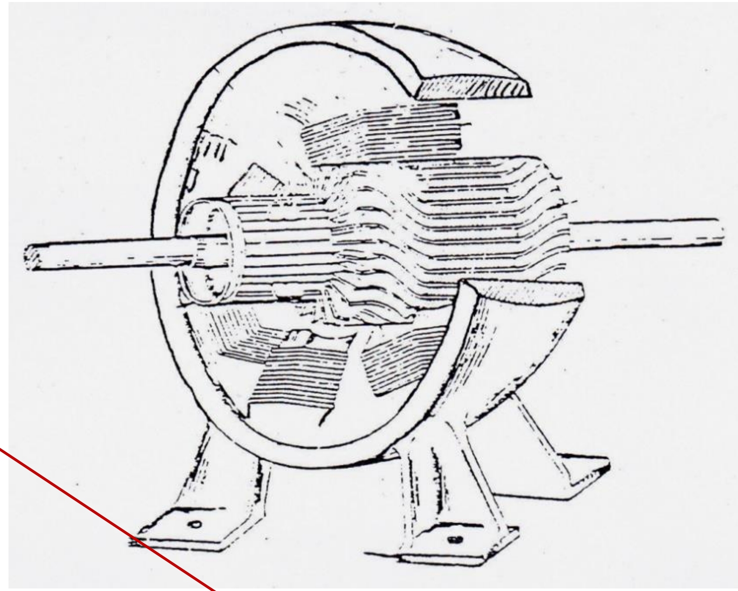
Introduction

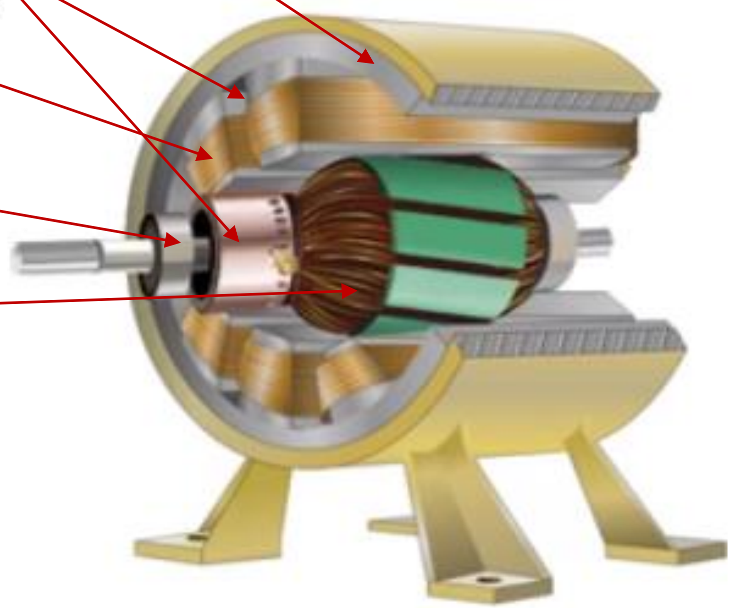
- DC machines are **rotating electrical machines** which can be used as **either motors or generators.**
- **DC motors convert electrical input to mechanical output(rotation).**
- **DC generators convert mechanical input (kinetic energy) to electrical output (induced emf).**
- The **working principle** of DC generators is based on the **Faraday's law of electromagnetic induction**



Basic constructional details of DC machine



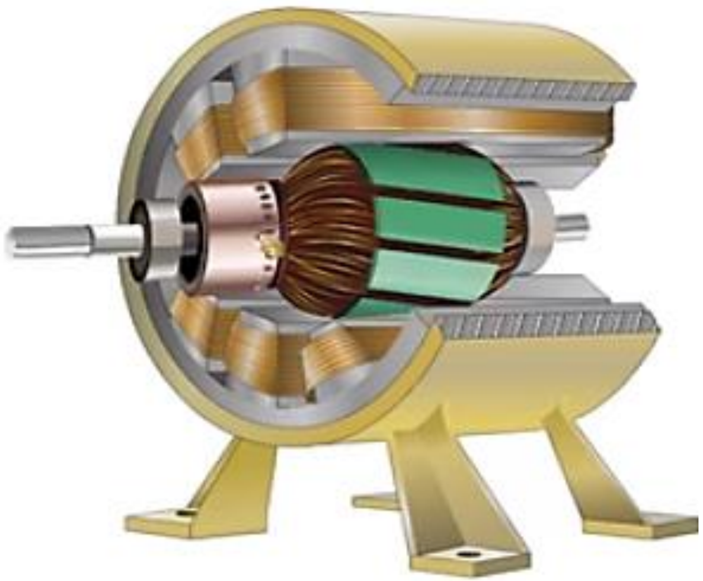




MK

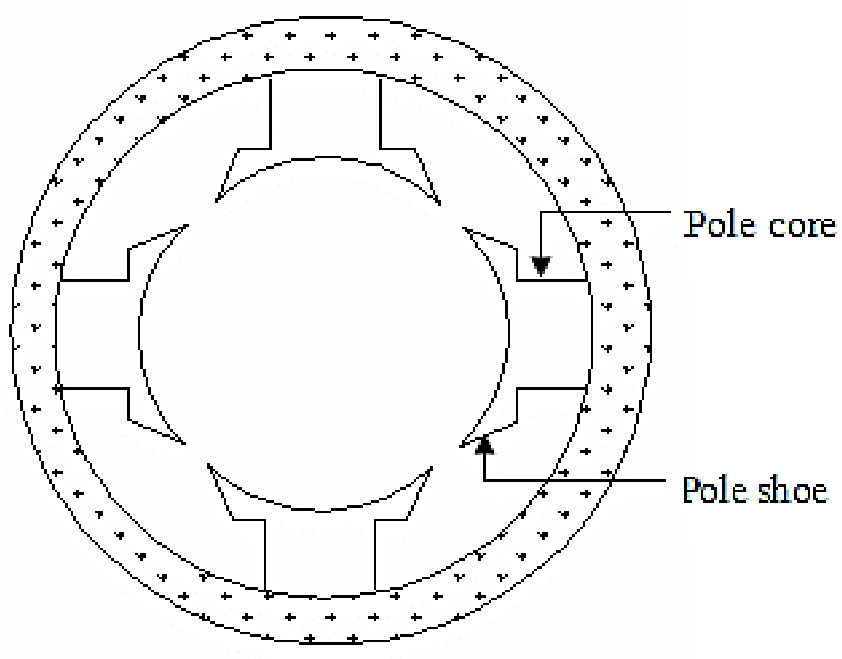
Yoke:.

- It is the **outermost frame** of the machine.
- It provides **mechanical support** to the field pole and also acts as **protecting cover** for the whole machine.
- It also **carries the magnetic flux** produced by the field poles.
- For the sake of cheapness, yoke is usually made of **cast iron** in small machine. Whereas, in case of large machine, efficiency is more concerns. Hence, yoke of the large machine is made of **cast steel** or rolled steel having **higher value of permeability**.

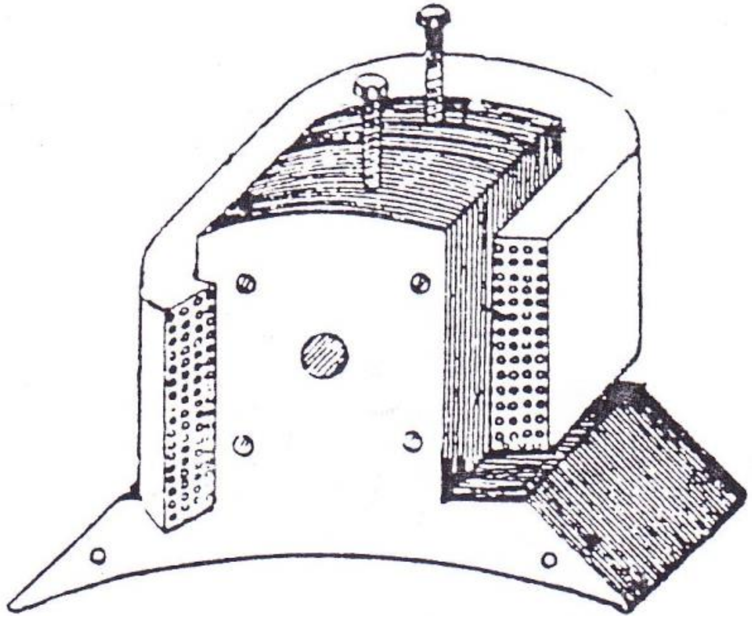


Field poles:

- Field poles are the **iron core projected from the yoke.**
- The upper part of the pole, which is connected to the yoke, is known as **pole-core**.
- The lower and wider part is known as **pole-shoe**.
- The field poles are generally **made of laminated annealed steel sheet.**

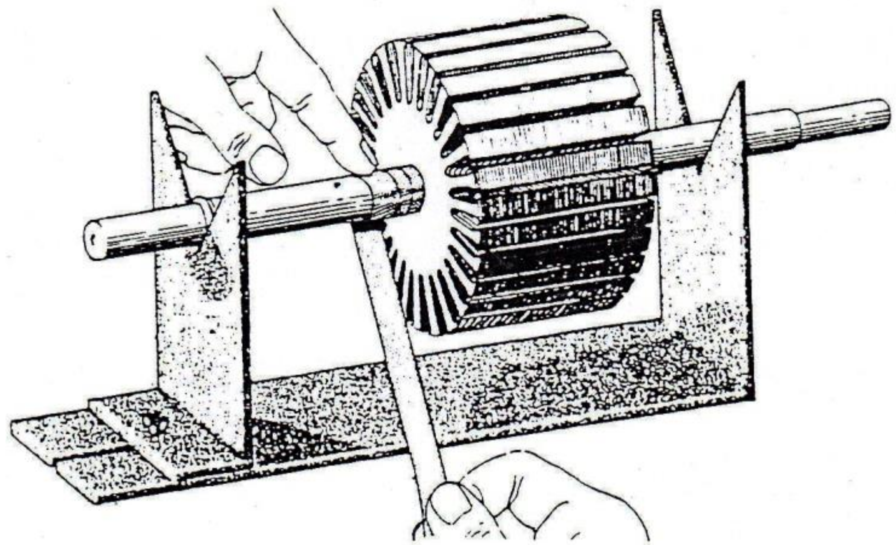


Field windings



- It is the **copper wire wound on the field pole.**
- The windings are **insulated from the core** and each turns of windings are also **insulated from each other** to protect from turn to turn short circuit.
- When **DC current is passed** through these windings, the pole core **gets magnetized and produces magnetic flux** in the central space of the machine.

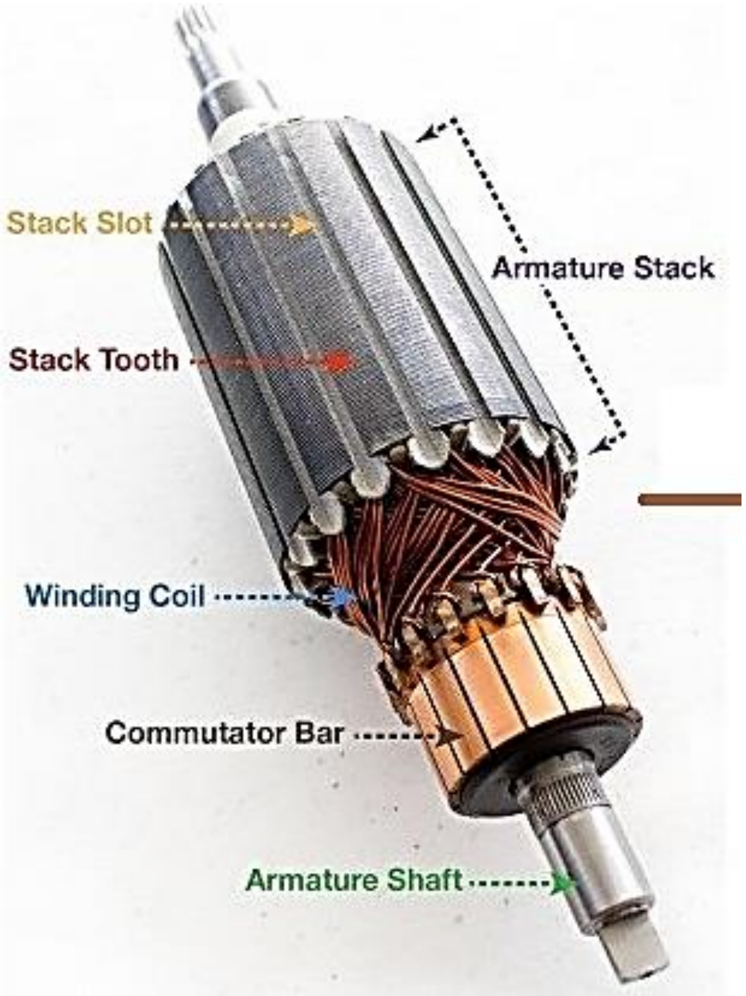
Armature

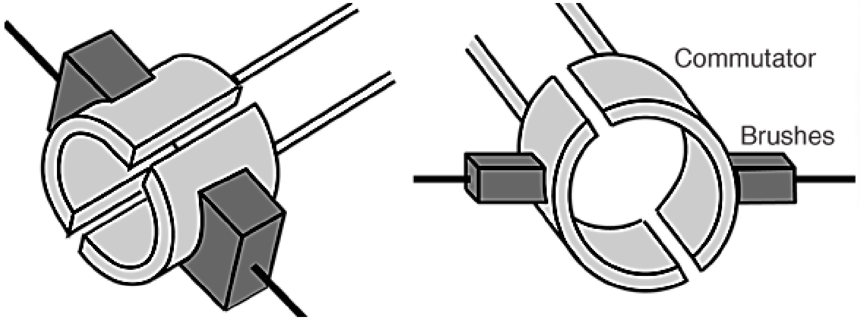


- It is the **rotating part of the machine.**
- The various parts of an armature are **shaft**, armature **core**, armature **winding** and **commutator**.
- The bearings at both ends hold the shaft on the central empty space of the machine.
- The armature core is made of **laminated silicon steel sheet insulated with varnish.**

Commutator

- It is made of many numbers of **copper segments insulated from each other and from the shaft**.
- The **coil ends of the armature windings are connected to each commutator segments.**
- Depending upon the manner in which the armature conductors are connected to the commutator segments, there are two types of the armature winding in a DC machine:
    - **Lap winding**
    - **Wave winding**



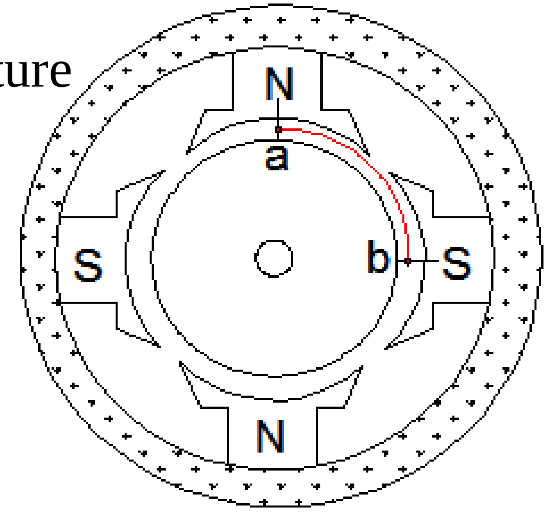


Carbon brush

- A carbon brush is a component used to **conduct electrical current between the stationary and rotating parts of a motor.**
- In a generator or motor, the **commutator rotates on a shaft and the fixed carbon brush rides on it to permit the flow of electricity and complete a circuit**

Armature Winding:

- It is **enamel insulated copper wire wound on the slots** of the armature core. There are definite rules and methods for armature winding.

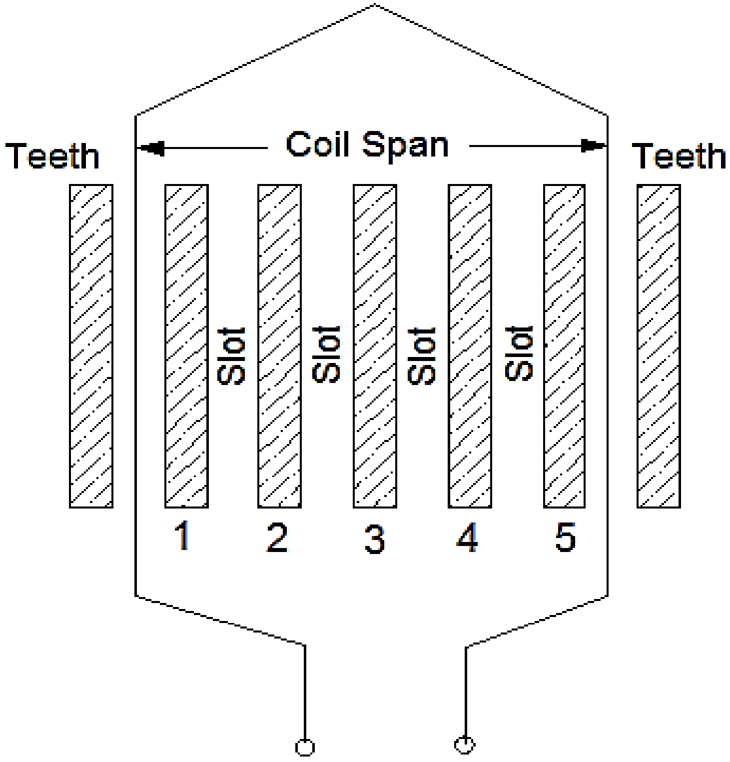


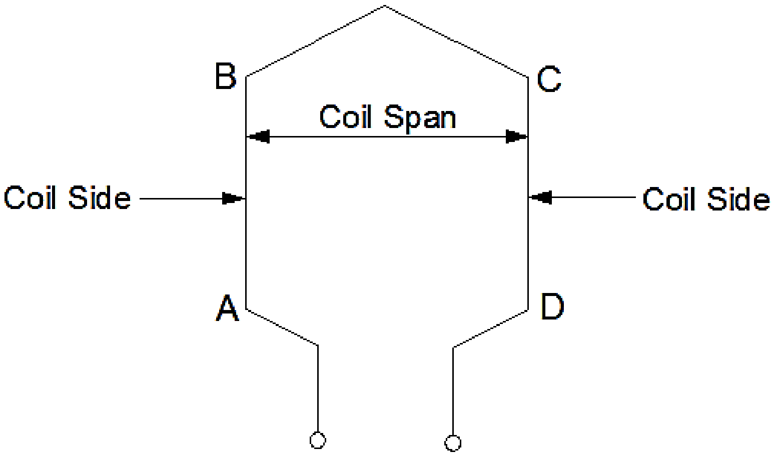
i) Pole pitch :

- It is defined as the **peripheral distance of armature core divided by number of poles** or it is the **distance between adjacent poles.**

ii) Conductor:

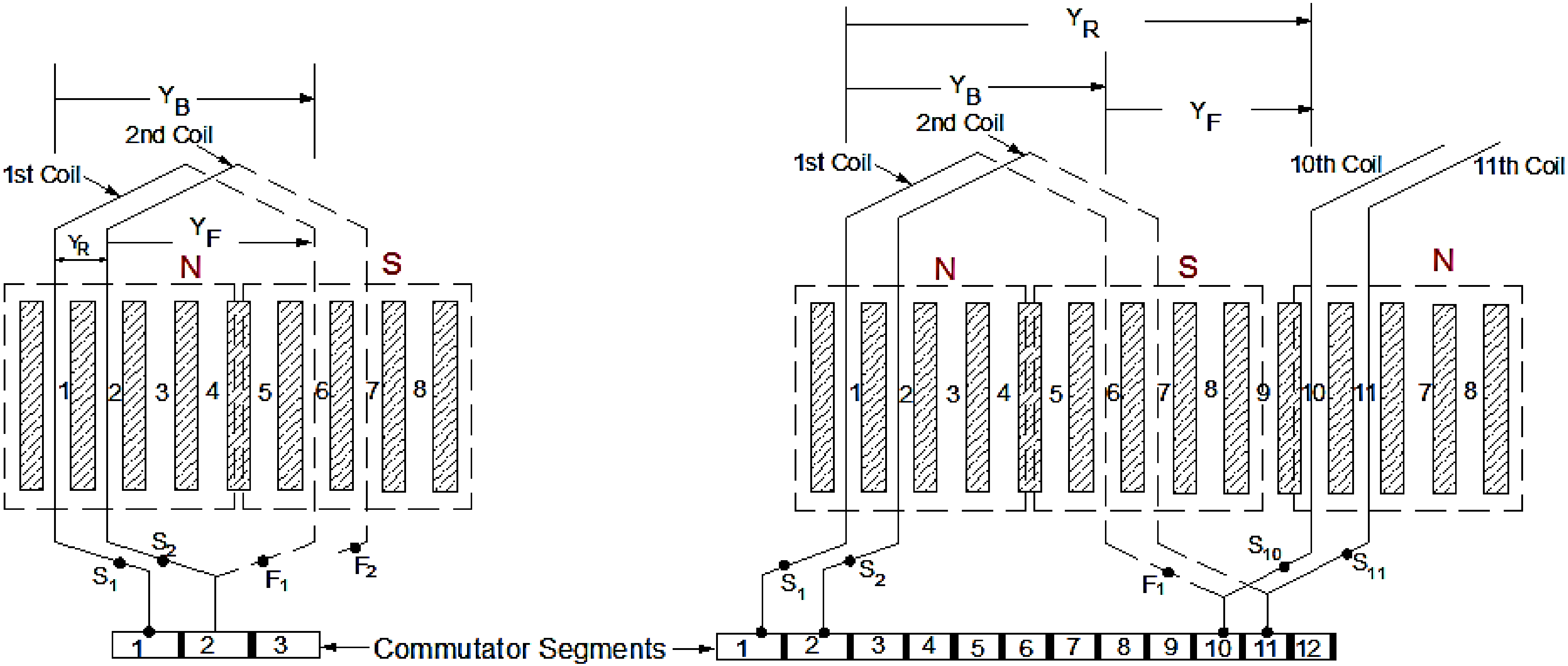
- The **length of the armature winding conductor lying within the magnetic field is the conductor.**
- Fig. shows a coil ABCD. The length AB and CD are known as conductor but length BC is not a conductor as emf does not induce in this section.





Types of armature winding:

Lap winding **Wave winding**



- **In case of Lap winding, the number of parallel path = Number of field poles.**
- **In case of Wave winding, the number of parallel path = 2 (irrespective of no of poles)**

Working Principle:

- **Faraday's law of electromagnetic induction : REVISION**

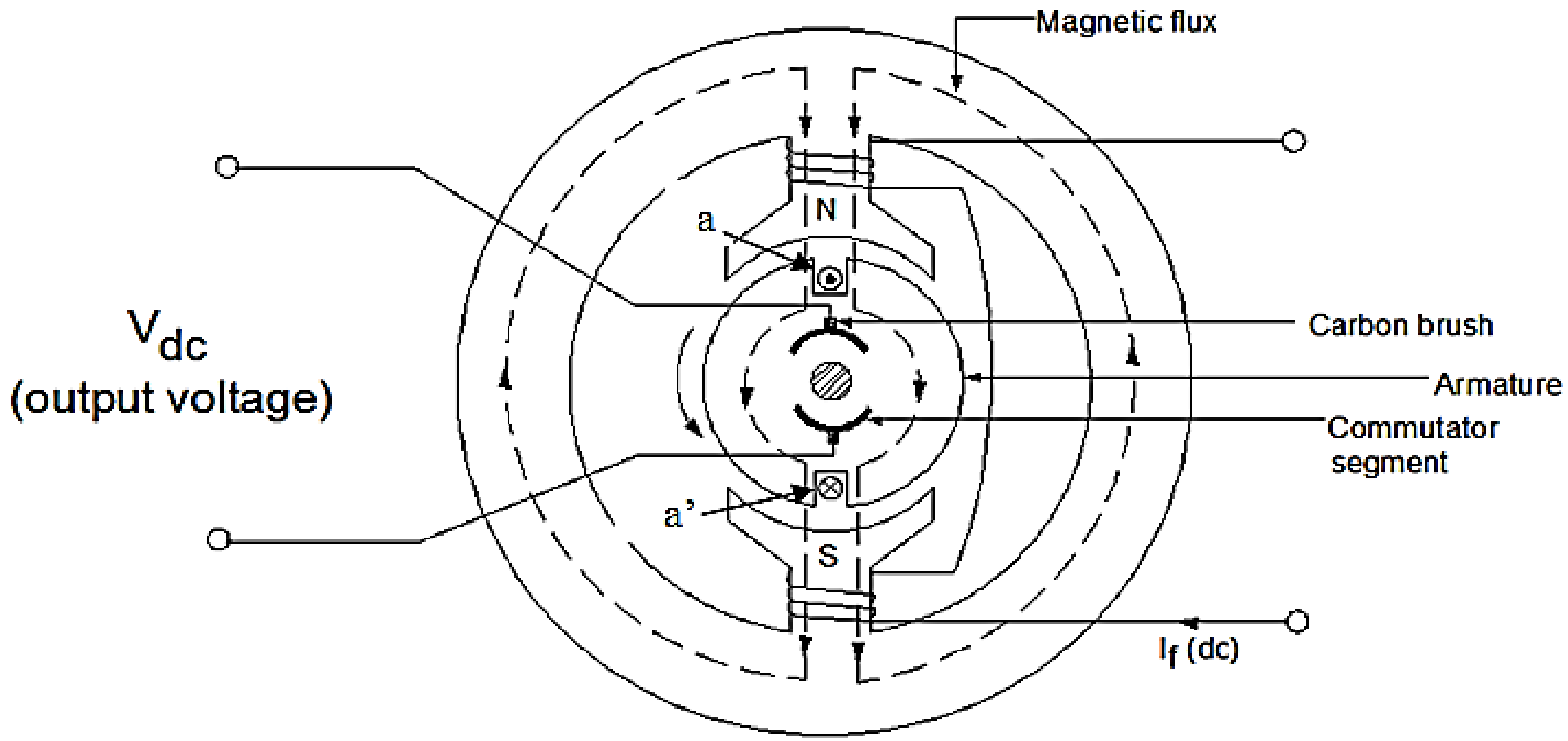
  - **First law: "Whenever the magnitude of magnetic flux linking with a coil changes with respect to time, an emf will be induced in the coil'.**
  - **Second law: "The magnitude of induced emf is equal to the rate of change of flux linkage".**

- Change in flux linkage can occur in three ways:
  (i) Coil is stationary w.r.t flux but magnitude of flux through the coil changes w.r.t time **(Statically induced emf)**
  (ii) Magnetic flux is constant and stationery but coil moves relative to the magnetic flux **(Dynamically induced emf)**
  (iii) Both (i) & (ii)

- Generators basically work on principle of **dynamically induced emf** therefore, the essential components of a generator are:
  (a) Magnetic flux
  (b) Conductor or a coil
  (c) Relative motion between the conductor and the flux

Working Principle:

- When the **field winding is excited by DC current (I_f)**, the **field poles get magnetized** and **magnetic flux flows** as shown in Fig.
- If the **armature is rotated continuously by some prime mover**, then the armature conductors **a** and **a'** continuously cut the magnetic flux.
- Hence, according to **Faraday's law of electromagnetic induction emf will induce in the armature conductors.**



Voltage Generation

- When load is connected across the coil then current flows through the load and the direction of current is given by the **Fleming's Right Hand Rule**.
- From the analysis it is clear that the nature of emf induced in the conductors **a and a'** is alternating (ac) in nature.

Position of armature (θ)	Magnitude of emf (e)	Direction of emf
0^0	**0**	
30^0	**$0.5\ E_m$**	**positive**
90^0	**E_m**	**positive**
135^0	**$0.707\ E_m$**	
180^0	**0**	
210^0	**$-0.5\ E_m$**	**Negative**
270^0	**$-\ E_m$**	**Negative**
360^0	**0**	

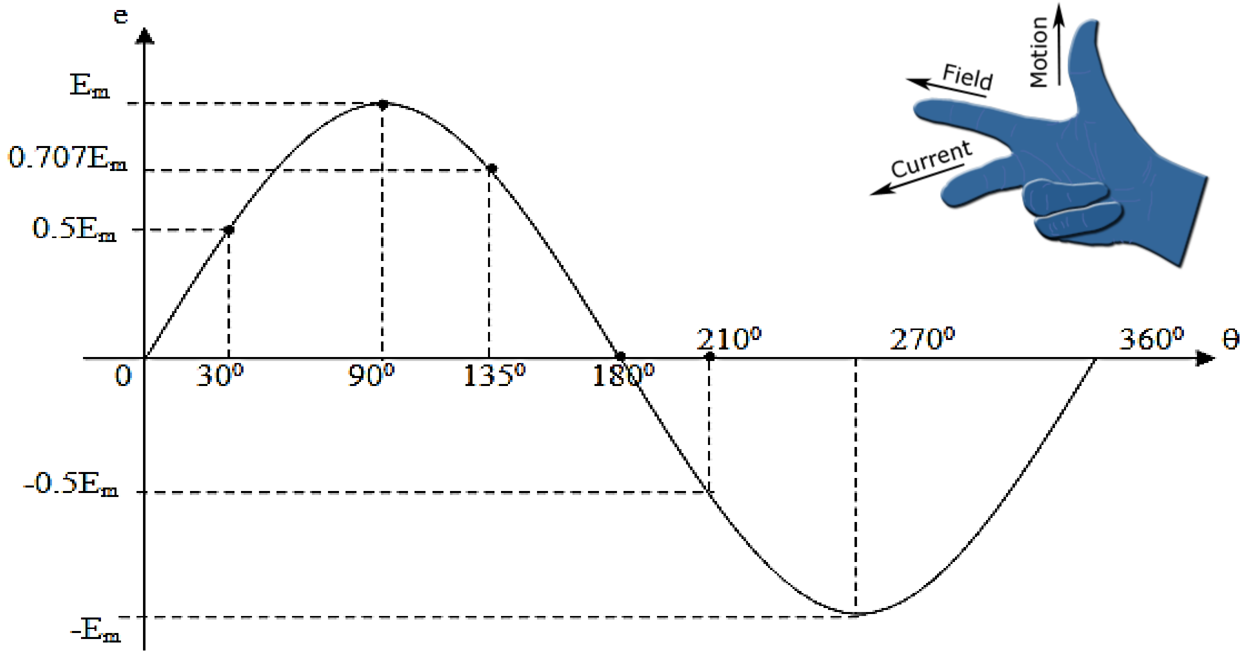
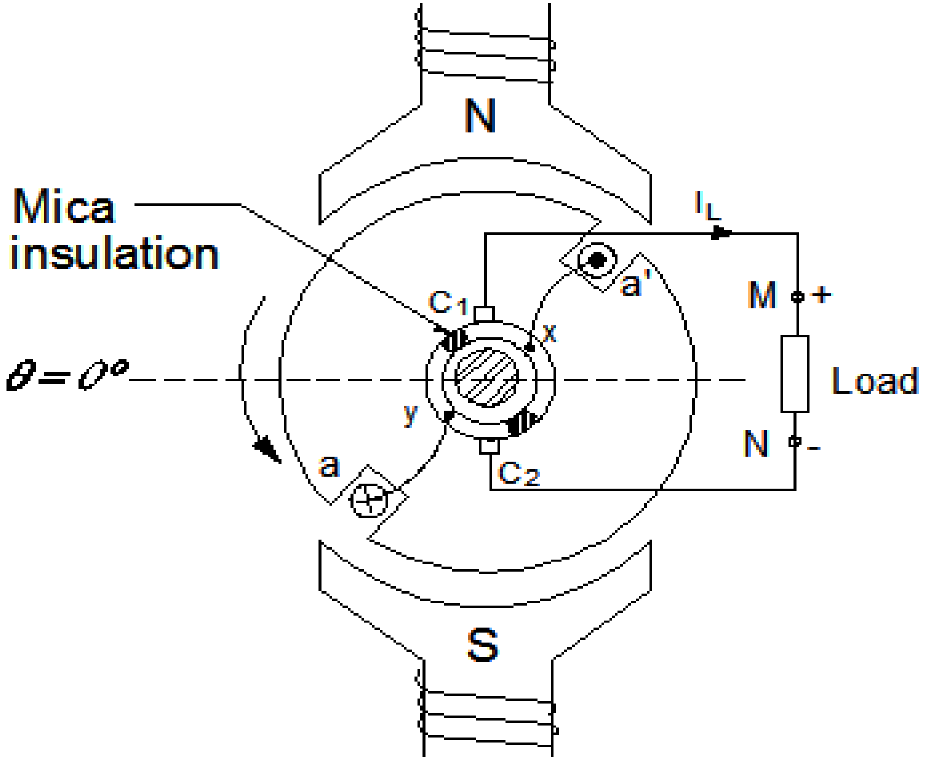


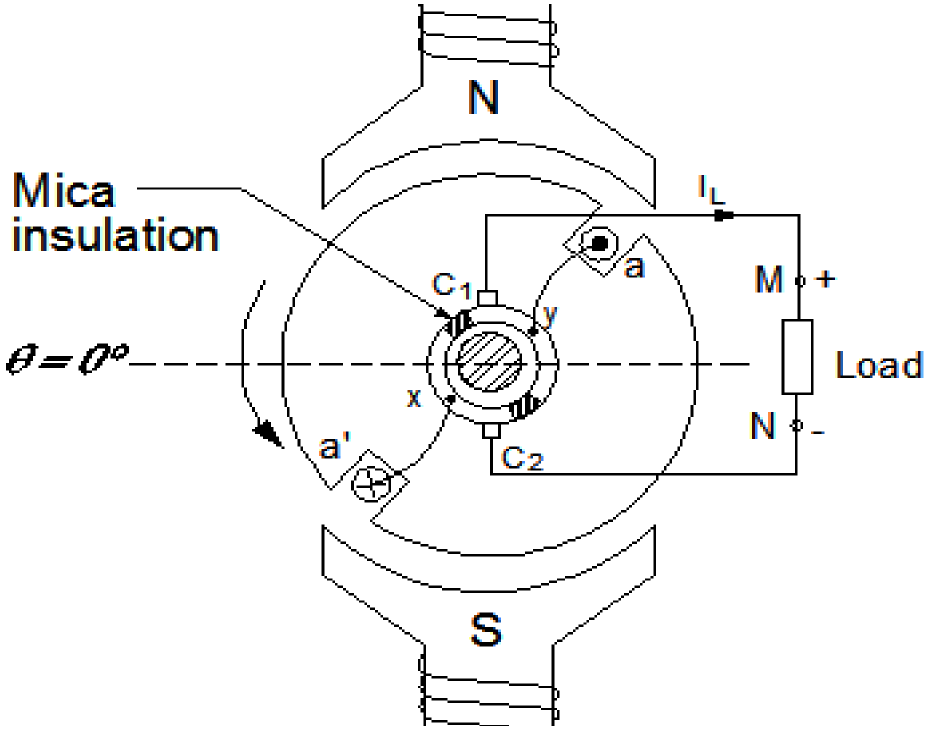
Fig. Waveform of emf induced in the armature coil.

- We encounter **two problems** here:
  - Connection of stationary external load to the rotating coil (armature) **→ Carbon Brush**
  - Output from the coil is ac but we are looking for DC voltage **→ Commutator Segments**
- These problems can be overcome **by the use of commutator segments and the carbon brushes.**

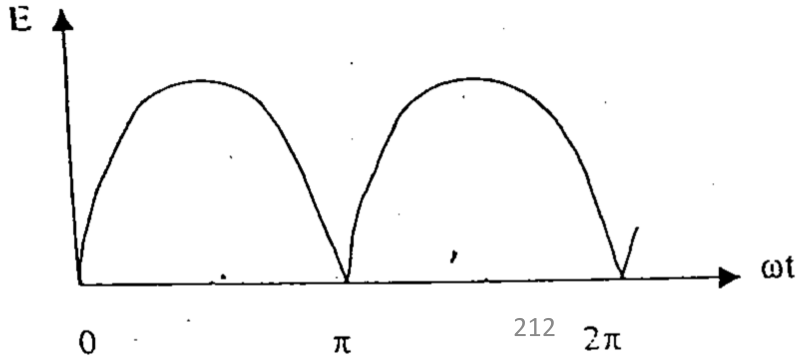
Commutator segments and carbon brushes

- Conductors **a** and **a'** are connected to the commutator segment X and Y respectively
- Commutator segments rotates along with the armature coil but the carbon brushes C1 & C2 are fixed and touching over the commutator segments surface as shown in Fig.



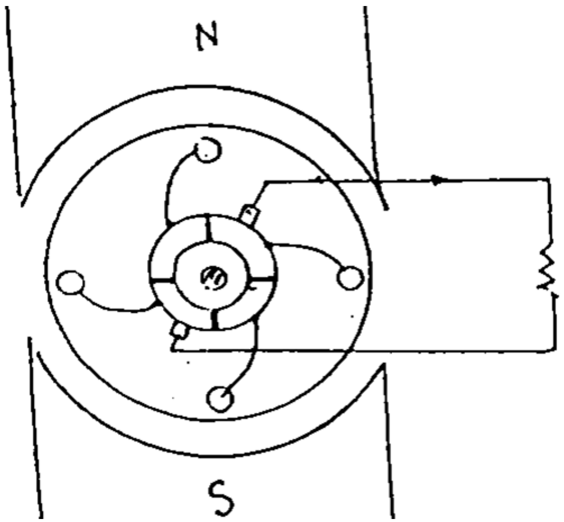


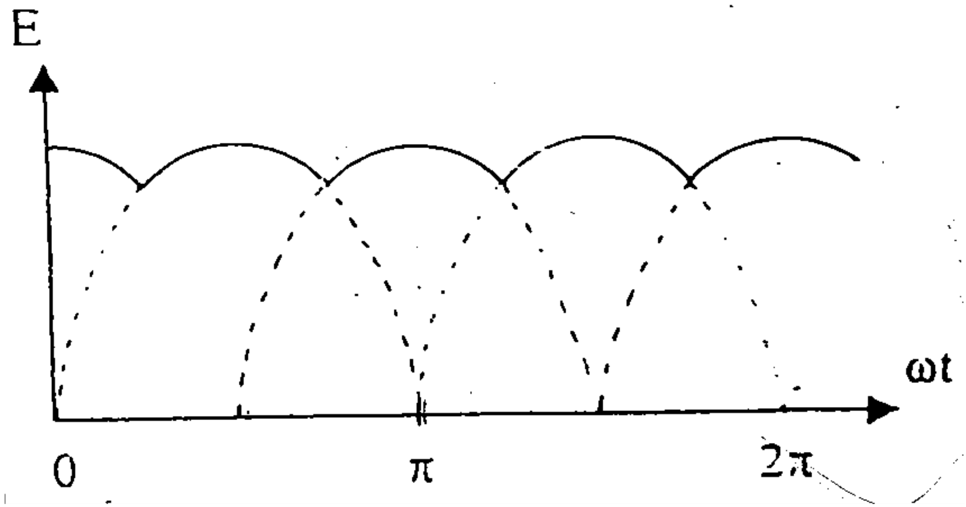
- In both cases the direction of the current through the load is from **M** to **N**.
- The nature of emf across the load is as shown in figure.



Output voltage waveform

- If we **increase number of armature coils** as shown in fig(5), then the nature of emf across the load will be as shown in fig (6) which is **more smooth than that in case of a single coil.**





EMF equation

Let **φ** = Magnetic flux per pole (wb)
P = Number of magnetic poles
Z = total numbers of armature conductors
N = speed of the armature in RPM

Average emf generated per conductor = $\frac{d\varphi}{dt}$

Magnetic flux cut by each conductor in one revolution = $d\varphi = \varphi \, .P$

Time for one revolution $dt \; = \frac{60}{N} sec$

EMF equation for a DC Generator

Average emf generated per conductor = $\frac{d\varphi}{dt} = \frac{\varphi.P.N}{60}$ volts

If **A** = number of parallel paths in the armature winding

Total conductors in series $= \frac{Z}{A}$

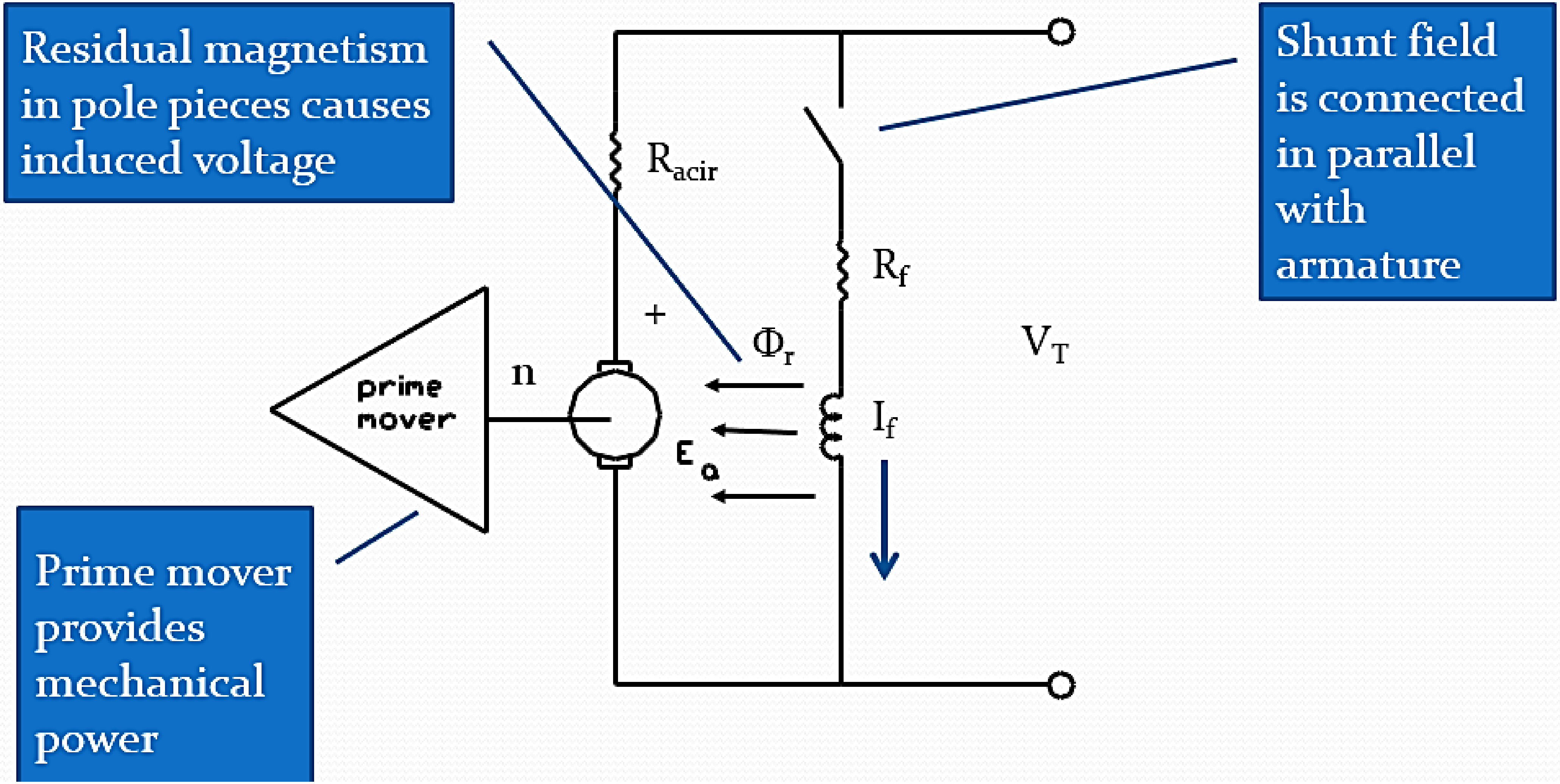
Total emf across the brushes (E) = $\frac{\varphi.P.N}{60} \times \frac{Z}{A}$ **volts**

$$E = \frac{Z.\phi.N}{60} \times \frac{P}{A} \text{ volts}$$

***A = P for lap winding**
A = 2 for wave winding

Typical Circuit representation for a DC Generator

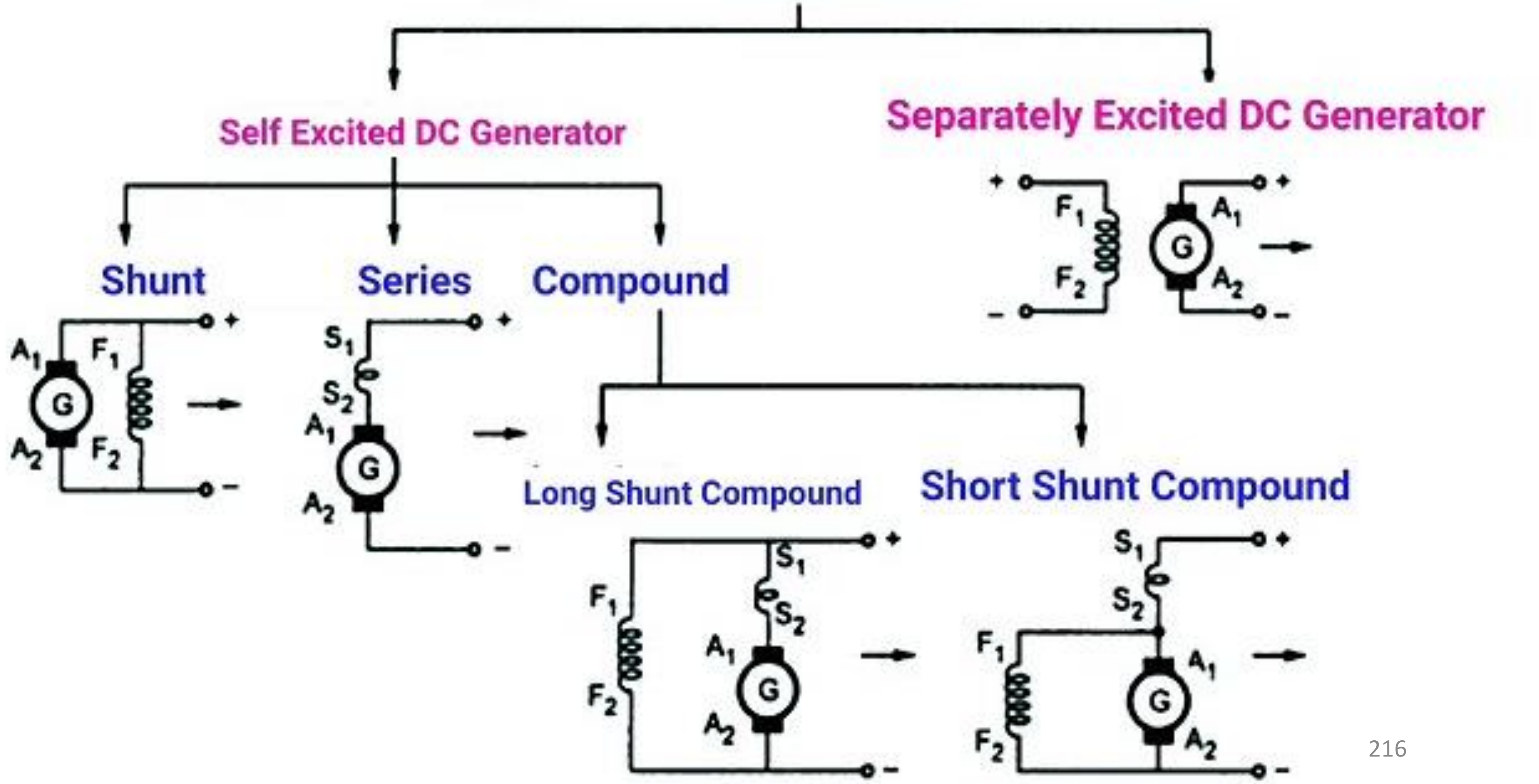
With field switch open only residual flux can produce E_a



Types of DC generator:

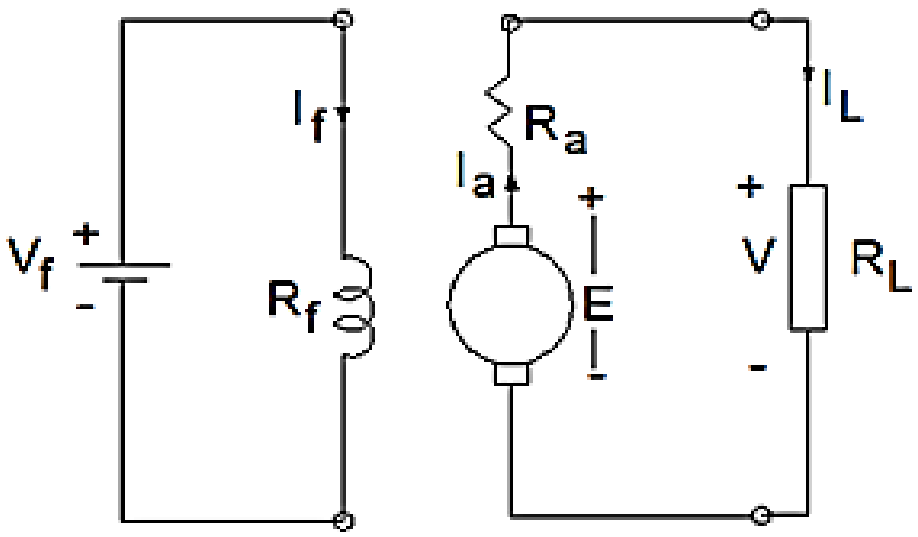
- The field winding of a DC generator has to be supplied by DC current in order to produce magnetic field. The supply of DC current to the field winding is known as "**excitation**".

- The excitation can be provided by various ways and accordingly DC generators are classified as follows **(based on excitations)**:
  - **a) Separately excited DC generator**
  - **b) Self-excited DC generator**



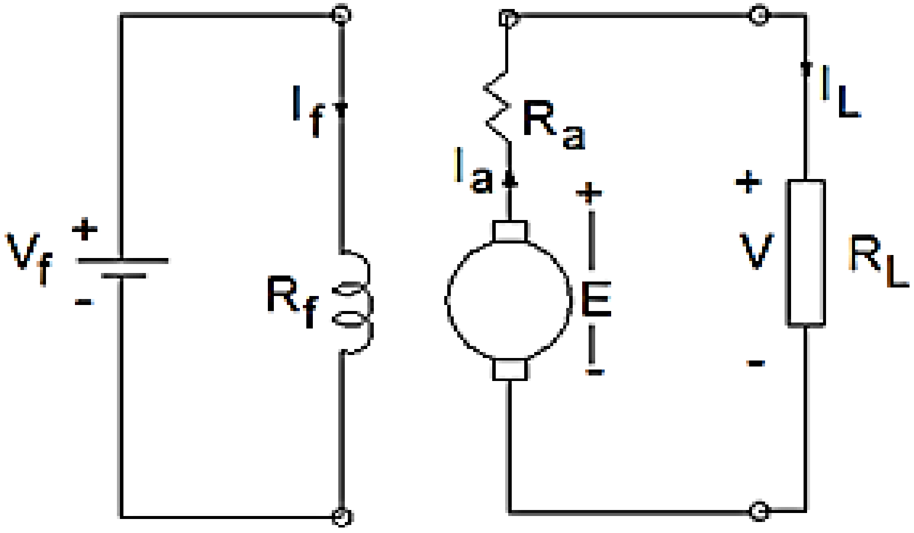
a) Separately excited DC generator:

- It is the generator, whose field winding is excited by an independent external DC voltage source as shown in Fig.
- There is no electrical connection between field winding and armature winding



Here,
R_f = Resistance of field winding
I_f = Current through the field winding
E = Emf induced across the armature circuit
R_a = Resistance of armature circuit
V = Terminal voltage across the load
R_L = Load resistance
I_L = Load current

a) Separately excited DC generator:



$$I_f = \frac{V_f}{R_f}$$

Here, $I_a = I_L$

Using KVL in armature and load circuit:

$$E - I_a.R_a - I_L.R_L = 0$$

Therefore, $E - I_a.\ R_a = V$

[$I_L.R_L = V =$ **load terminal voltage]**

- The terminal voltage is always less than the emf generated, because there will be some voltage drop in the armature resistance.
- Some voltage drop also takes place in the contact resistance between carbon brushes and commutator segments. Hence, the actual terminal voltage is given by:

$$\boxed{V = E - I_a.\ R_a - \text{Voltage drop in the brushes}}$$

Power developed by armature, $P_g = E * I_a$

Power delivered to external load, $P_L = V * I_a$

b) Self-excited DC generator

- A dc generator whose **field winding is excited by the current supplied by the generator itself,** is called a self-excited generator.

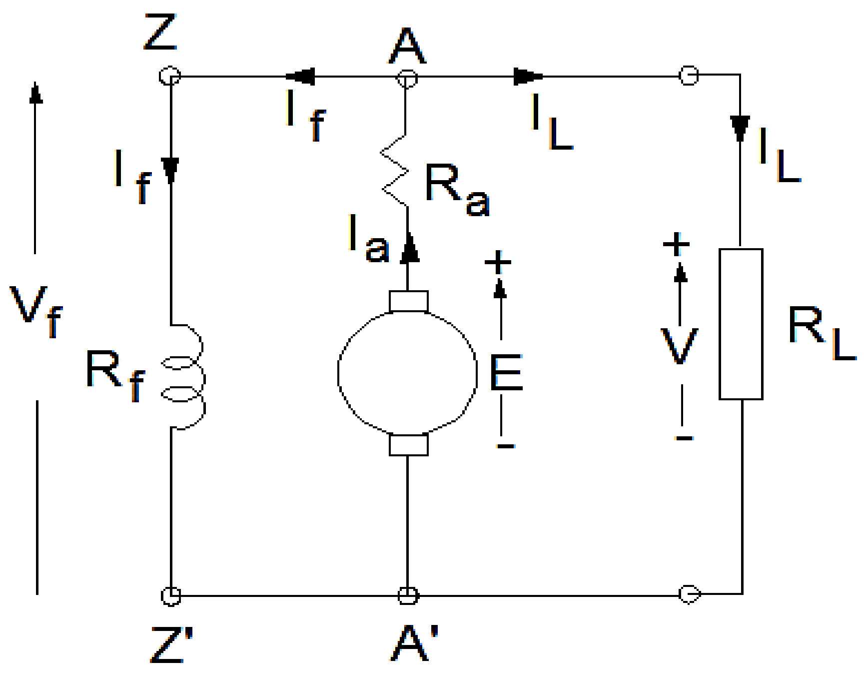
- In such machines the field coils are interconnected with the armature winding. The field coils may be connected either in series with the armature, in parallel with the armature or partly in series and partly in parallel with the armature.

- Accordingly the self-excited generators may be classified as:
  - **i. DC Shunt generators**
  - **ii. DC Series generators**
  - **iii. DC Compound generators**

i) DC Shunt generator:

In this type of generator, **the field winding and armature winding are connected in parallel..**

$$\text{Field winding curreny } I_f = \frac{V_f}{R_f} = \frac{V}{R_f}$$



Here, $\mathbf{I_a = I_L + I_f}$

Terminal voltage across the load $\mathbf{V = E - I_a . R_a}$

$$\text{Load current } I_L = \frac{V}{R_L}$$

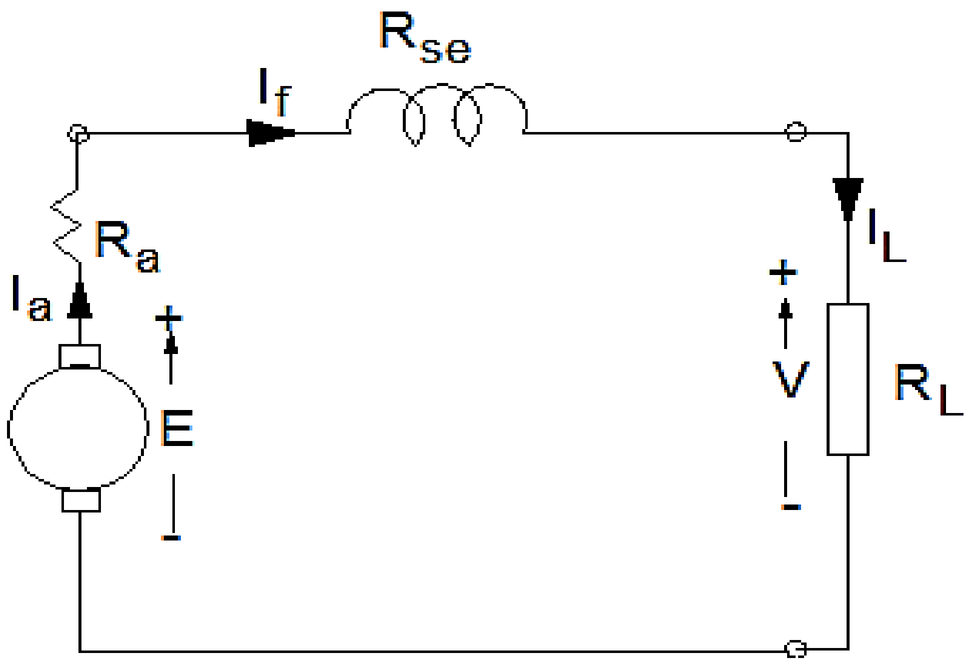
As the field winding current is much less with compare to armature current & load current, the **field winding is made of thin wire and it will have higher resistance with compare to R_a.**

ii) DC Series Generator:

- In a series wound generator, the field winding is connected in series with the armature winding,
- In this case, the **field winding** is made up of **thick winding wires** such that the armature current can flow through the wires of the field winding without overheating and **resistance must be low enough to reduce the voltage drop across field winding.**
- Thus, in the case of series connection, flux $\emptyset \propto I_a$

Field winding current = Armature Winding current = Load current

$$\mathbf{I_f = I_a = I_L = I}$$



Terminal voltage across the load

$$V = E - I_a R_a - I_a R_{se}$$

iii) DC Compound Generators

- In compound wound generators, there are **two field windings**

- One of them (having many turns of fine wire) is **connected across the armature** and the other having few turns of thick wire is **connected in series with the armature winding.**

- Therefore, such type of generators will have a mixed **characteristics lying between shunt and series generator.**

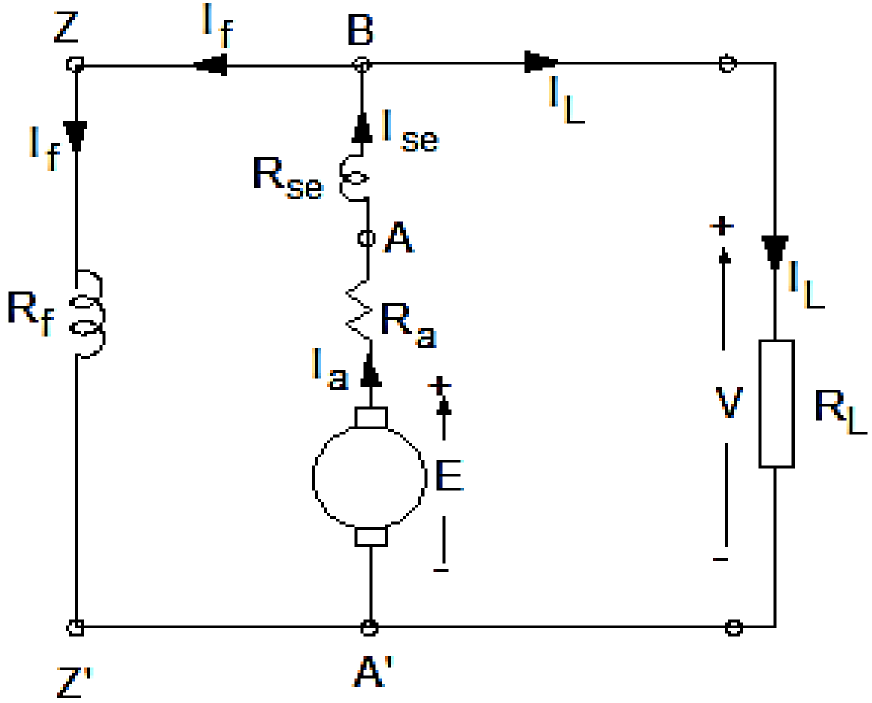
- The **series winding** is made from **thick wire** with **few turns** because it has to **carry full load current** whereas **shunt field** winding is made from **thin wire** with many **number of turns** because **full rated voltage appears across it.**

- The compound generator had been further classified into following two types:
  - **i. Long shunt compound generator**
  - **ii. Short shunt compound generator**

For long shunt generator:

$$I_f = \frac{V}{R_f}$$

$$V = E - I_a R_a - I_a R_{se}$$

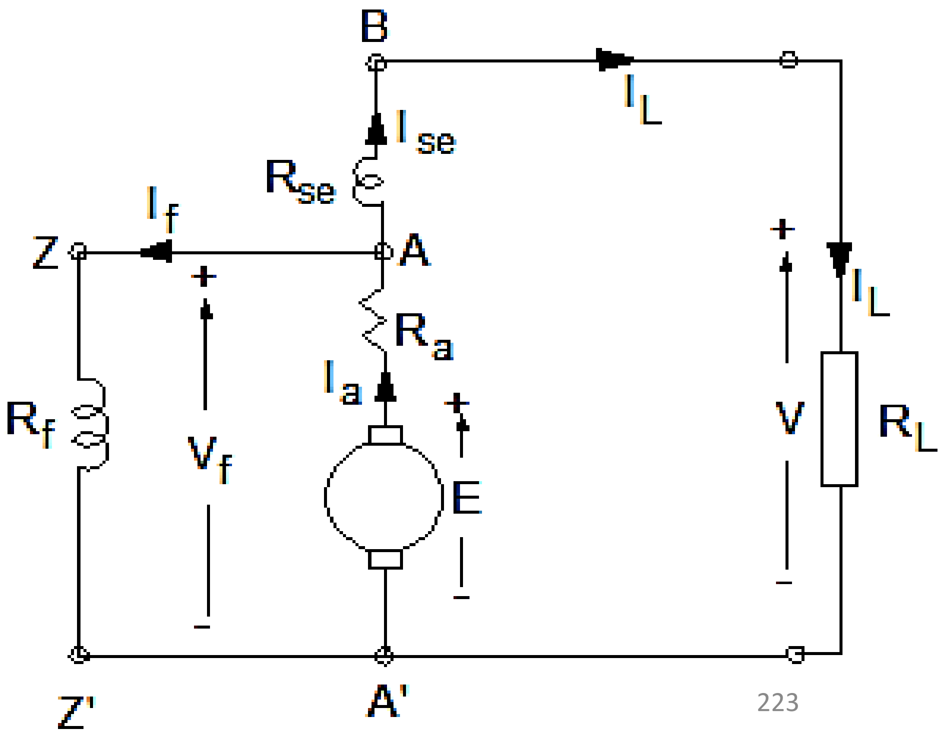


For short shunt generator:

$$I_f = \frac{V_f}{R_f} = \frac{E - I_a R_a}{R_f}$$

$$V_f = V - I_{se.} R_{se}$$

$$V = E - I_a R_a - I_L R_{se}$$



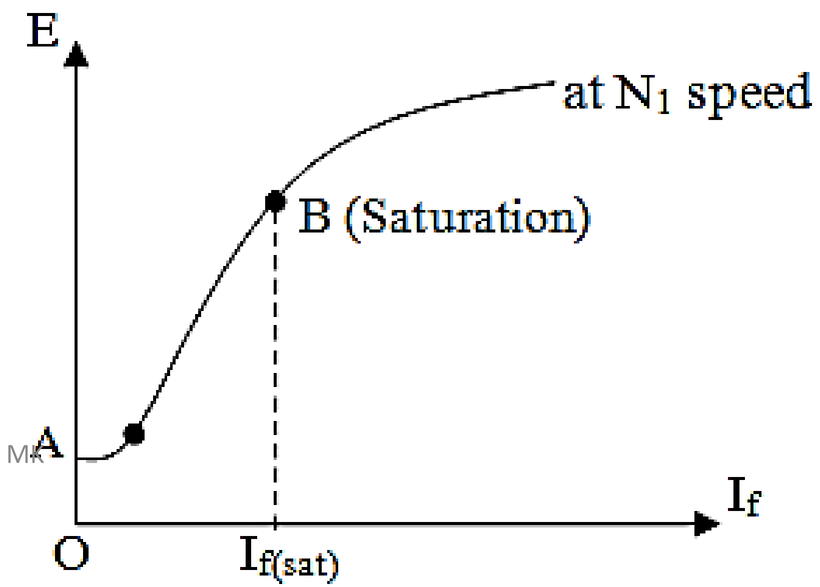
Characteristics of DC Generator

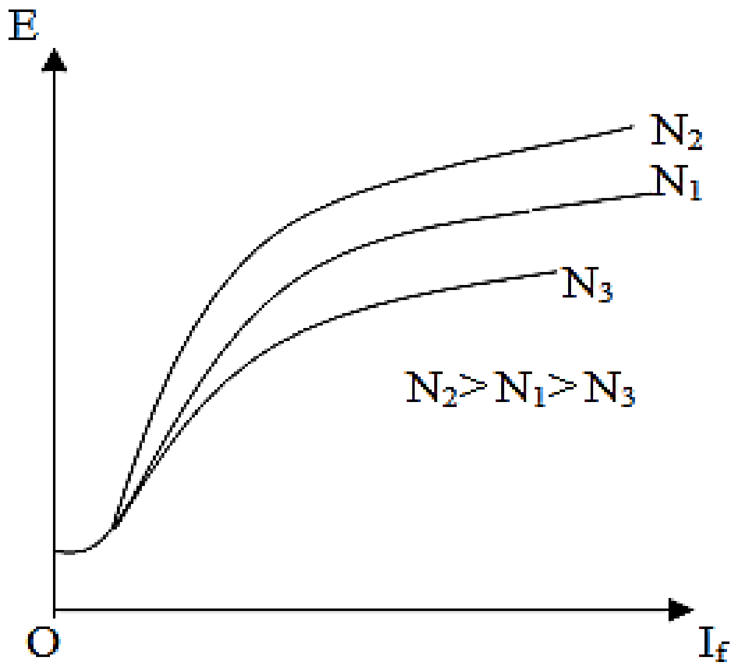
Different types of generators will have different characteristics and these characteristics can be expressed in the following two curves.

1. **No-load characteristics (or open circuit characteristics)**
2. **Load Characteristics**

No load characteristics or OCC or Magnetic characteristics

- It is a curve showing the **magnitude of emf generated across the armature at different values of field current at constant rated speed.**
- The no load characteristics of all types of dc generators are similar.

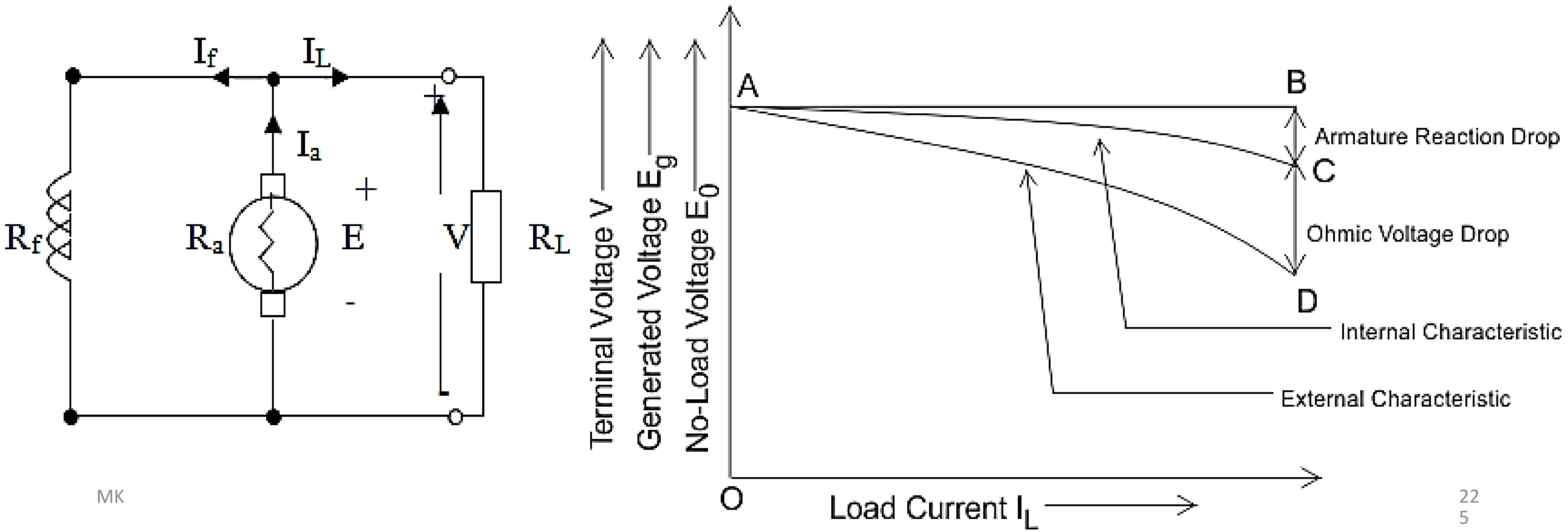




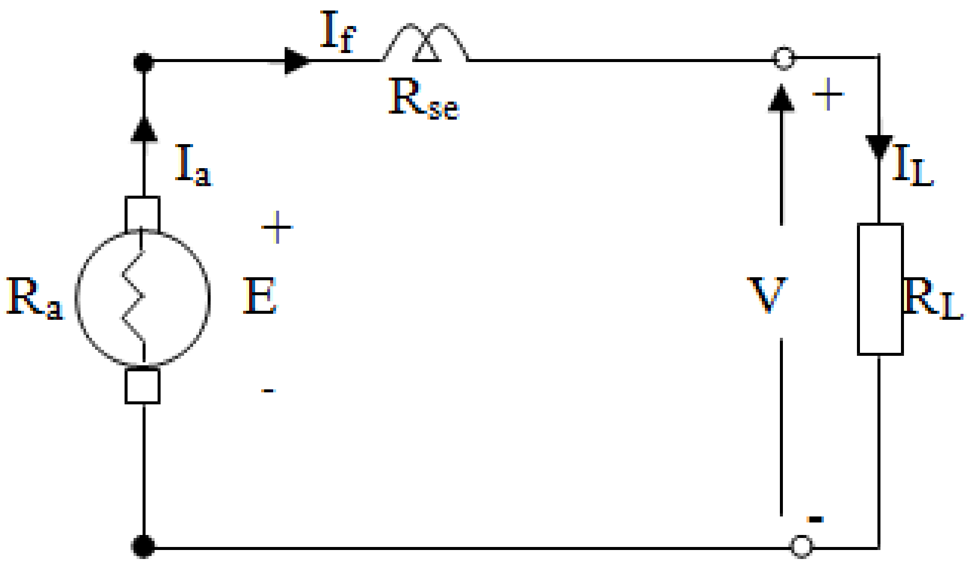
Load characteristics or external characteristics or performance characteristics

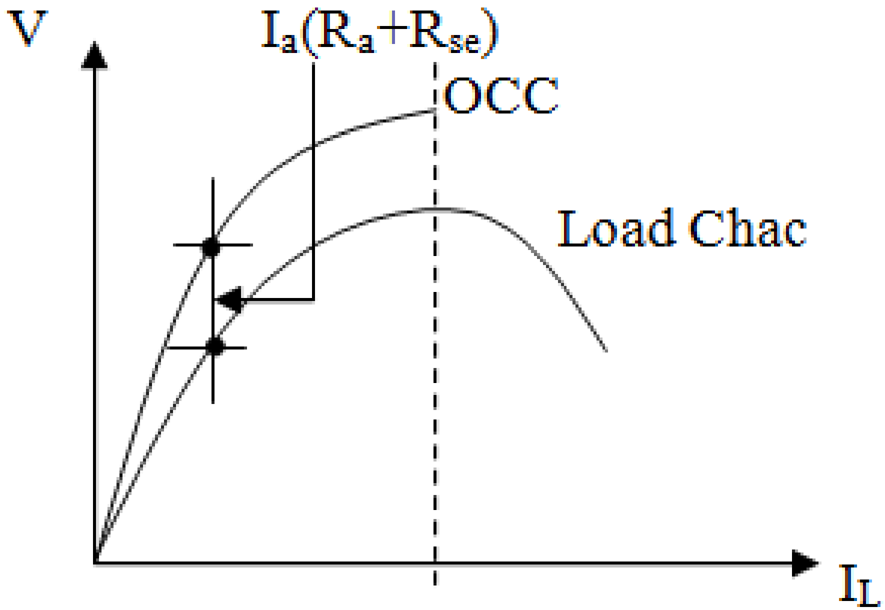
- It is the curve showing the **magnitude of load terminal voltage (V) at different values of load current** when driven at rated speed and rated field current is applied in field.
- It is very important to determine the suitability of a generator for a given purpose.

<u>Shunt generator load characteristics</u>:



Series generator load Characteristics:



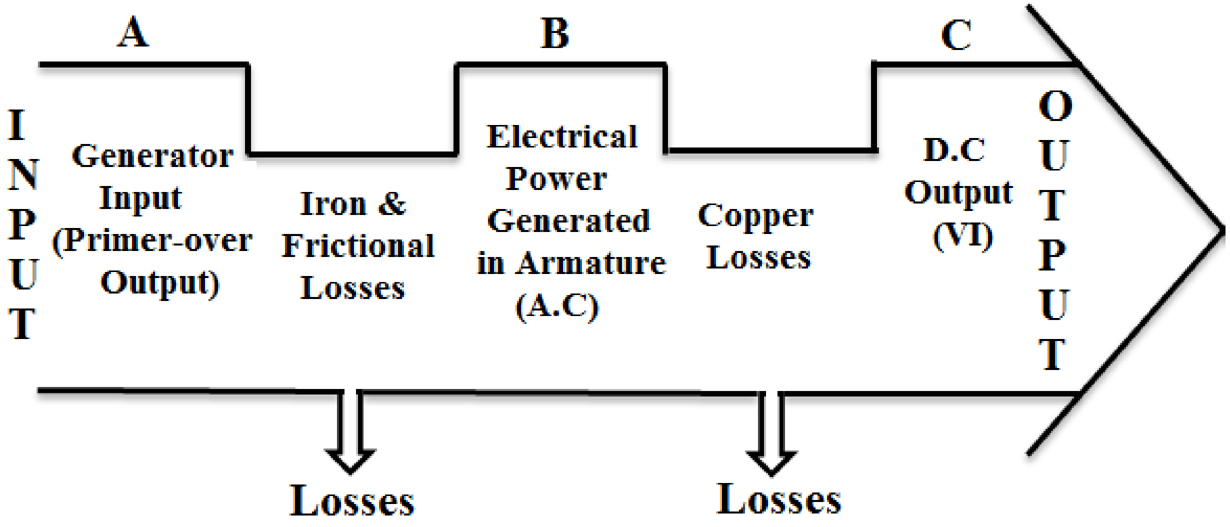


- When the **load current (I_L) increases**, the armature current as well as the field current increases, the voltage drop $I_a(R_a + R_{se})$ increases. But, at the same time, **the air gap flux increases due to increase in I_f. Therefore, magnitude emf induced 'E' increases.**

- **Before the magnetic saturation**, the increase in emf dominates the armature voltage drop. Therefore, **load terminal voltage increases with load current up to the saturation** as shown in Fig.

- However **at over-load condition**, the load terminal voltage starts decreasing **due to excessive demagnetizing effect of armature reaction and saturation effect.**

Power Stages in DC Generators:



(*i*) **Mechanical efficiency**

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

(*ii*) **Electrical efficiency**

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

(*iii*) **Commercial or overall efficiency**

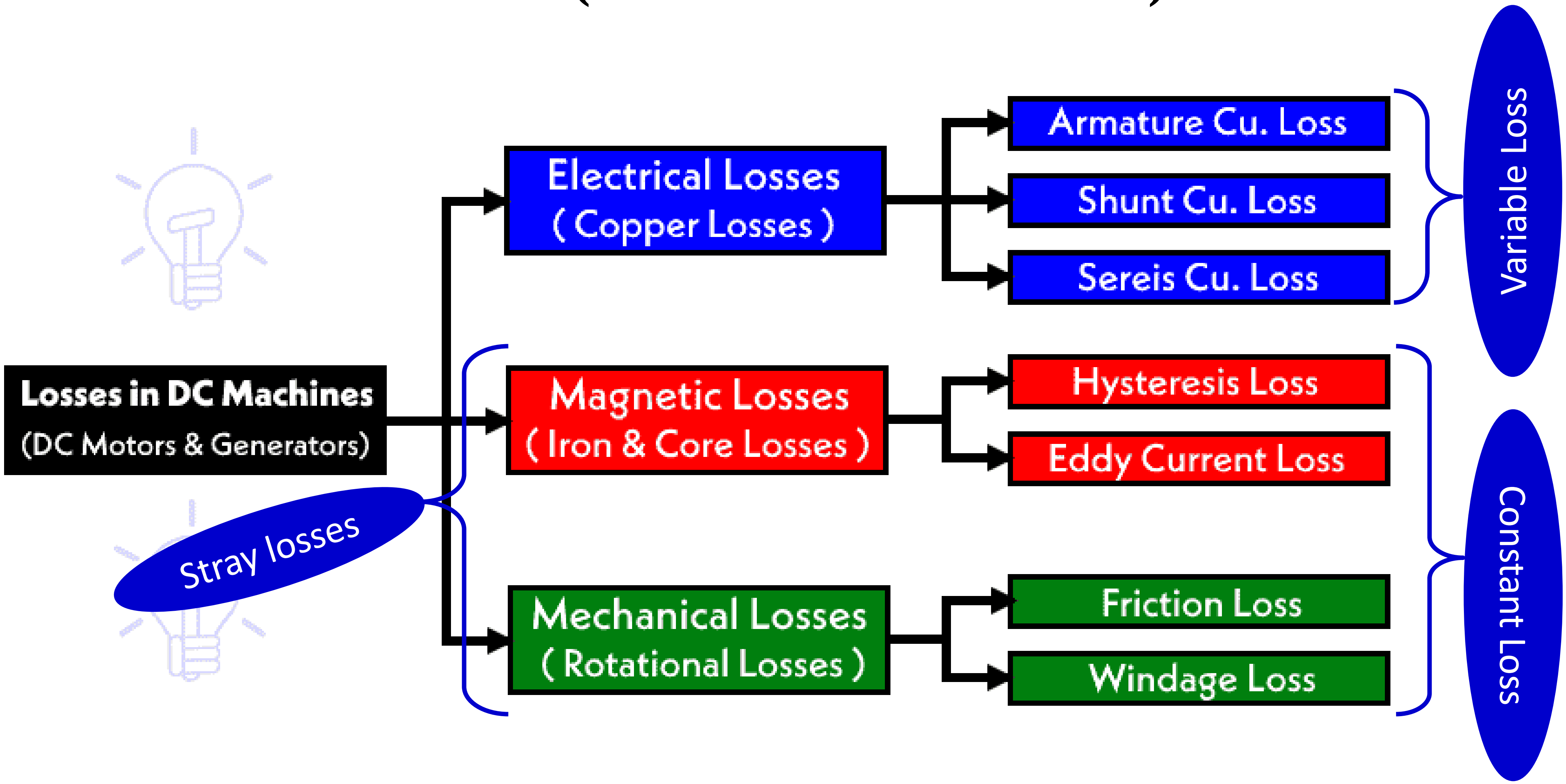
$$\eta_c = \frac{C}{A} = \frac{V I_L}{\text{Mechanical power input}}$$

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

Unless otherwise stated, commercial efficiency is always understood.

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

Losses in DC Machines (Generators and Motors):



MK

Voltage Regulation of DC generator

Let $_{0}V_{L}$ = load terminal voltage at no-load
$_{f}V_{L}$ = load terminal voltage at full-load

The total voltage drop from no-load to full-load = $_{0}V_{L}$ - $_{f}V_{L}$

Voltage regulation of dc generator is defined as change in load terminal voltage (from no-load to full-load) expressed as percentage of no-load terminal voltage.

Hence, Voltage Regulation (%) $= \dfrac{{}_{0}V_{L} - {}_{f}V_{L}}{{}_{0}V_{L}} \times 100$

Illustrative Example :

A 4 pole generator with wave wound armature has 51 slots each having 24 conductors rotate to give an induced emf of 220 V. What will be the voltage developed if the winding is lap and the armature rotates at the same speed?

Solution:

$$
\begin{aligned}
E_g &= \frac{\phi Z N}{60} \times \frac{P}{A} \\
220 &= \frac{0.01 \times 51 \times 24 \times N}{60} \times \frac{4}{2} \\
N &= 539.2156 rpm
\end{aligned}
$$

Voltage developed with lap wound

$$
\begin{aligned}
E_g &= \frac{\phi Z N}{60} \times \frac{P}{A} \\
&= \frac{0.01 \times 51 \times 24 \times 539.215}{60} \times \frac{4}{4} \\
&= 110V
\end{aligned}
$$

MK

Illustrative Example :

A 4 pole lap wound DC shunt generator delivers 200 A at terminal voltage of 250 V. It has a field and armature resistance of 50 Ω and 0.05 Ω respectively. Neglecting brush drop determine i) armature current ii) current per parallel path iii) EMF generated iv) power delivered.

Solution:

i) armature current

$$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{50}$$
$$= 5A$$

$$I_a = I_L + I_{sh} = 200 + 5$$
$$= 205A$$

ii) current per parallel path

$$= \frac{I_a}{4} = \frac{205}{4}$$
$$= 51.25A$$

iii) EMF generated

$$E_g = V + I_a R_a = 250 + 205 \times 0.05$$
$$= 260.25V$$

iv) power delivered

$$= E_g I_a = 260.25 \times 205$$
$$= 53.35kW$$

MK

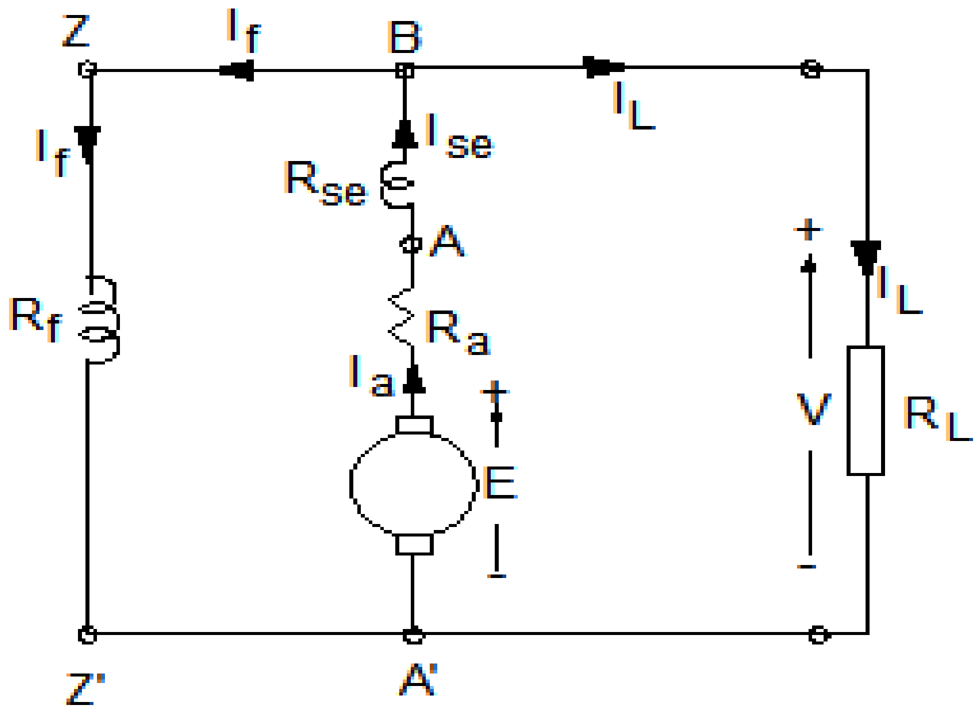
Illustrative Example :

A DC compound generator delivers 50A to the load at 500V. The armature, series field and field windings resistances are 0.05 Ω, 0.03 Ω and 250 Ω respectively. The voltage drop in carbon brush is 1 V per brush. Calculate the generated emf a) for long shunt compound b) Short shunt compound

Solution:

Given parameters : Ra = 0.05 ohm, R_{se} = 0.03 ohm and R_f = 250 ohms

a) Long shunt compound: $I_L = 50$ A



Voltage across the load V = 500 V

$$\text{Shunt field current } I_f = \frac{V}{R_f} = \frac{500}{250} = 2A$$

$\therefore \quad I_a = I_L + I_f = 50 + 2 = 52$ A

Then emf induced $E = V + I_a (R_a + R_{se})$ + drop in brushes

$= 500 + 52\times(0.05+0.03) + 1\times2$

= <u>506.16 V</u>

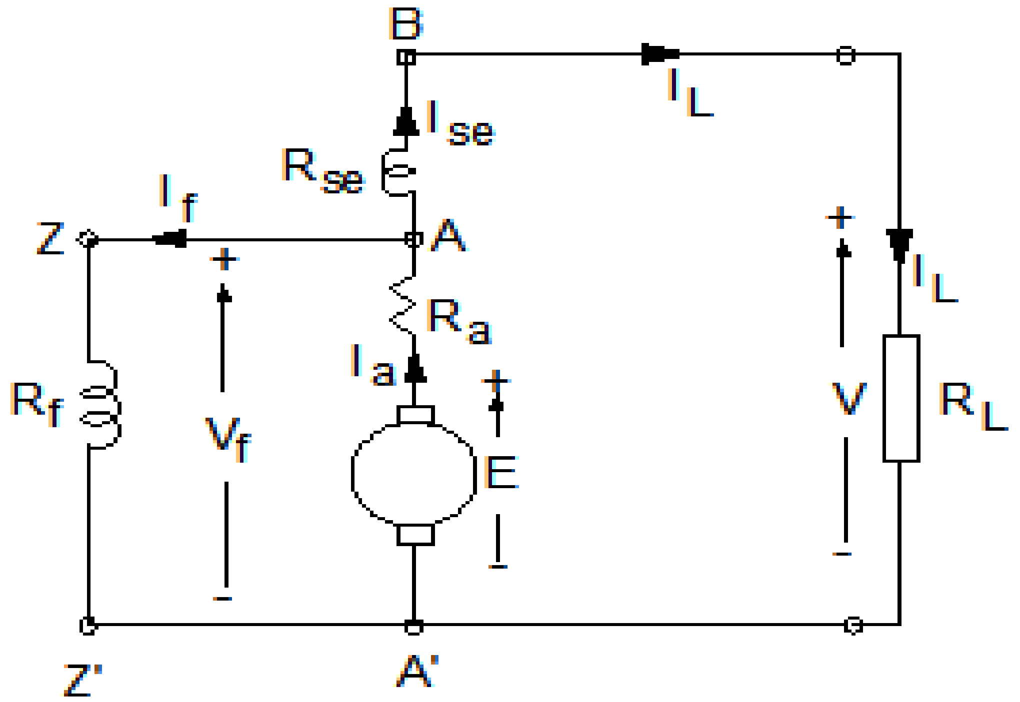
Illustrative Example :

A DC compound generator delivers 50A to the load at 500V. The armature, series field and field windings resistances are 0.05 Ω, 0.03 Ω and 250 Ω respectively. The voltage drop in carbon brush is 1 V per brush. Calculate the generated emf a) for long shunt compound b) Short shunt compound

Solution:

Given parameters : Ra = 0.05 ohm, R_{se} = 0.03 ohm and R_f = 250 ohms

b) Short shunt compound:



Voltage across the shunt field winding:

$V_f = V + I_L R_{se} = 500 + 50\times0.03 = 501.5$ V

$$I_f = \frac{V_f}{R_f} = \frac{501.5}{250} = 2.006\,A$$

$\therefore\ I_a = I_L + I_f = 50 + 2.006 = 52.006$ A

Then Emf $E = V_f + I_a R_a$ + drop in brushes

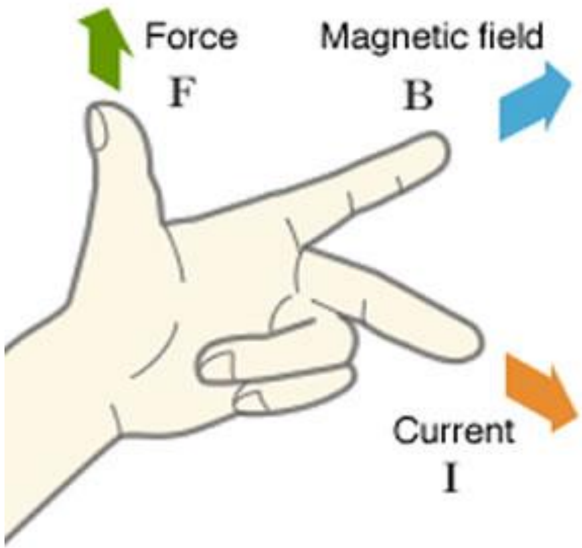
$= 501.5 + 52.006\times0.05 + 1\times2$

MK $= \underline{506.1\ \text{V}}$

DC MOTORS

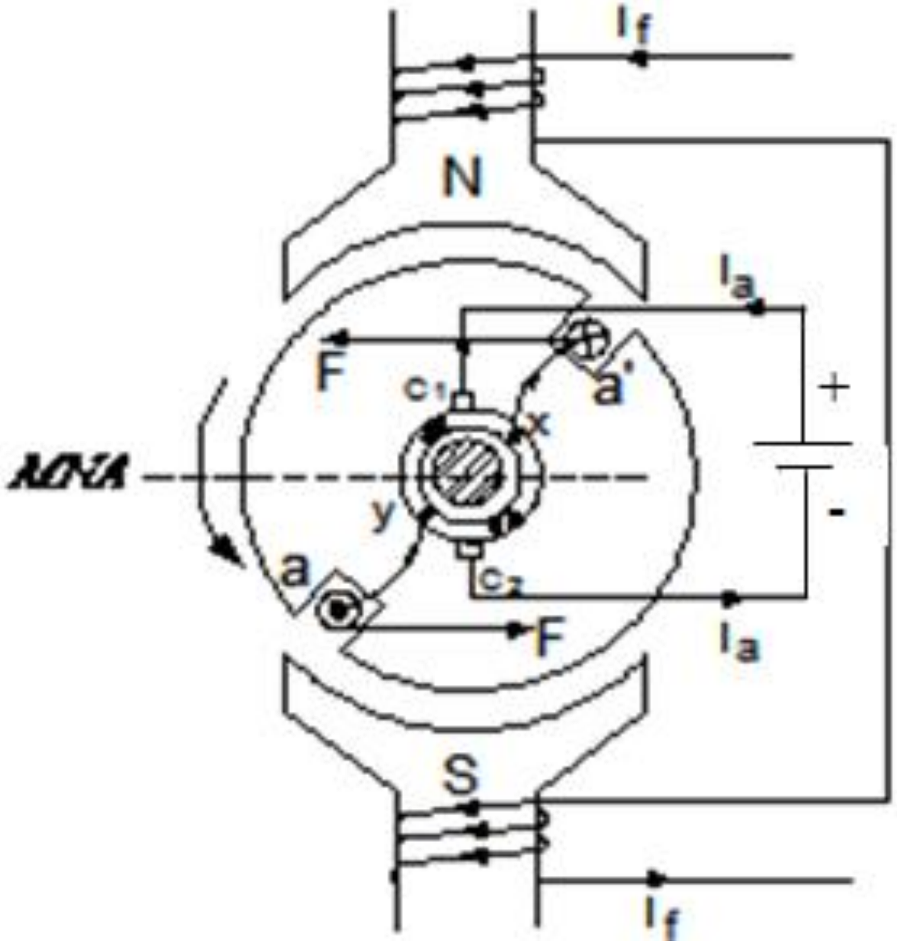
Basic Concept of DC Motors

- DC machines converts electrical energy into mechanical energy
- When we **apply certain field current (I_f),** then field poles will gets magnetized and **magnetic poles develop.**
- Also, when the **current is given to armature conductors** then, the **current carrying conductors lie in the magnetic field.**
- Hence, **force develops on the conductors** and under the action of this force, **whole armature rotates.**
- The **direction of force is given by Fleming's Left hand rule**.
- **In case of DC motors, both the field and armature windings are supplied by DC current.**

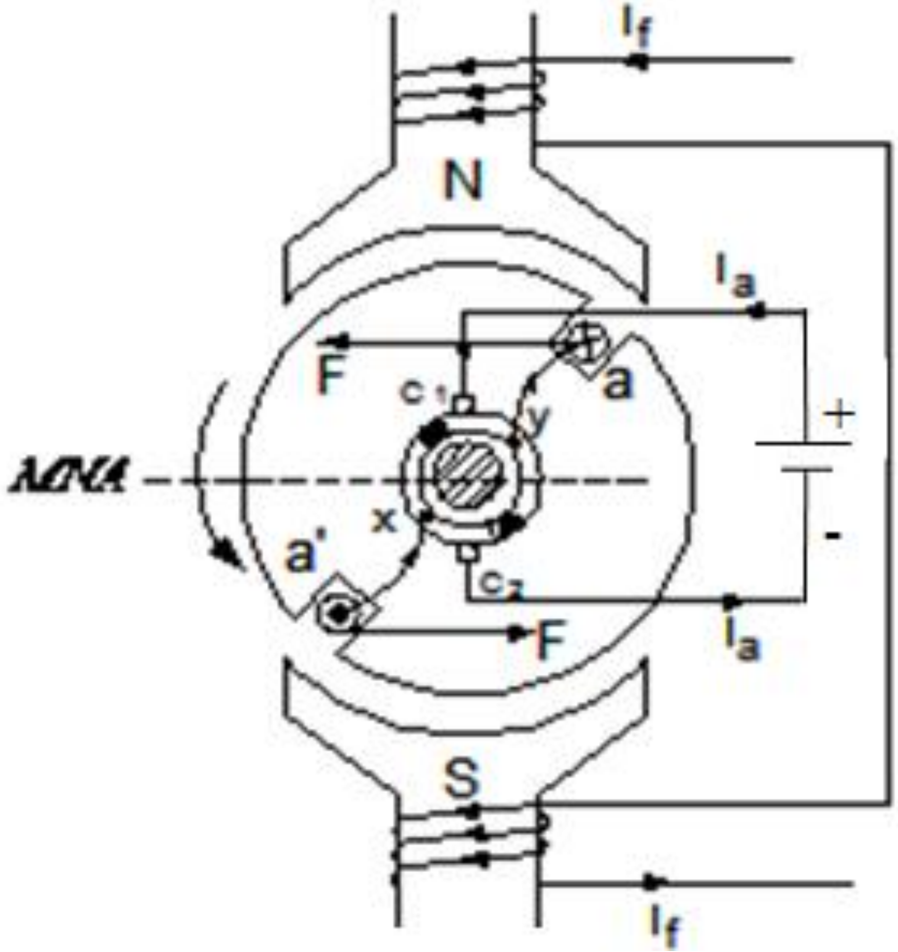


Operating Principle of DC Motor:

<u>Operation of DC motor with carbon brushes and commutator segments</u>

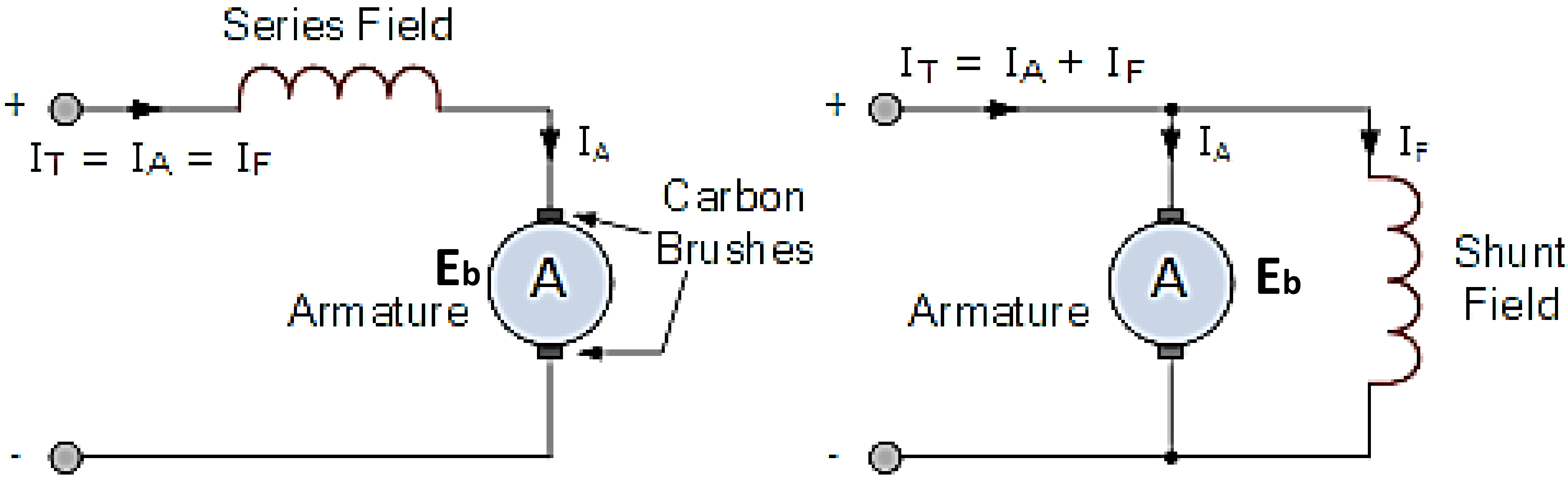


(a) Initial position



(b) After 180^0 rotation

Typical Circuit representation for a DC motor



The voltage V applied across the motor armature has to
(i) overcome the back e.m.f. E_b and
(ii) supply the armature ohmic drop $I_a R_a$

$$V = E_b + I_a R_a$$

This equation is known as the voltage equation of a motor.

Voltage and Power Equation:

The voltage V applied across the motor armature has to
(i) overcome the back e.m.f. E_b and
(ii) supply the armature ohmic drop $I_a R_a$

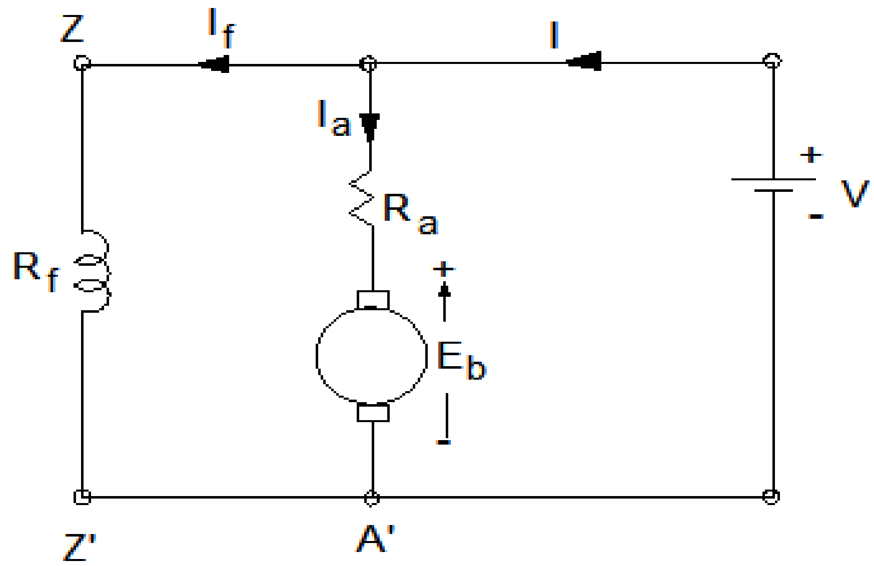
$$V = E_b + I_a R_a$$

This equation is known as the voltage equation of a motor.

Now, multiplying both sides by I_a, we get;

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

This equation is know as the power equation of a motor.



VI_a = armature input (electric power supplied to armature)

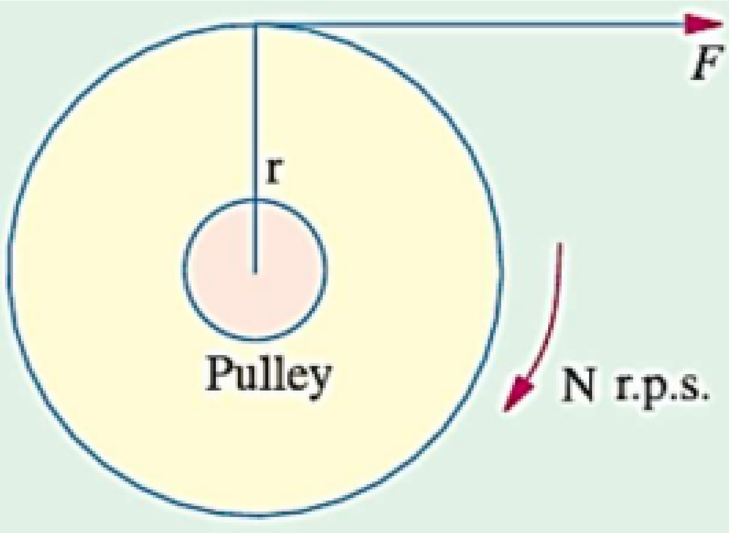
$E_b I_a$ = electrical equivalent of the armature output or the power developed by armature

$I_a^2 R_a$ = armature Cu loss (electric power wasted in armature)

Hence, out of the armature input, some is wasted in I^2R loss and the rest is converted into mechanical power within the armature.

Torque and Speed of DC Motors

By the term ***torque*** is meant the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts.



Consider a pulley of radius r meter acted upon by a circumferential force of F Newton which causes it to rotate at N r.p.s.

Then torque $T = F \times r$ Newton-metre (N - m)

Work done by this force in one revolution = Force × distance = $\mathbf{F \times 2\pi r}$ Joule

Power developed = $\mathbf{F \times 2\pi r \times N}$ Joule/second or Watt = $\mathbf{(F \times r) \times 2\pi N}$ **Watt**

Now $\mathbf{2\pi N}$ = Angular velocity $\boldsymbol{\omega}$ in radian/second and $\mathbf{F \times r}$ = **Torque T**

$\therefore$ Power developed, $\mathbf{P} = \mathbf{T}\,\boldsymbol{\omega}$ watt

Moreover, if N is in R.P.M., then $\boldsymbol{\omega} = \mathbf{2\pi N / 60}$ rad/s

$\therefore \mathbf{P = 2\pi N / 60 \times T}$ or $\mathbf{P = 2\pi/60 \times NT = NT/9.55}$

Armature Torque of a DC Motor

Let T_a be the torque developed by the armature of a motor running at N r.p.s, If T_a is in N-m, then power developed $P = T_a \times 2\,\pi\, N$ watt ---------- (i)

The electrical power converted into mechanical power in the armature

$$P = E_b\, I_a \text{ watt} \quad \text{---------- (ii)}$$

Equating (i) and (ii), we get $T_a \times 2\,\pi\, N = E_b\, I_a$ ---------- (iii)

Since $E_b = (\Phi Z N) \times (P/A)$ volts, we have **Here, N in rps**

$$T_a \times 2\,\pi\, N = (\Phi Z N) \times (P/A)\, I_a$$

as $$T_a = \frac{1}{2\pi} \,.\, \Phi Z\, I_a \left(\frac{P}{A}\right) N\text{-}m$$

$\therefore$ $$T_a = 0.159\, \Phi Z\ I_a \times (P/A) \text{ N-m}$$

From this, we can see that, $T_a \propto \Phi\, I_a$

As seen from (iii) above $T_a = \dfrac{E_b I_a}{2\pi N}$ Newton-meter (N in r.p.s)

If N is in r.p.m, then $T_a = \dfrac{E_b I_a}{2\pi N/60} = \dfrac{60}{2\pi}\dfrac{E_b I_a}{N} = 9.55\dfrac{E_b I_a}{N}$

(a) In the case of a series motor, Φ is directly proportional to I_a (before saturation) because field windings carry full armature current.

$\therefore T_a \propto I_a^2$

(b) For shunt motors, Φ is practically constant, hence $T_a \propto I_a$

Speed of a DC Motor

From the voltage equation of a DC motor, we get

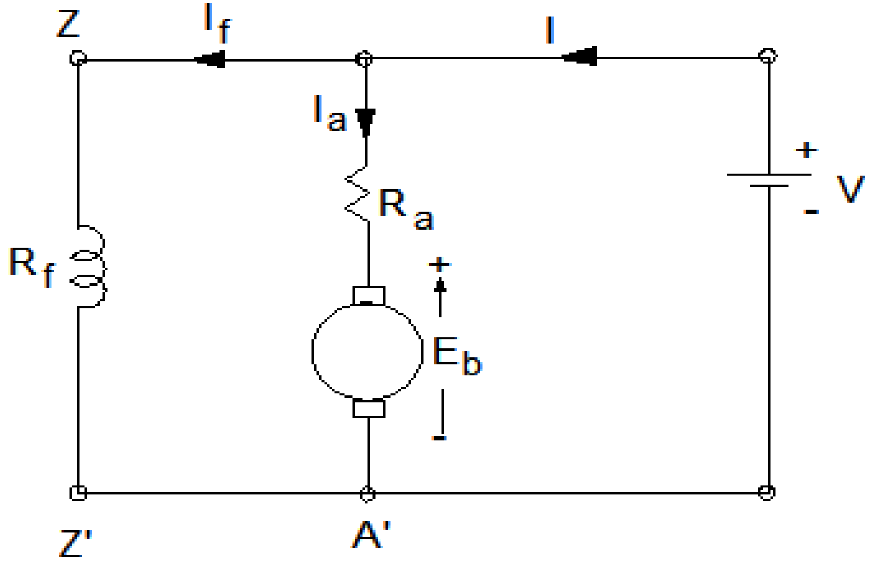
$$E_b = V - I_a R_a \quad or \quad \frac{\Phi Z N}{60}\left(\frac{P}{A}\right) = V - I_a R_a$$ (Speed is taken in r.p.m)

$$\therefore N = \frac{V - Ia\,Ra}{\Phi} \times \left(\frac{60A}{ZP}\right) \text{ r.p.m}$$

Now, as $E_b = V - I_a R_a$

$$N = \frac{E_b}{\Phi} \times \left(\frac{60A}{ZP}\right) \text{ r.p.m} \quad \text{or} \quad N = K\frac{E_b}{\Phi} \quad \text{or} \quad N \propto \frac{E_b}{\Phi}$$

It is seen that the speed is directly proportional to the back e.m.f. E_b and inversely to the flux Φ.

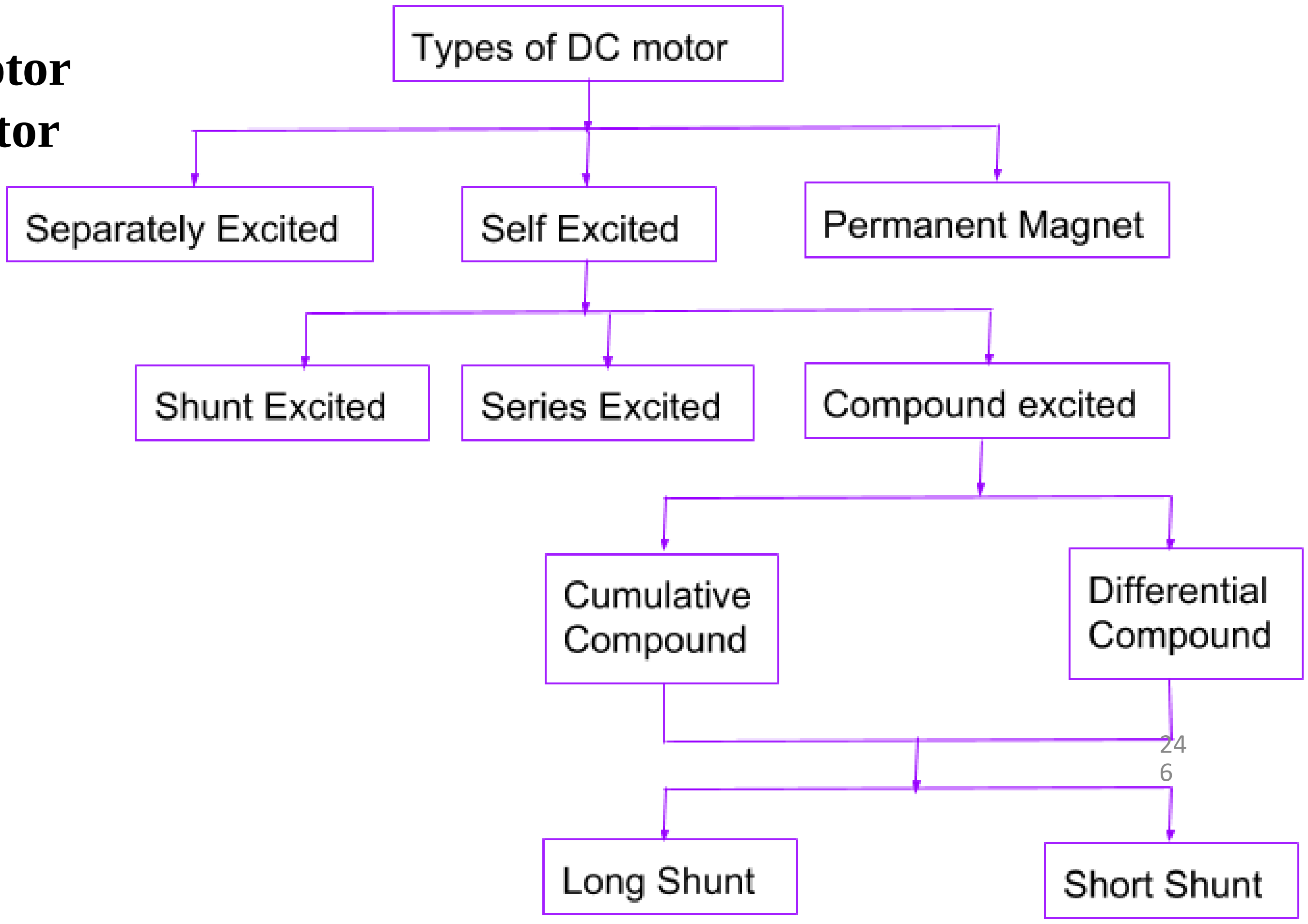


Methods of Excitation, Types of DC Motors

- Field winding of a dc motor is supplied by DC current to produce the magnetic field. The supply of DC current to the field winding is known as **Excitation.**

- The excitation can be provided by various method and accordingly the dc motors can be classified as follows:

  - **Permanent Magnet DC Motor**
  - **Separately Excited DC Motor**
  - **Self Excited DC Motor**



DC Motors and their characteristics:

- Different types of motor have different characteristics and accordingly they are used in various applications.

- The characteristics of DC motors are distinguished by the following characteristics curves.

  1. Torque – Armature current characteristics(T/Ia)

  – Also called as **electrical characteristics**. It gives the relation between torque developed in the armature and current flowing through the armature.

  2. Speed – Armature current characteristics(N/Ia)

  – It is also called as **speed characteristics**, which gives the relation between armature current and speed of rotation of the motor.

  3. Torque – Speed characteristics(N/T)

  – It gives the relation between torque and speed of the motor, hence called as **mechanical characteristics.**

Characteristics of DC series motor:

1. Torque – Armature current characteristics(T/Ia)

$$Pm = Pa$$

$$T_a \times 2\pi N = E_b I_a \quad \text{----------} \ (iii)$$

$E_b = (\Phi ZN) \times (P/A)$ volts, we have

$$T_a \times 2\pi N = (\Phi ZN) \times (P/A)\, I_a$$

$$T_a = \frac{1}{2\pi} . \Phi Z I_a \left(\frac{P}{A}\right) N\text{-}m$$

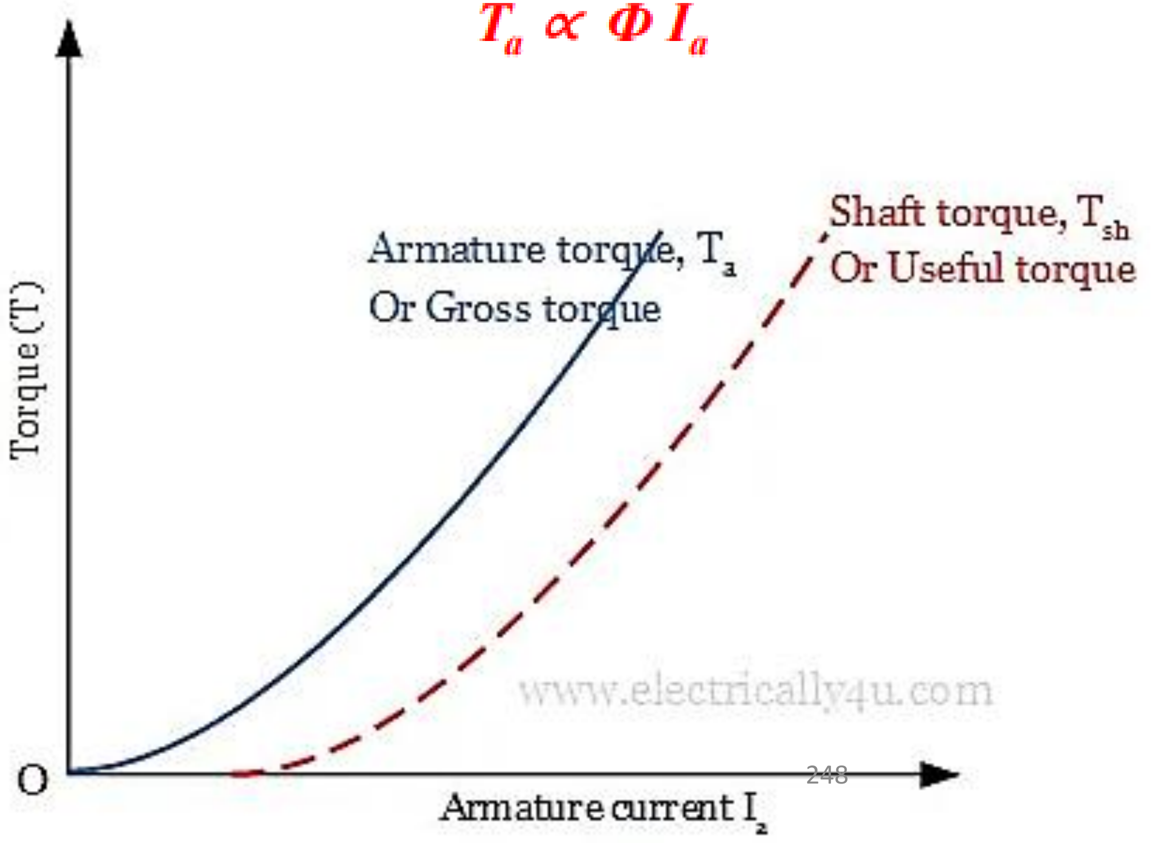
$$T_a \propto \Phi I_a$$

- As the field winding is connected in series with the armature winding ($\varphi \ \alpha \ I_a$), **an increase in field flux will increase the armature current.**

- **Before saturation**, torque is directly proportional to the square of the armature current **($T \ \alpha \ I_a^2$).**

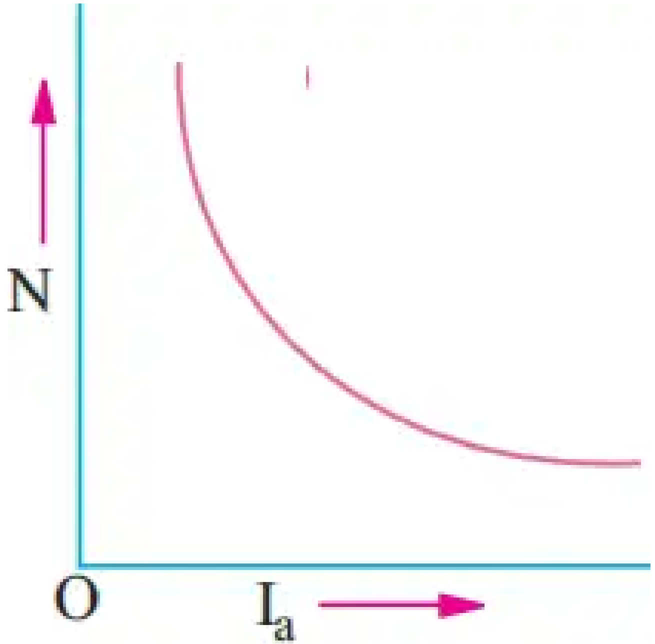
- **After the saturation**, torque is directly proportional to the armature current **($T \ \alpha \ I_a$).**

- The shaft torque or useful torque(red color dotted line) will be less than the armature torque. It is because of the loss due to iron, friction and windage losses.



Characteristics of DC series motor:

2. Speed – Armature current characteristics(N/Ia)



$$E_b = \frac{Z.\varphi.N}{60} \times \frac{P}{A}$$

$$\text{Or, } N = \frac{E_b}{\varphi} \times \frac{60 \times A}{Z \times P}$$

$$\text{or } N \, \alpha \, \frac{E_b}{\varphi} \quad \text{and} \quad E_b = V - I_a(R_a + R_{se})$$

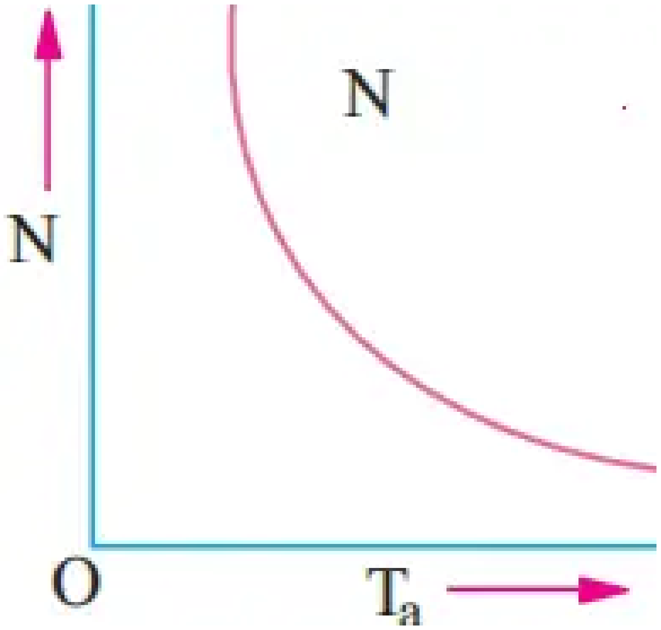
$$i.e. \, N \, \alpha \, \frac{(V - I_a(R_a + R_{se}))}{\varphi}$$

- In a **DC series motor**, initially, the **field flux φ rises in proportion to the current** but **after saturation, it is independent of the armature current.**
- Consequently, **speed N is roughly proportional to the current**. The speed may become dangerously high if the load reduces to a small value.
- Hence, as it should not be operated without load. DC series motors are always connected to loads by gears so that **minimum load is always maintained to keep the speed within safe limits.**

Characteristics of DC series motor:

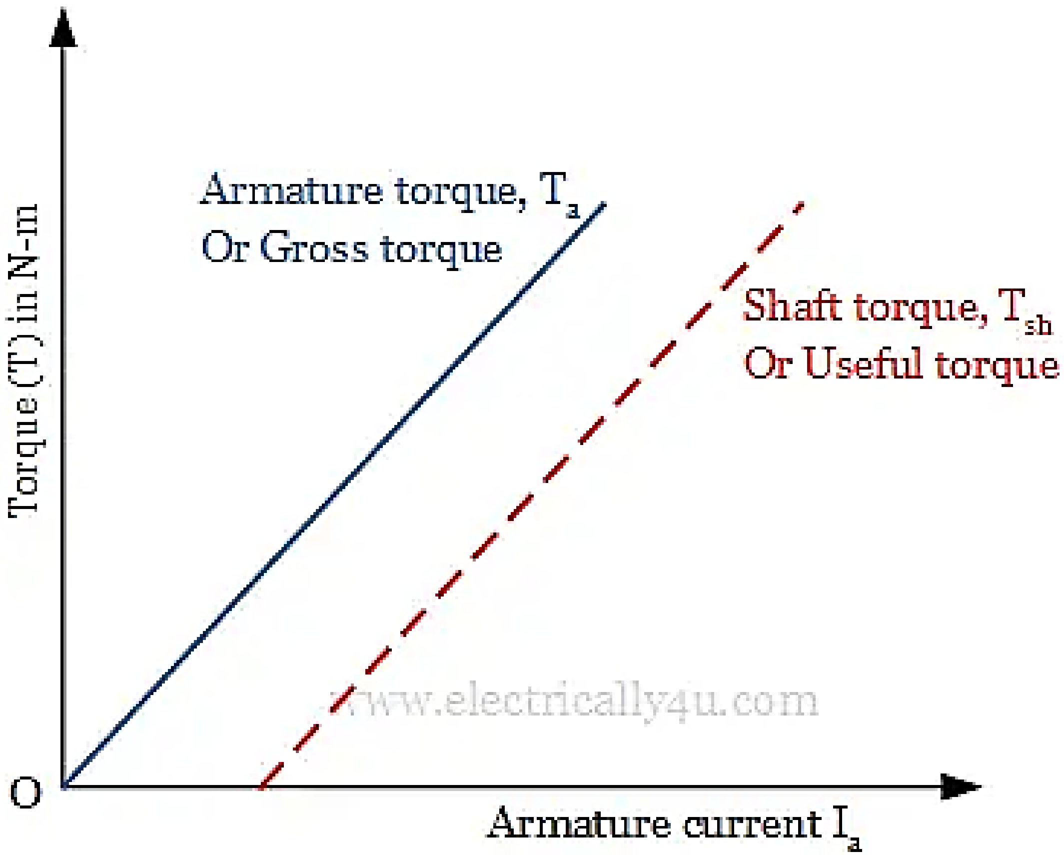
3. Torque – Speed characteristics (N/T)

- Since a series motor develops high starting torques at low speeds and low torque at high speeds, therefore, speed – torque characteristics of a DC series motor is a hyperbola.



Characteristics of DC shunt motor:

1. Torque – Armature current characteristics(T/Ia)



$$T_a \times 2\pi N = E_b I_a \quad \text{----------} \; \text{(iii)}$$

$E_b = (\Phi ZN) \times (P/A)$ volts, we have

$$T_a \times 2\pi N = (\Phi ZN) \times (P/A)\, I_a$$

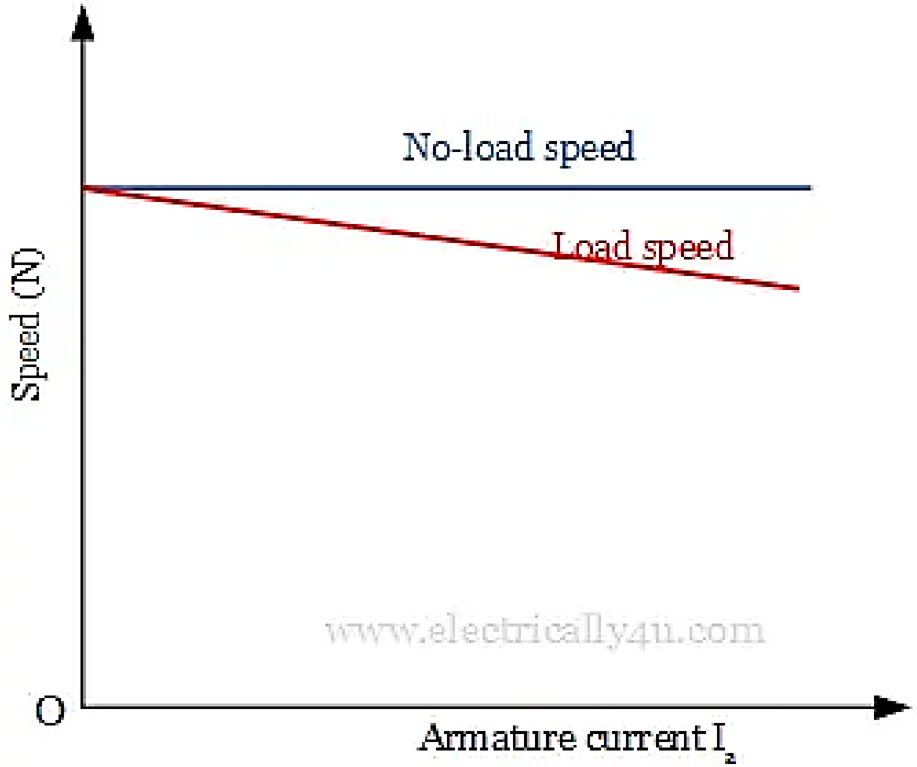
$$T_a = \frac{1}{2\pi} . \Phi Z I_a \left(\frac{P}{A}\right) N\text{-}m$$

$$T_a \propto \Phi I_a$$

- Since in the case of DC shunt motor, the **flux per pole is considered to be constant**. Hence **Torque is proportional to the armature current.**
- With the **increase in armature load current, the torque increases**, which gives a linear relationship.

Characteristics of DC shunt motor:

2. Speed – Armature current characteristics(N/Ia)



$$E_b = \frac{Z.\varphi.N}{60} \times \frac{P}{A}$$

$$\text{Or, } N = \frac{E_b}{\varphi} \times \frac{60 \times A}{Z \times P}$$

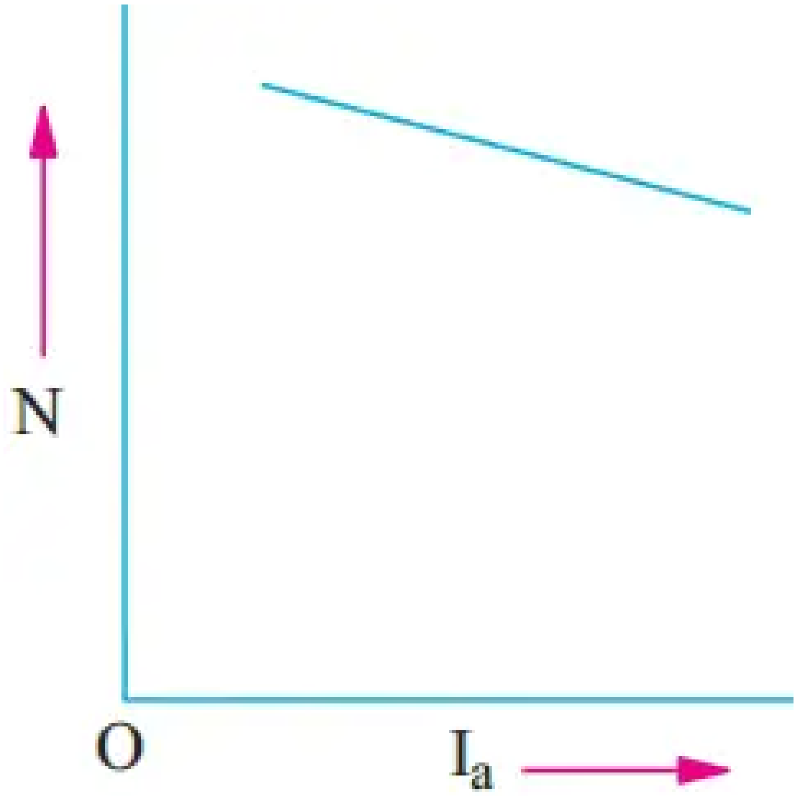
$$\text{or } N \,\alpha\, \frac{E_b}{\varphi} \quad \text{and} \quad E_b = V - I_a R_a)$$

$$i.e. N \,\alpha\, \frac{(V - I_a R_a)}{\varphi}$$

- For the shunt motor, the **flux is considered to be constant**. Hence the speed equation becomes, $N \,\alpha\, E_b$. Practically, E_b is constant, and therefore **speed is also constant.**
- However, **when the load current is increased**, **both the back emf and flux per pole decreases**. Comparatively, back emf decreases more than the flux, and hence there will be **a small drop in speed.**

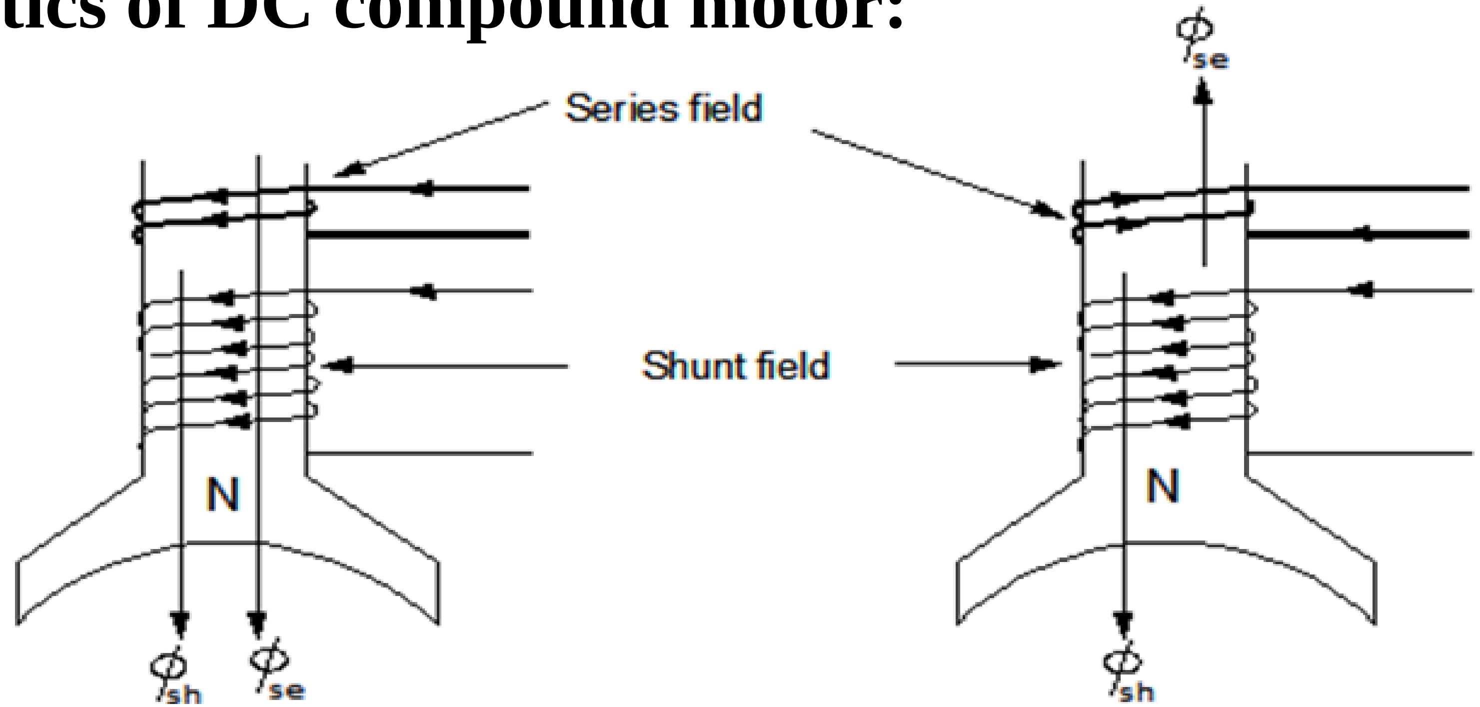
Characteristics of DC shunt motor:

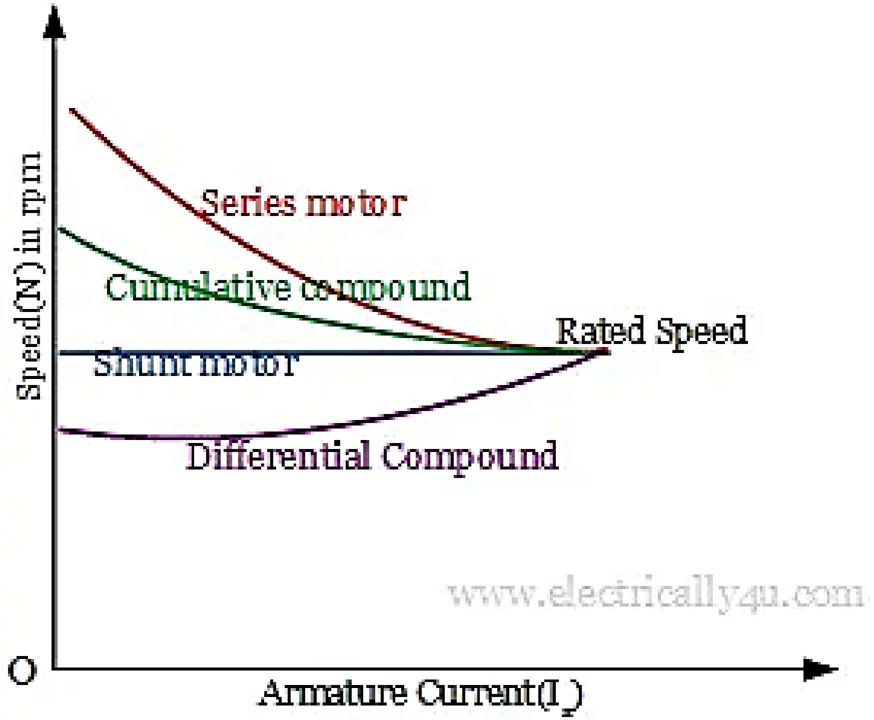
3. Torque – Speed characteristics (N/T)

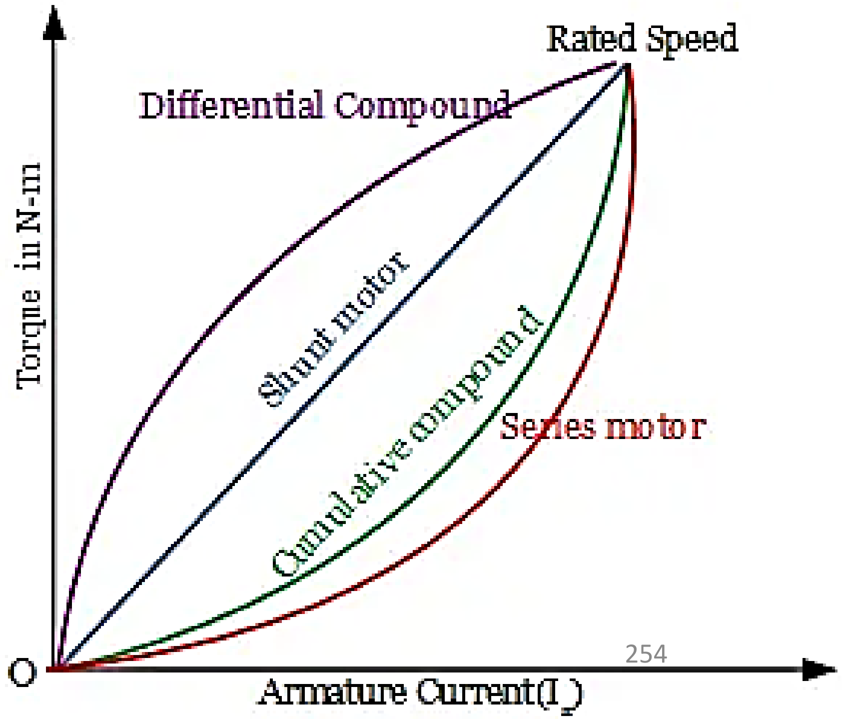


Because there is no appreciable change in the speed of a shunt motor from no-load to full-load, it may be connected to loads that are totally and suddenly thrown off without any fear of excessive speed resulting.

Characteristics of DC compound motor:







Speed Control of DC motor

Factors affecting the speed of DC motor:

$$\text{Back emf } E_b = \frac{Z.\varphi.N}{60} \times \frac{P}{A}$$

$$\text{or, } N = \frac{E_b \times 60 \times A}{Z \times \varphi \times P}$$

$$\text{or, } N \,\alpha\, \frac{E_b}{\varphi}$$

For DC shunt motor,

$E_b = V - I_a(R_a)$

and $T_a \propto \varphi.I_a$

For DC series motor,

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

and $T_a \propto I_a^2$

Therefore,

the factors affecting the speed are:

- **Applied voltage (V)**
- **Armature resistance (R_a)**
- **Magnetic flux per pole (ϕ) or field**

By varying these parameters, speed of a DC motor can be varied.

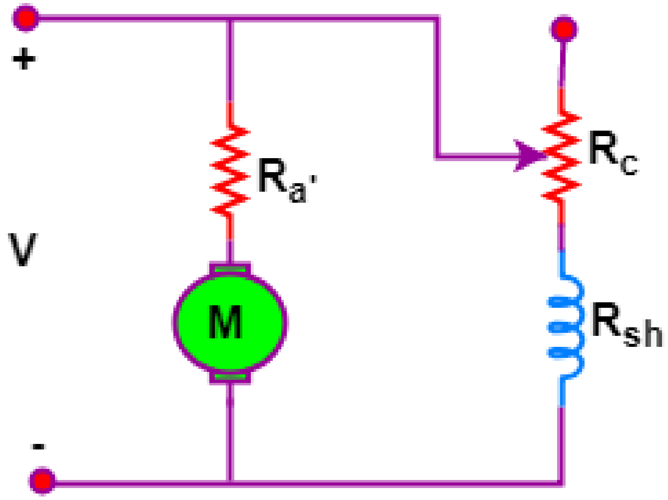
Speed Control of DC motor

i) Field Control Method in shunt motor:

- Since the field current produces the flux, and if we control the field current then the speed can be controlled.
- The advantages of field control are as follows:
  - ✓ This is an easy and convenient method.
  - ✓ The power loss in the shunt field is small because shunt field current I_{sh} is very small.

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

gives the shunt field current



(a)

Figure: (a) Speed control of a D.C. shunt motor by variation of field flux.

In the shunt motor, speed can be controlled by connecting a variable resistor R_c in series with the shunt field winding. In the diagram below resistor, R_c is called the **shunt field regulator**.

Speed Control of DC motor

i) Field Control Method in series motor:

- A variable resistance R_d is connected in parallel with the series field winding. The resistor connected in parallel is called the **diverter**. A portion of the main current is diverted through R_d.

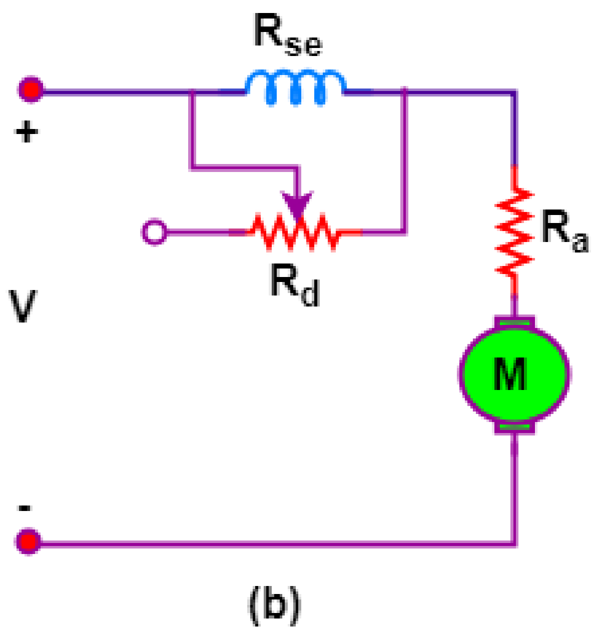


Figure (b) The diverter in parallel with the series of D.C. Motor.

- Here the ampere-turns are varied by varying the number of field turns. This arrangement is used in electric traction.

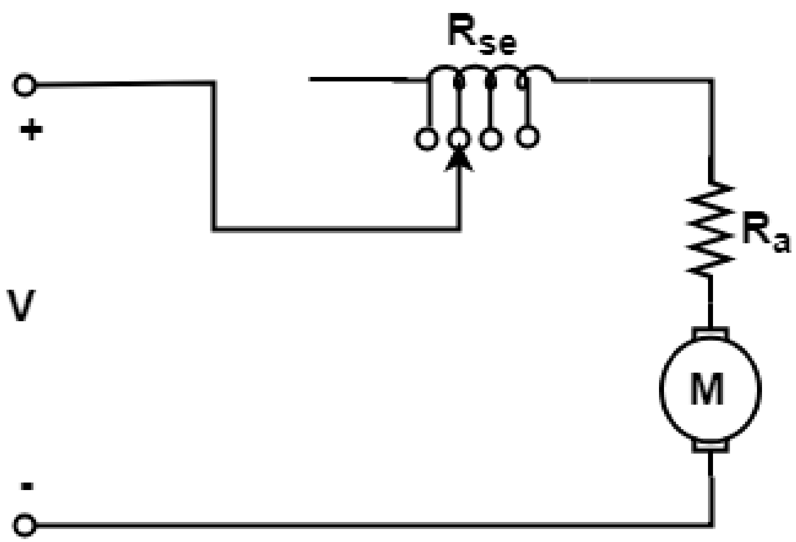
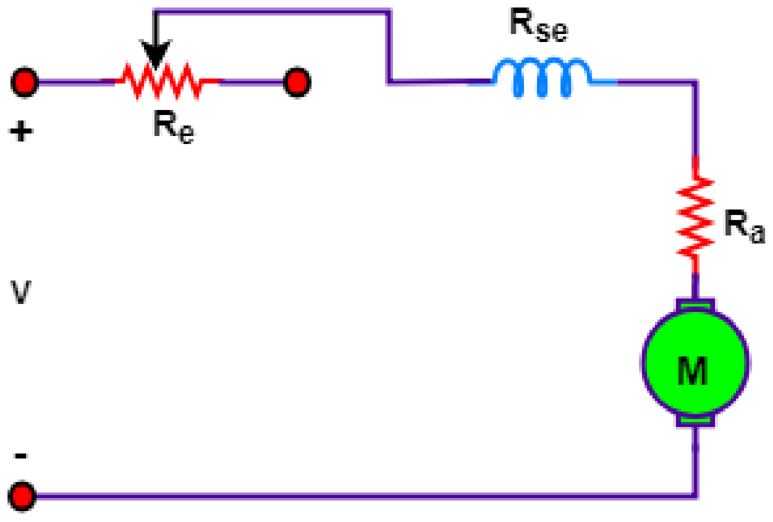


Figure: Tapped series field on D.C. motor

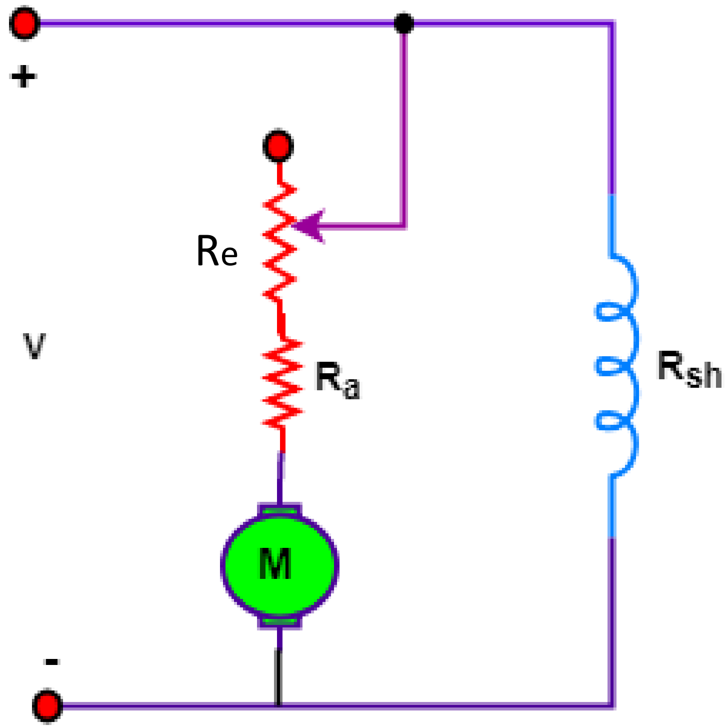
Speed Control of DC motor

ii) Armature Control Method:



Armature diverter method

(b)



(a)

Figure: (a) Speed control of a d.c. Shunt motor by armature resistance control.
(b) Speed control of a D.C. Series motor by armature resistance control.

Figure (b) shows the method of connection of external resistance R_e in the armature circuit of a D.C. series motor. In this case, the current and hence the flux is affected by the variation of the armature circuit resistance.

In this method, a variable series resistor R_e is put in the armature circuit. In this case, the field is directly connected across the supply and therefore the flux Φ is not affected by variation of R_e.

Speed Control of DC motor

ii) Armature Control Method:

- The voltage drop in R_e reduces the voltage applied to the armature, and therefore the speed is reduced.

- This method has the following drawbacks:
  - ✓ In the external resistance R_e **a large amount of power is wasted**.
  - ✓ Control is limited to **give speed below normal** and increase of speed cannot be obtained by this method.
  - ✓ For a given value of R_e, the **speed reduction is not constant but varies with the motor load.**
  - ✓ This method is **only used for small motors.**

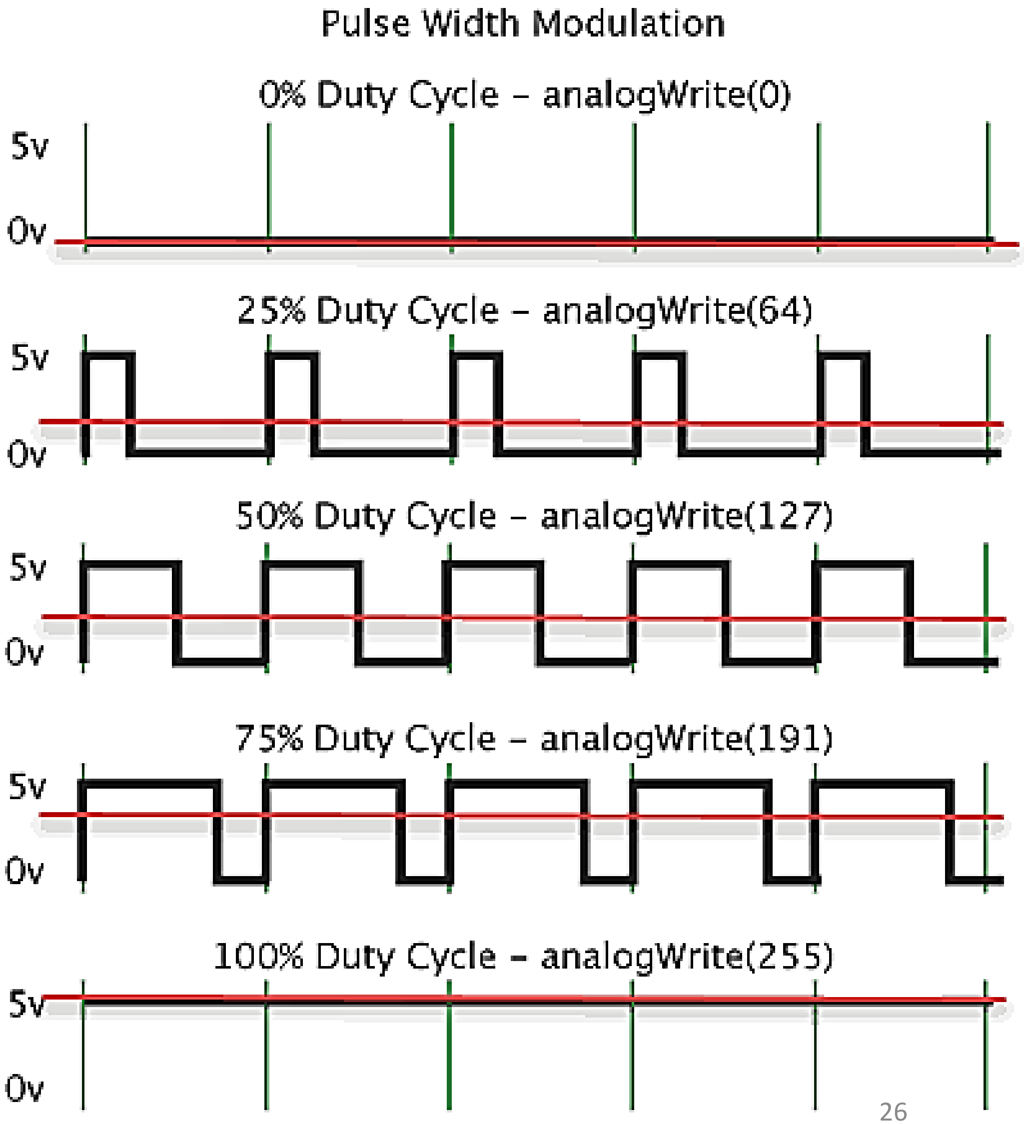
Speed Control of DC motor

iii) Armature Voltage control:

- This method is the **most extensively used** method for controlling the speed of the motor in which we **change the supply voltage to the motor and vary its speed.**

- So, increasing or decreasing the supply voltage to the motor will increase or decrease the speed of the motor respectively.

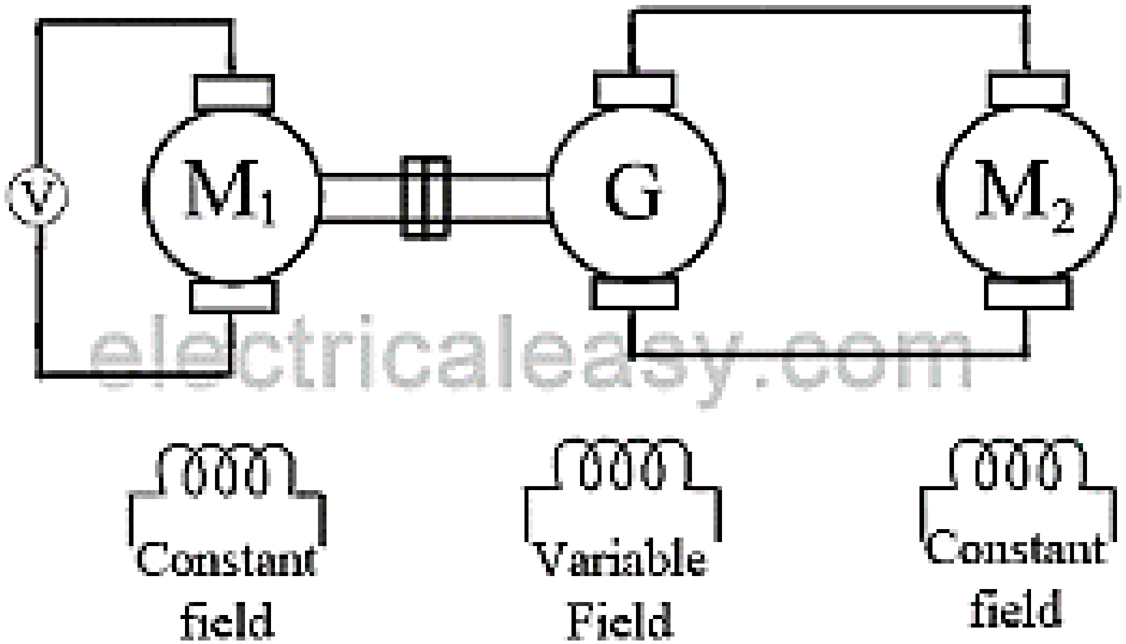
  ✓ <u>**One method**</u> is by varying the voltage across the motor **by applying a PWM (pulse width modulation) signal** which can be generated from microcontroller or IC 555.

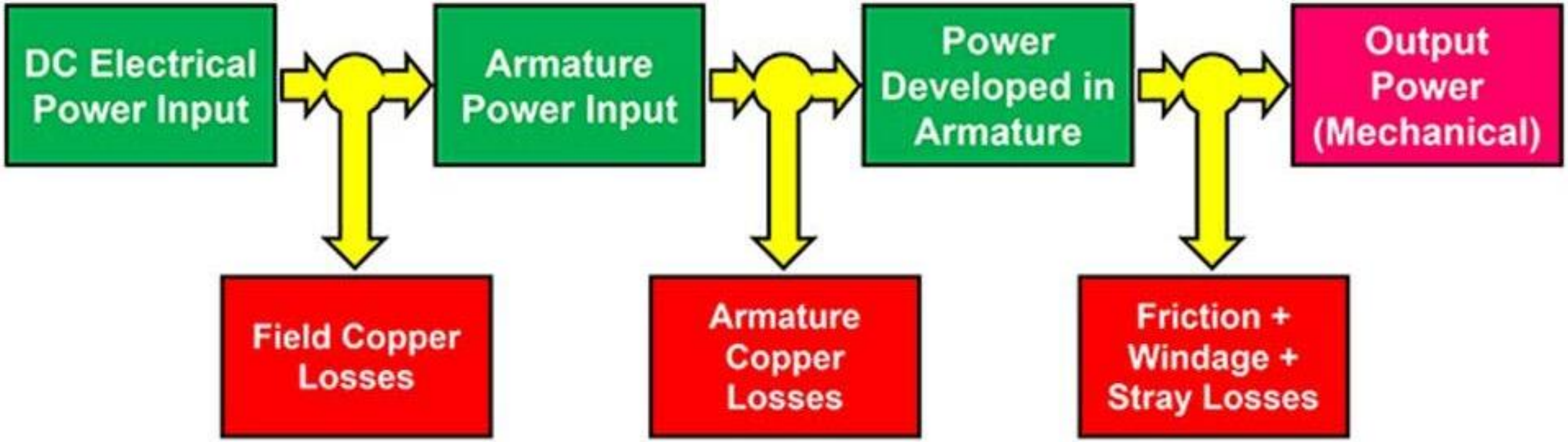


Speed Control of DC motor

iii) Armature Voltage control:

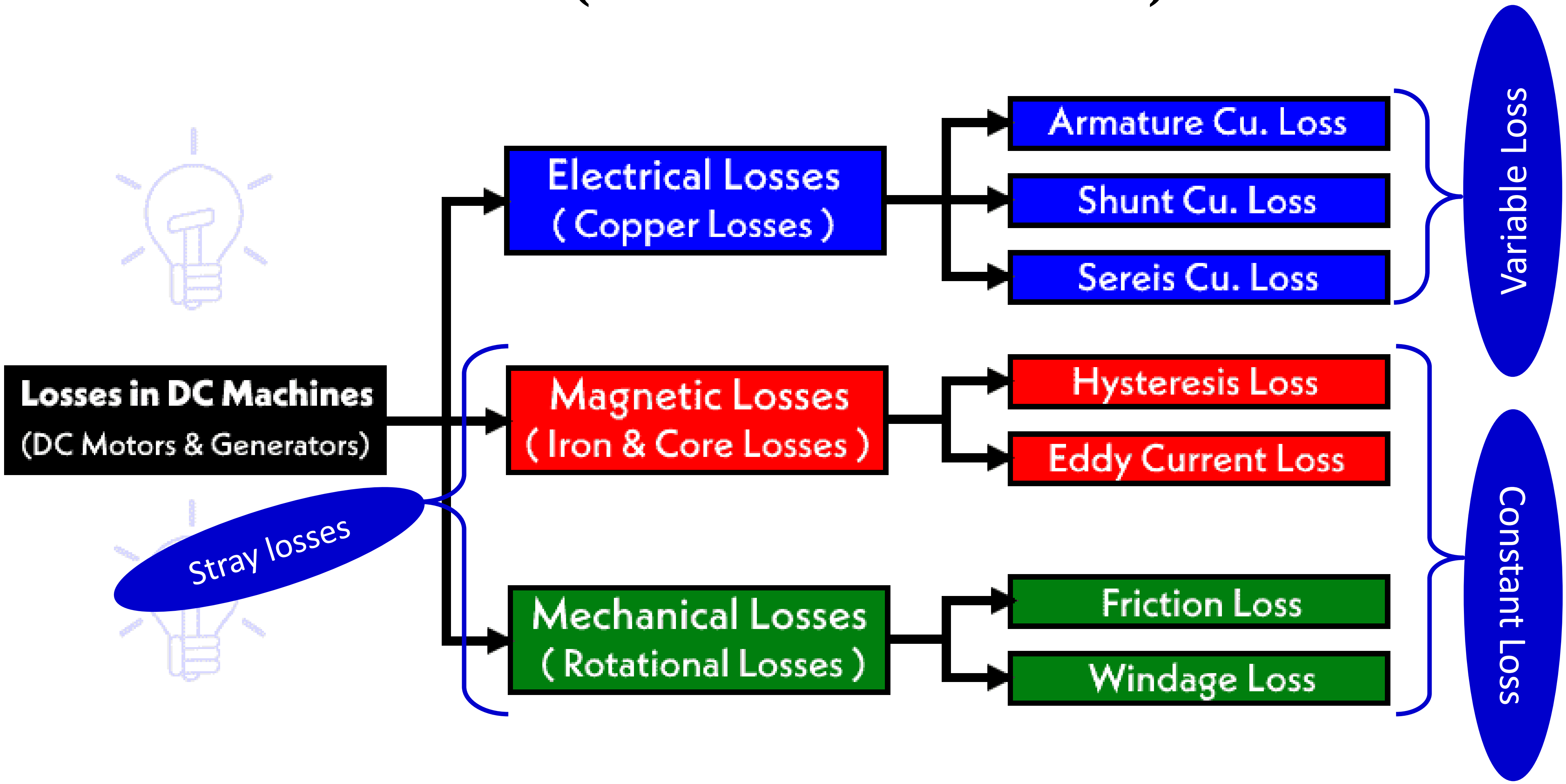
- ✓ **Second method** could be using **Ward-Leonard system** of speed control which works on this principle of armature voltage control.
  - ➢ In this system, M is the main dc motor whose speed is to be controlled, and G is a separately excited dc generator. The generator G is driven by a 3- phase driving motor which may be an induction motor or asynchronous motor. The combination of ac driving motor and the dc generator is called the motor-generator (M-G) set.





Power Flow Block Diagram of DC Motor

Losses in DC Machines (Generators and Motors):



MK

Applications of DC Motors

Type of motor	*Characteristics*	*Applications*
Shunt	Approximately constant speed Adjustable speed Medium starting torque (Up to 1.5 F.L. torque)	For driving constant speed line shafting Lathes Centrifugal pumps Machine tools Blowers and fans Reciprocating pumps
Series	Variable speed Adjustable variying speed High Starting torque	For traction work *i.e.* Electric locomotives Rapid transit systems Trolley, cars etc. Cranes and hoists Conveyors
Comulative Compound	Variable speed Adjustable varying speed High starting torque	For intermittent high torque loads For shears and punches Elevators Conveyors Heavy planers Heavy planers Rolling mills; Ice machines; Printing presses; Air compressors

Applications of DC Motors

- From the characteristics, it can be understood that the torque exerted by the motor is proportional to the square of the current, until saturation. It implies that the **DC series motor has a high starting current.**
- Hence the series motor is used where high starting torque is required as in hoists, electric traction, trolleys, etc.

- Generally, **a shunt motor is called a constant speed motor**, as there is no appreciable change in the motor speed from no load to full load.
- Due to its characteristics, the DC shunt motor is used for applications such as machining tools, lathes, wood-working machines, etc..

Numerical:

A 4 pole DC shunt motor takes 22 A from 220 V supply. The armature and field resistances are 0.5 Ω and 100 Ω respectively. The armature is lap connected with 300 conductors. If the flux per pole 20 mWb, Calculate the speed and gross torque.

Solution:

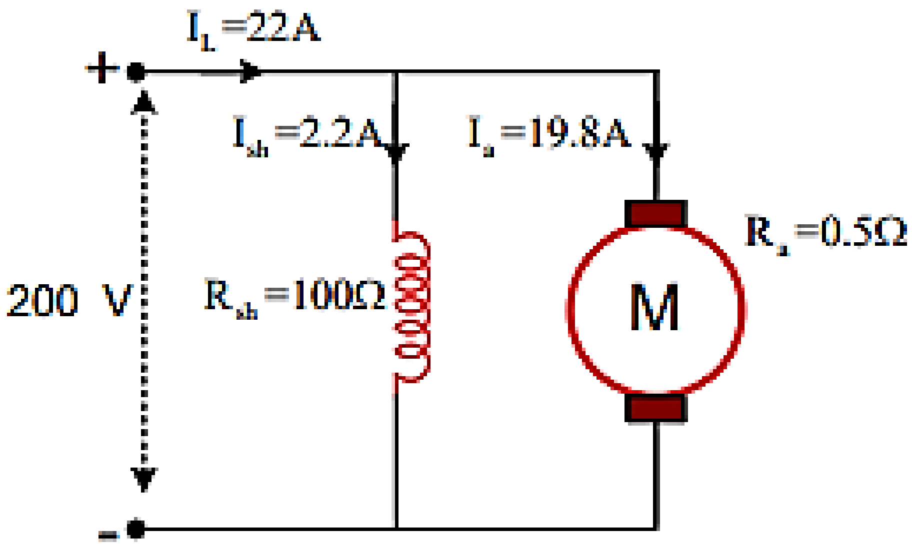


Figure 21

Shunt current

$$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{100} = 2.2A$$

Armature Current and back emf:

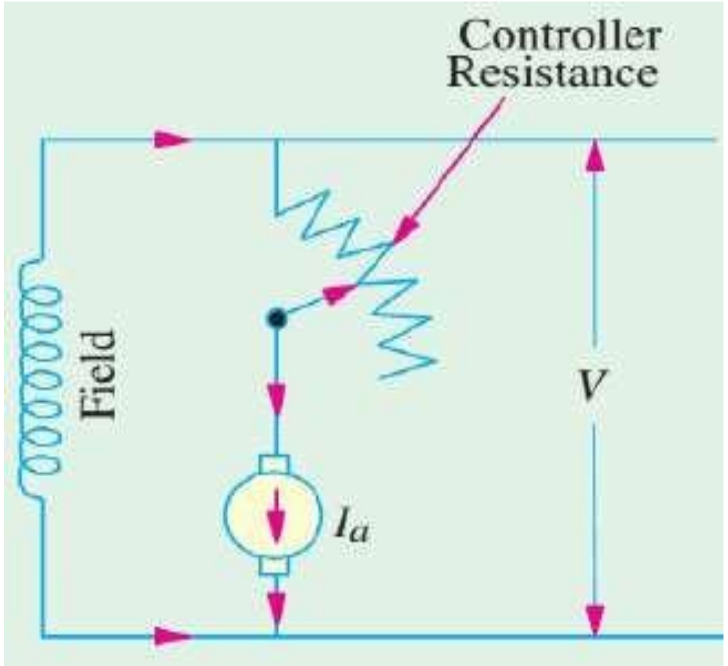
$$I_a = I_L - I_{sh} = 22 - 2.2 = 19.8A$$

$$E_b = V - I_a R_a = 220 - 19.8 \times 0.5 = 210.1V$$

$$\begin{aligned} E_b &= \frac{\phi ZNP}{60A} \\ N &= \frac{E_b 60A}{\phi ZP} \\ &= \frac{210.1 \times 60 \times 4}{20 \times 10^{-3} \times 300 \times 4} \\ &= 525.25\ rpm \end{aligned}$$

$$\begin{aligned} T &= \frac{1}{2\pi}\frac{\phi ZPI_a}{A} \\ &= \frac{1}{2\pi}\frac{20 \times 10^{-3} \times 300 \times 19.8 \times 4}{4} \\ &= 18.89\ N - m \end{aligned}$$

4) A 200 V d.c. shunt motor running at 1000 r.p.m. takes an armature current of 17.5 A. It is required to reduce the speed to 600 r.p.m. What must be the value of resistance to be inserted in the armature circuit if the original armature resistance is 0.4 Ω ? Take armature current to be constant during this process.



Solution:

$\mathbf{N_1}$ = 1000 r.p.m. ; $\mathbf{E_{b1}}$ = 200 − 17.5 × 0.4 = 193 V
$\mathbf{R_t}$ = total arm. circuit resistance
$\mathbf{N_2}$ = 600 r.p.m. ; $\mathbf{E_{b2}}$ = (200 − 17.5 $\mathbf{R_t}$)
Since $\mathbf{I_{sh}}$ remains constant ; $\mathbf{\Phi_1 = \Phi_2}$

$$\frac{600}{1000} = \frac{(200 - 17.5\,R_t)}{193}\;;\; R_t = 4.8\ \Omega$$

Additional resistance reqd. R = $\mathbf{R_t - R_a}$ = 4.8 − 0.4 = 4.4 Ω.

Numerical Examples:

1) A 250 V shunt motor runs at 1000 r.p.m and at no load takes 8 A. The total armature and shunt field resistances are 0.2 Ω and 250 Ω respectively. Calculate the speed when loaded and taking 50 A. Assume the flux is constant.

Solution:

The current distribution is shown in the figure. I_L, I_f and I_a are load current, field current and armature current respectively. Let N_0 and N be the speed (RPM) at no load and load respectively.

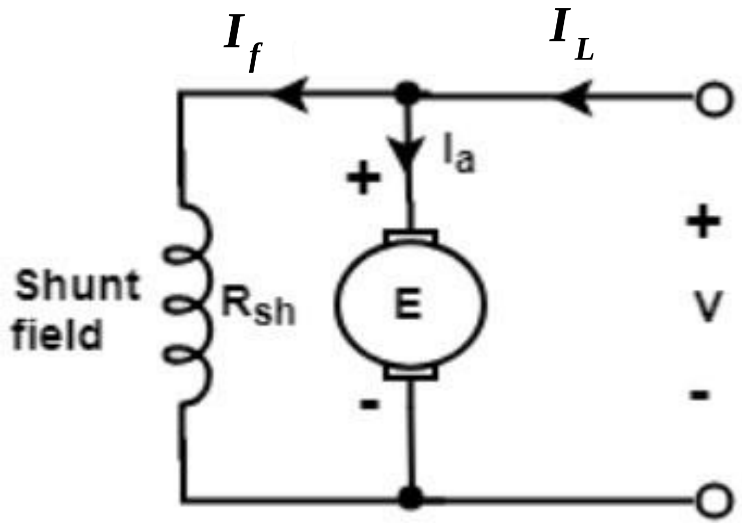
At no load, $I_L = 8$ amp, $I_f = V/R_{sh} = 250/250\text{ A} = 1\text{ A}$

Hence, $I_a = 7$ amp

$\mathbf{E_{b0}} = 250 - 7 \times 0.2 = 248.6$ volts,

Now, since $\phi_0 = \phi$ (given)

$N/N_0 = E_b/E_{bo}$ or, $N/100 = E_b/248.6$



At load, $I_a = 49$ amp (as field current is constant)

$E_b = V_b - I_aR_a = 250 - 49 \times 0.2 = 240.2$ V

: $\mathbf{N = E_b/248.6 \times 100 = 240.2/248.6 \times 100 = 966.2}$ **r.p.m**

References

- https://www.electricaleasy.com/2014/01/losses-in-dc-machine.html
- https://www.electrically4u.com/characteristics-of-dc-motor/
- https://www.yourelectricalguide.com/2017/09/characteristics-of-dc-motor.html