Module-1

DC Motors: *Construction and working principle. Back EMF and its significance. Torque equation, Classification. Characteristics of shunt, series & compound motors, speed control shunt Application 0f motors.*

Losses and Efficiency: *Losses in DC motors power flow diagram. efficiency, condition for maximum efficiency.*

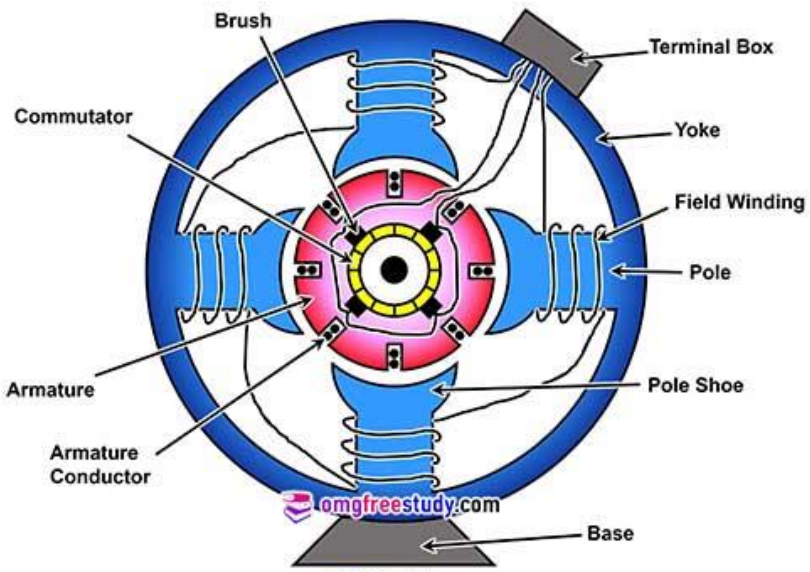
Testing of DC Motors: *Direct & indirect method of testing of motors- Swinburne's test, Field's test, merits and demerits of tests. (numerical as applicable)*

Introduction: A motor is an electrical device that converts electrical energy into mechanical energy. It utilizes the principles of electromagnetism to generate rotational motion, causing a physical output or mechanical work. Motors are commonly used in various applications, such as machinery, vehicles, appliances, and industrial processes.

On the other hand, a motor is an electrical device that converts mechanical energy into electrical energy. It operates based on the principle of electromagnetic induction, where a rotating shaft or mechanism drives a conductor through a magnetic field, resulting in the production of electrical power. Motors are essential for generating electricity in power plants, backup systems, and portable devices like motors for camping or emergencies.

While alternating current is the standard for most applications, there are specialized cases where converting AC power to DC power is advantageous. D.C. motors offer significant advantages, such as better speed/torque characteristics, making them an ideal option for certain settings like steel mills, mines, and electric trains. For businesses requiring industrial drives, they are nearly as popular as their 3-phase induction counterparts.

Construction of DC Motor:



DC Machine

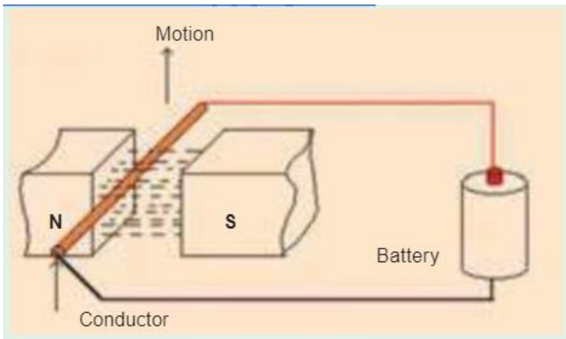
The above figure shows the constructional details of a simple 4-pole DC machine. A DC machine consists of two basic parts; stator and rotor. The basic constructional parts of a DC machine are described below.

1. **Yoke:** The outer frame of a dc machine is called a yoke. It is made of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in the air gap uniformly.
3. **Field winding:** They are usually made of copper. Field coils are former wounds placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.
4. **Armature core:** The Armature core is the rotor of a DC machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial airflow for cooling purposes. The armature is keyed (fixed) to the shaft.
5. **Armature winding:** It is usually a former wound copper coil that rests in armature slots. The armature conductors are insulated from each other and the armature core. Armature winding can be wound by one of the two methods: lap winding or wave winding. Double-layer lap or wave windings are generally used. A double-layer winding means that each armature slot will carry two different coils.
6. **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator in a DC generator is to collect the current generated in armature conductors. Whereas, in the case of a DC motor, the commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments that are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed (or fixed) to the shaft. Brushes are 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.

Working Principle of DC Motor:

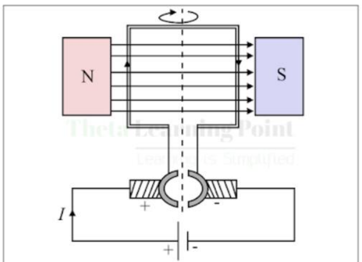
An Electric motor is a machine that converts electric energy into mechanical energy. Its actions is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand Rule and whose magnitude is given by $F = BIl$ Newton.

When the field magnets are excited and its armature conductors are supplied with current from the supply mains, they experience a force tending to rotate the armature. Armature conductors under N-pole are assumed to carry current downwards (crosses) and those under S-poles, are to carry current upwards (dots). By applying Fleming's Left-hand Rule, the direction of the force on each conductor can be found. It is shown by small arrows placed above each conductor. It will be seen that each conductor can be found. It will be seen that each conductor experiences a force F which tends to rotate the armature in an anticlockwise direction. These forces collectively produce a driving torque which sets the armature rotating.



Principle of Motor

It should be noted that the function of a commutator in the motor is the same as in a generator. By reversing current in each conductor as it passes from one pole to another, it helps to develop a continuous and unidirectional torque.

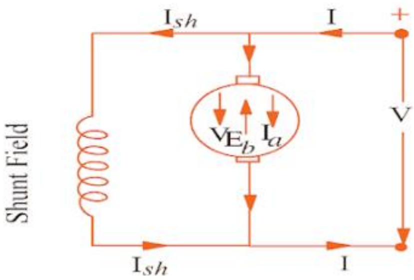


Working Principle of DC Motor

Back EMF:

When the armature of a d.c. the motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator. The induced e.m.f. acts in the opposite direction to the applied voltage V (Lenz's law) and in known as back or counter e.m.f.

The back e.m.f. Eb(= P φ ZN/60 A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.



Significance of Back EMF:

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

Armature current, $I_a = \frac{V - E_b}{R_a}$

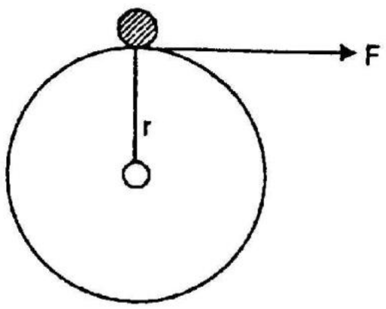
- When the motor is running on no load, small torque is required to overcome the friction and windage losses. Therefore, the armature current Ia is small and the back e.m.f. is nearly equal to the applied voltage.

- If the motor is suddenly loaded, the first effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced, and hence the back e.m.f. Eb falls. The decreased back e.m.f. allows a larger current to flow through the armature and a larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.
- If the load on the motor is decreased, the driving torque is momentarily more than the requirement so that the armature is accelerated. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.

It follows, therefore, that back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

Torque Equation:

Torque 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.



Consider the armature of the DC motor to have a radius **r** and let **F** be the force acting tangential to its surface as shown in figure.

Armature Torque $\mathbf{T_a = F \times r}$ **(N-m)**

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

Work done in one revolution of the armature is given by,

w = F * distance covered in one revolution

= F * 2Πr = (F * r) 2 Π = $\mathbf{T_a}$ 2Π

The power developed by the armature = work done in one second

= Work done / Time taken

$$= \frac{\mathbf{2\Pi Ta}}{\mathbf{60}/\boldsymbol{N}}$$

$$= \frac{\mathbf{2\Pi NTa}}{\mathbf{60}} \qquad \boldsymbol{W} \ldots\ldots\ldots.(\mathbf{1})$$

But also we have

The power developed in the armature = $\mathbf{E_b I_a}$ …………(2)

From equation (1) & (2)

$$\frac{\mathbf{2\Pi NTa}}{\mathbf{60}} = \boldsymbol{E_b I_a}$$

$$\mathbf{E_b} = \frac{\boldsymbol{ZP\emptyset N}}{\boldsymbol{60A}}$$

$$\frac{\mathbf{2\Pi NTa}}{\mathbf{60}} = \frac{\boldsymbol{ZP\emptyset N}}{\boldsymbol{60A}} \boldsymbol{I_a}$$

$$\mathbf{T_a} = \frac{\mathbf{ZP\emptyset}}{\mathbf{2\Pi A}} \mathbf{I_a}$$

$$\mathbf{T_a} = \frac{\mathbf{0.159\ ZP\emptyset}}{\mathbf{A}} \mathbf{I_a} \quad \boldsymbol{N-m}$$

The above equation gives the gross torque developed by the armature which includes iron losses and mechanical losses of the motor.

Since Z, P, and A are fixed for a given machine,

$$\therefore \quad T_a \propto \phi I_a$$

Hence torque in a d.c. the motor is directly proportional to flux per pole and armature current.

1. For a shunt motor, flux φ is practically constant.

$$\therefore \quad T_a \propto I_a$$

2. For a series motor, flux φ is directly proportional to armature current I_a provided magnetic saturation does not take place.

$$\therefore \quad T_a \propto I_a^2$$

Shaft Torque (T_{sh}):

The actual torque or shaft torque (torque available at the shaft) or Useful torque **= T_{sh} = T_a – T_L**

Where T_{sh}= shaft torque

T_a = armature torque

T_L = lost torque due to iron losses and mechanical losses

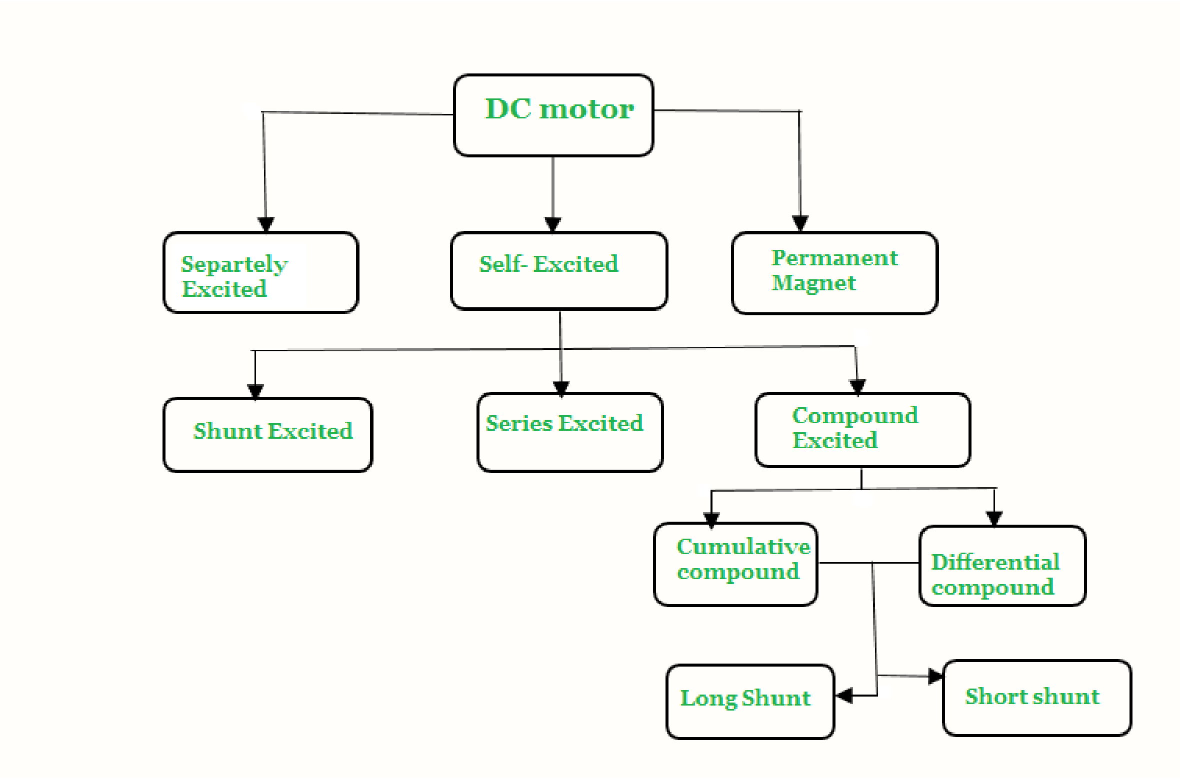
$$\mathbf{Output} = \frac{\mathbf{2\pi NT_{sh}}}{\mathbf{60}}$$

$$\mathbf{T_{sh}} = \frac{\mathbf{Output} * \mathbf{60}}{\mathbf{2\pi N}}$$

If output is in Horse Power,

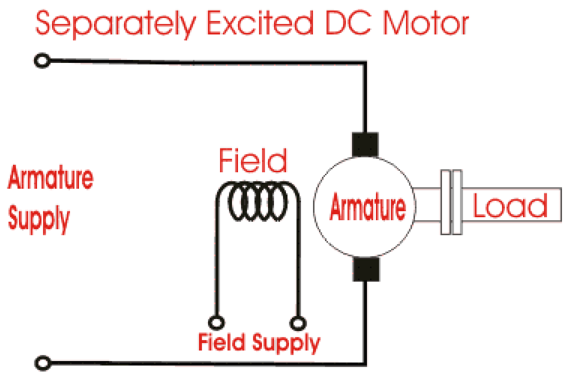
$$\mathbf{T_{sh}} = \frac{\mathbf{Output\ in\ H.P} * \mathbf{735.5}}{\mathbf{2\pi N/60}} \ldots\ldots\ldots..\mathbf{N-m}$$

Classification of DC Motor:



Separately Excited DC Motor:

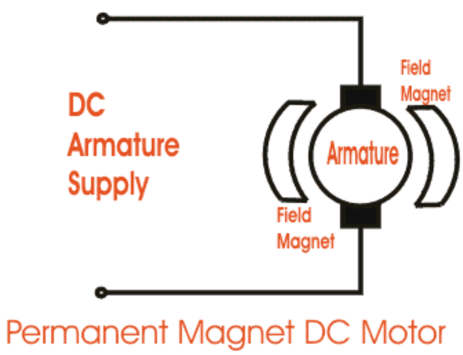
In the case of a separately excited DC motor, the supply is given separately to the field and armature windings. The main distinguishing fact in these types of DC motors is that the armature current does not flow through the field windings, as the field winding is energized from a separate external source of DC as shown in the figure beside.



Permanent Magnet DC Motor:

The permanent magnet DC motor (also known as a PMDC motor) consists of an armature winding as in the case of a usual motor but does not necessarily contain the field windings. The construction of these types of DC motors is such that, radially magnetized permanent magnets are mounted on the inner periphery of the stator core to produce the field flux.

The rotor on the other hand has a conventional DC armature with commutator segments and brushes.

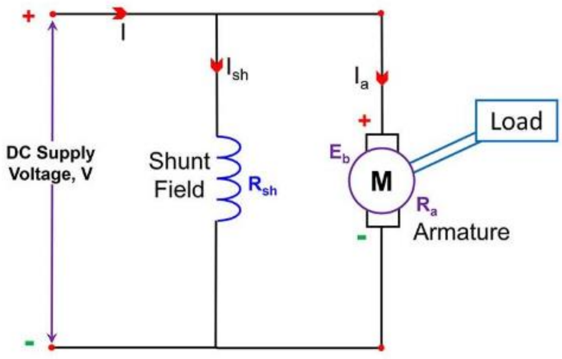


Self Excited DC Motor:

In case of a self-excited DC motor, the field winding is connected either in series or in parallel or partly in series, partly in parallel to the armature winding. Based on this, self-excited DC Motors can be classified as:

1. Shunt wound DC motor
2. Series wound DC motor
3. Compound wound DC motor

Shunt-wound DC Motor:



DC Shunt Motor

In the shunt dc motor type motor, the armature and field winding are connected in parallel as shown in fig. The parallel combination of the two windings is connected across a common dc power supply. Resistance of the shunt field winding (Rsh) is always much higher than that of the armature winding (Ra).

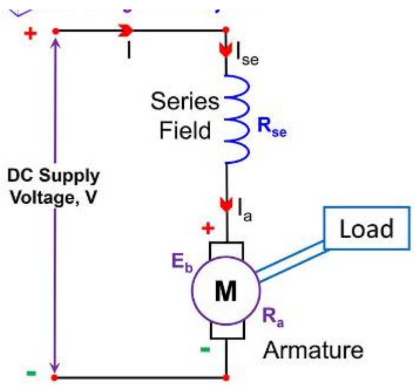
$$\mathbf{I = I_{sh} + I_a}$$

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

$$\mathbf{V = E_b + I_a R_a}$$

$$\emptyset = \boldsymbol{Ish}$$

Series-wound DC Motor:



DC Series Motor

In the D.C. series motor, the armature and field windings are connected in series with each other as shown in fig. The resistance of the series field winding (Rs) is much smaller as compared to that of the armature resistance (Ra). Current flowing through armature winding and field winding is the same name as I=Ia=Ise.

$$\mathbf{I = I_{se} = I_a}$$

$$\mathbf{V = E_b + I_a R_a + I_{se} R_{se}}$$

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

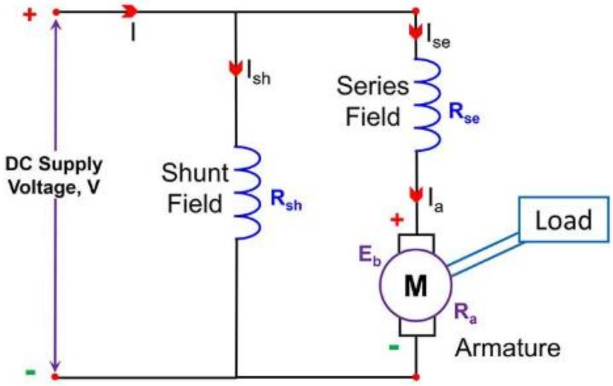
$$\boldsymbol{\phi \propto I_{se} \propto I_a}$$

DC Compound Motors:

The DC compound motors are classified into two types:

1. Long shunt compound motor.
2. Short shunt compound motor.

Long Shunt Compound Motor: The shunt field winding is connected across the series combination of the armature and series field winding.



Long Shunt DC Compound Motor

$$\mathbf{I = I_{se} + I_{sh}}$$

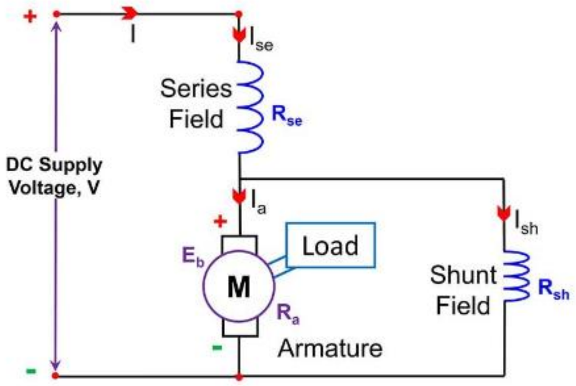
$$\mathbf{I_{se} = I_a}$$

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

$$\mathbf{V = E_b + I_a R_a + I_{se} R_{se}}$$

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

Long Shunt Compound Motor: The armature and shunt field windings are connected in parallel with each other and this parallel connection combination is then connected in series with the series field winding.



Short Shunt DC Compound Motor

$$\mathbf{I = I_{se} = I_a + I_{sh}}$$

$$\mathbf{V = E_b + I_aR_a + I_{se}R_{se}}$$

$$\mathbf{V = E_b + I_aR_a + IR_{se}}$$

$$\mathbf{I_{sh} = \frac{V - I\,R_{se}}{R_{sh}} = \frac{E_b + I_aR_a}{R_{sh}}}$$

Cumulative compound motor: The flux produced by the shunt field winding enhances the effect of the main field flux which is produced by series winding.

Differential compound motor: The flux produced due to the shunt field winding reduces the effect of the main series winding.

Characteristics of DC Motor: The performance of a DC motor under various conditions can be judged by the following characteristics.

1. Torque – Armature current characteristics (T_a Vs I_a)
2. Speed – Armature current characteristics (N Vs I_a)
3. Speed – Torque characteristics (N Vs T_a)

Characteristics of DC Shunt Motor: The shunt motors are the constant flux machines i.e. their magnetic flux remains constant because their field winding is directly connected across the supply voltage which is assumed to be constant.

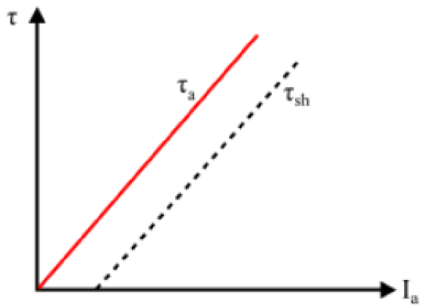
Torque – Armature current characteristics (T_a Vs I_a): The armature torque in a DC motor is directly proportional to the flux and the armature current, i.e.,

$$\tau_a \propto \varphi I_a$$

In case of a shunt motor, the flux is also constant. Therefore,

$$\tau_a \propto I_a$$

Hence, the torque and armature current characteristics of DC shunt motor is straight line passing through the origin (see the figure). The shaft torque is less than the armature torque which is represented by the dotted line.



From the characteristics, it can be seen that a very large current is required to start a heavy load. Thus, the shunt motor should not be started on heavy loads.

Speed – Armature current characteristics (N Vs I_a):

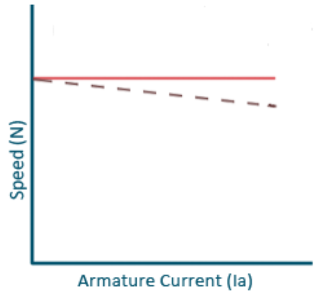
The Speed of a shunt DC motor is given by,

$$N \propto E_b$$

$$\because E_b = V - I_a R_a$$

$$\therefore N \propto (V - I_a R_a)$$

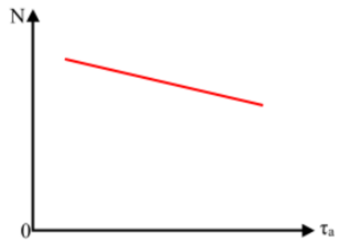
For a DC shunt motor, the back EMF and flux both are constant under normal operating conditions. Therefore, the speed of a shunt motor will remain constant with respect to the armature current as shown by a dotted line.



However, when the load is increased, the back EMF and flux decreases due to the drop in armature resistance and armature reaction respectively. Although the back EMF decreases somewhat greater than the flux so that speed of motor decreases slight with the increase in load.

Speed – Torque characteristics (N Vs T_a):

This is the curve plotted between the speed and the torque for various armature currents. It can be seen that the speed of the shunt motor decreases as the load torque increases.



Characteristics of DC Series Motor: In a DC series motor, the field winding is connected in series with the armature and hence carries the full armature current. When the load on shaft of the motor is increased, the armature current also increases. Hence, the flux in a series motor increases with the increase in the armature current and vice-versa.

Torque – Armature current characteristics (T_a Vs I_a):

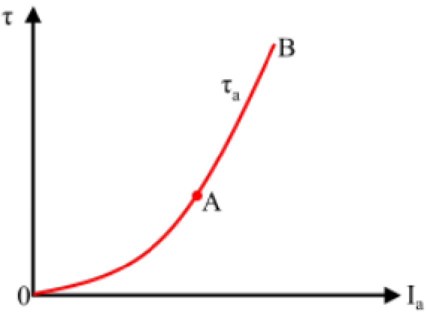
In a DC motor,

$$\tau_a \propto \varphi I_a$$

Up to magnetic saturation, $\varphi \propto I_a$; so that $\tau_a \propto I_a^2$

After magnetic saturation ,φ becomes constant so that, $\tau_a \propto I_a$

Therefore, up to magnetic saturation, the armature torque is directly proportional to the square of the armature current. Hence, the torque versus armature current curve upto magnetic saturation is a parabola (part OA of the curve).



After the magnetic saturation, the armature torque is directly proportional to the armature current. Hence, torque versus armature current curve after magnetic saturation is a straight line (Part AB of the curve).

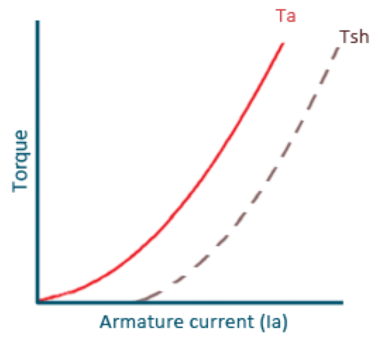
From the torque versus armature current curve, it is clear that the starting torque of a DC series motor is very high.

Speed – Armature current characteristics (N Vs I_a):

The speed of a DC series motor is given by,

$$N \propto \frac{E_b}{\varphi}; \text{ Where, } E_b = V - I_a(R_a + R_{se})$$

With the increase in the armature current, the back EMF is decreased due to the ohmic drop in armature and series field resistances whereas the flux is increased. Although, the resistance drop is very small under normal operating conditions and can be neglected, thus,



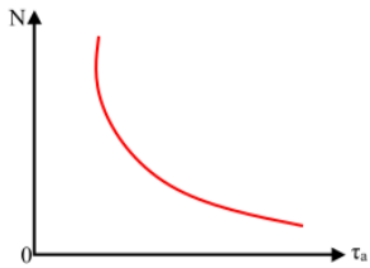
$$N \propto \frac{1}{\varphi} \propto \frac{1}{I_a}; \text{ Up to magnetic saturation.}$$

Hence, up to magnetic saturation, the speed versus armature current curve is a hyperbola while after the magnetic saturation, the flux becomes constant and hence the speed.

Speed – Torque characteristics (N Vs T_a):

The speed torque characteristics of a DC series motor can be obtained from its speed-armature current and torque-armature current characteristics as follows

For a given value of Ia determine τa from the torque-armature current curve and N from the speed-armature current curve. This will give a point (τ,N) on speed-torque curve. Repeat this procedure for different values of armature current and determine the corresponding values of speed and torque (τ1, N1), (τ2, N2) etc.



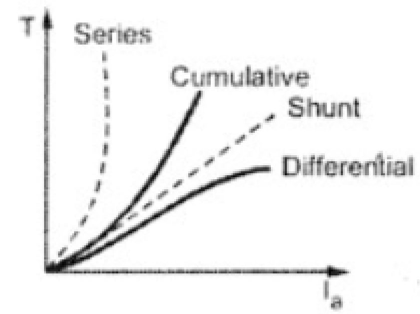
When these points are plotted on the graph, we obtain the speed and torque characteristics of a DC series motor as shown in the figure.

It is clear from the characteristics that the series motor has high torque at low speed and vice-versa. Thus, the series DC motor is used where high starting torque is required.

Characteristics of DC Compound Motor:

Torque – Armature current characteristics (T_a Vs I_a):

As the load increases, the series field fluxes increase but the shunt field flux remains constant consequently, total flux is increased and hence the armature torque. It may be noted that the torque of a cumulative compound motor is greater than that of a shunt motor for a given armature current due to the series field. Differential compound motor characteristics is reverse of the cumulative compound motor.

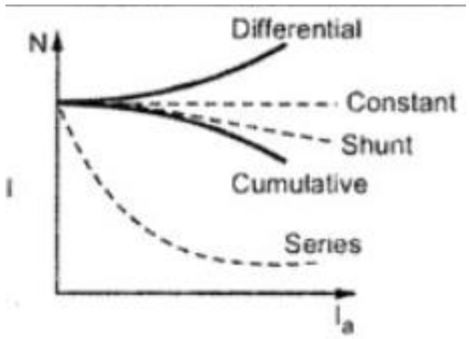


Speed – Armature current characteristics (N Vs I_a):

We have, $N \propto \frac{E_b}{\varphi}$

E_b is practically constant.

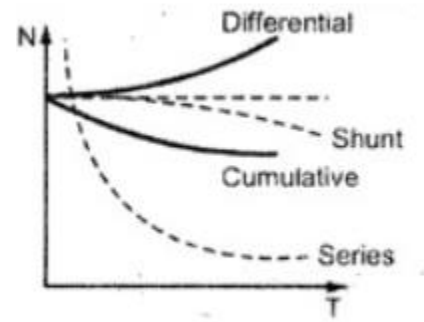
$$N \propto \frac{1}{\varphi}$$



As the load increases the flux per pole also increases consequently the speed of the motor falls. Thus the speed regulation of a cumulative compound motor is poorer than of a shunt motor.

Speed – Torque characteristics (N Vs T_a):

For a given armature current, the torque of a cumulative compound motor is more than that of a series motor.



Speed Control of DC Shunt Motor:

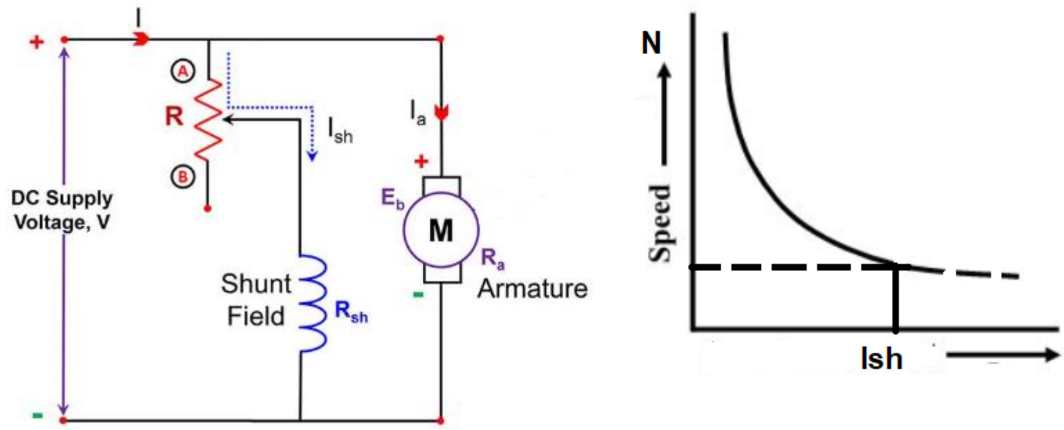
DC shunt motor speed can be controlled by

1. Flux control method
2. Armature voltage control method (Rheostat control method)
3. Applied voltage control method

Flux Control Method :

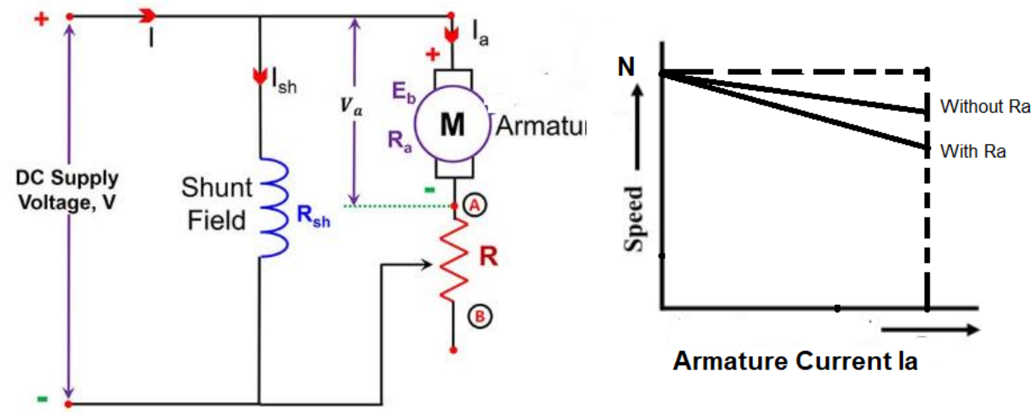
The speed of a DC motor is inversely proportional to the flux per pole. Thus by decreasing the flux, speed can be increased and vice versa.

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux. In shunt motors, as field current is relatively very small, I_{sh}^2R loss is small. Therefore, this method is quite efficient. Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of field flux beyond a limit will adversely affect the commutation.



Armature Voltage Control Method:

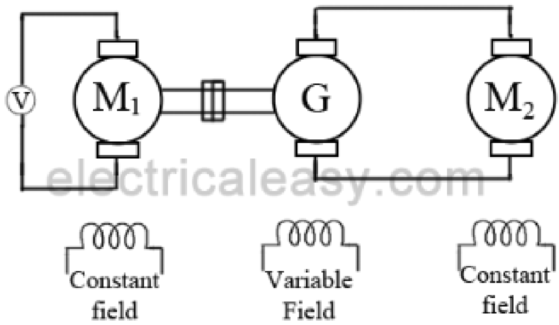
The speed of a dc motor is directly proportional to the back emf E_b and $E_b = V - I_aR_a$. That means, when the supply voltage V and the armature resistance Ra are kept constant, then the speed is directly proportional to armature current Ia. Thus, if we add resistance in series with the armature,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



Voltage Control Method:

Multiple voltage control: In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of suitable switchgear. The speed is approximately proportional to the voltage across the armature.

Ward-Leonard System:



This system is used where very sensitive speed control of motor is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right. M_2 is the motor to which speed control is required.

M_1 may be any AC motor or DC motor with constant speed. G is a generator directly coupled to M_1.In this method, the output from generator G is fed to the armature of the motor M2 whose speed is to be controlled. The output voltage of generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M2 is varied very smoothly. Hence, very smooth speed control of the dc motor can be obtained by this method.

Applications of DC Motors:

1. **DC Shunt Motor:** When constant speed is required DC shunt motors are used.
   Examples: Lathes, Centrifugal pumps, fans, drilling machines. etc.

2. **DC Series Motor:** For high starting torque we prefer DC series motor.
   Examples: Electric traction, electric locomotives, cranes, hoists, conveyors etc.

3. **DC Compound Motor:** When we require constant speed and high starting torque Cumulative compound motors are preferred.
   Examples: shears, punches, coal-cutting machines, elevators, conveyors, printing presses, etc. Differential compound motors have no practical applications (being unstable).

Losses in DC motors: The losses taking place in the motor are the same as a generator are classified into three groups are

1. Copper losses
   - Armature Cu loss
   - Field Cu loss
   - Loss due to brush contact resistance
2. Iron Losses
   - Hysteresis loss
   - Eddy current loss
3. Mechanical losses
   - Friction loss
   - Windage loss

Copper Losses: These losses occur in the armature and field copper windings. Copper losses consist of Armature copper loss, Field copper loss, and loss due to brush contact resistance.

Armature copper loss = $I_a^2R_a$ (where, I_a = Armature current and R_a= Armature resistance)

This loss contributes about 30 to 40% to full load losses. The armature copper loss is variable and depends upon the amount of loading of the machine.

Field copper loss = $I_f^2R_f$ (where, I_f = field current and R_f = field resistance)

In the case of a shunt-wounded field, field copper loss is practically constant. It contributes about 20 to 30% to full load losses.

Brush contact resistance also contributes to the copper losses. Generally, this loss is included into armature copper loss.

Iron Losses (Core Losses): As the armature core is made of iron and it rotates in a magnetic field, a small current gets induced in the core itself too. Due to this current, eddy current loss and hysteresis loss occur in the armature iron core. Iron losses are also called as Core losses or magnetic losses.

Hysteresis loss is due to the reversal of magnetization of the armature core. When the core passes under one pair of poles, it undergoes one complete cycle of magnetic reversal. The frequency of magnetic reversal is given by, $f=P.N/120$ (where, P = no. of poles and N = Speed in rpm)

The loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. Hysteresis loss is given by, Steinmetz formula:

$W_h=\eta B_{max}^{1.6}fV$ (watts)

where, η = Steinmetz hysteresis constant

V = volume of the core in m^3

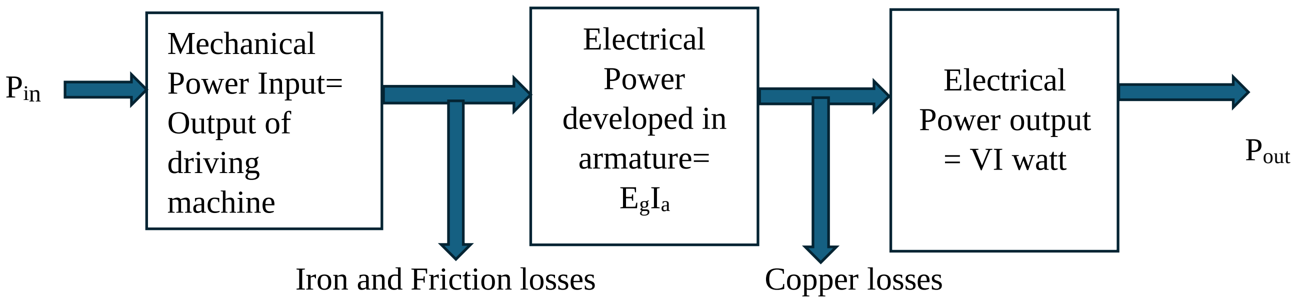
Eddy current loss: When the armature core rotates in the magnetic field, an emf is also induced in the core (just like it induces in armature conductors), according to the Faraday's law of electromagnetic induction. Though this induced emf is small, it causes a large current to flow in the body due to the low resistance of the core. This current is known as eddy current. The power loss due to this current is known as eddy current loss.

Mechanical Losses: Mechanical losses consist of losses due to friction in bearings and commutator. Air friction loss of rotating armature also contributes to these losses are about 10 to 20% of full load losses.

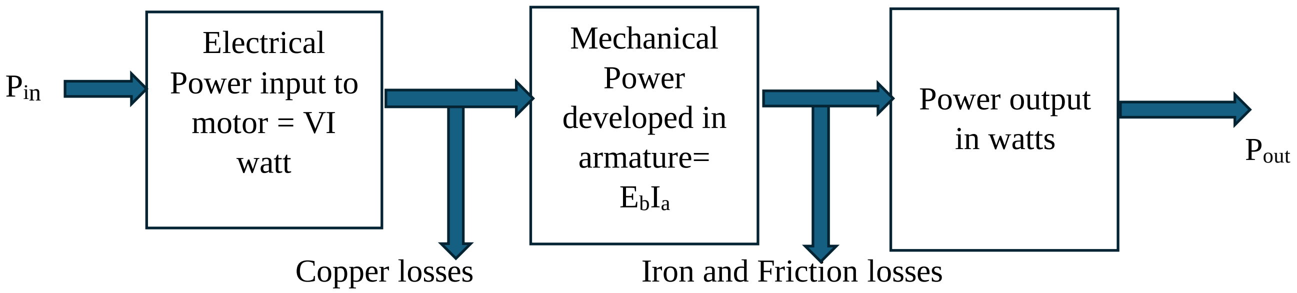
Stray Losses: In addition to the losses stated above, there may be small losses present which are called stray losses or miscellaneous losses. These losses are difficult to account. They are usually due to inaccuracies in the design and modeling of the machine. Most of the time, stray losses are assumed to be 1% of the full load.

Power Flow Diagram: The most convenient method to understand these losses in a dc generator or a dc motor is using the power flow diagram. The diagram visualizes the amount of power that has been lost in various types of losses and the amount of power which has been actually converted into the output. Following are the typical power flow diagrams for a dc generator and a dc motor.

Power flow diagram of Generator



Power flow diagram of Motor



The efficiency of DC motor:

For a D.C. machine, its overall efficiency is given by,

$$\% \eta = \frac{\text{total output}}{\text{total input}} \times 100$$

Let P_{out} = total output of a machine

P_{in} = total input of a machine

P_{cu} = variable losses

P_i= constant losses

Then Pin = $P_{out} + P_{cu} + P_i$

$$\therefore \qquad \% \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{out}}{P_{out} + \text{losses}} \times 100$$

$$\boxed{\therefore \qquad \% \eta = \frac{P_{out}}{P_{in} + P_{cu} + P_i} \times 100}$$

Condition for Maximum Efficiency: The condition for maximum efficiency of a DC generator or of a DC motor is the same and for a DC generator it is derived as follows.

Generator output = VI

V= Terminal Voltage

I = Output or Load current

Generator input = Output + Total losses

= VI + $P_{cu} + P_i$

P_{cu} = Variable losses = $I^2 R_a = I^2 R_a$

$I_a = I$ ……. Neglecting shunt field current

R_a = Total resistance of armature circuit

$$\text{Generator efficiency n} = \frac{\text{Output}}{\text{Input}} * 100$$

$$\therefore \qquad \% \eta = \frac{VI}{VI + I^2 R_a + P_i} \times 100 = \frac{1}{1 + \left(\frac{I R_a}{V} + \frac{P_i}{VI} \right)} \times 100$$

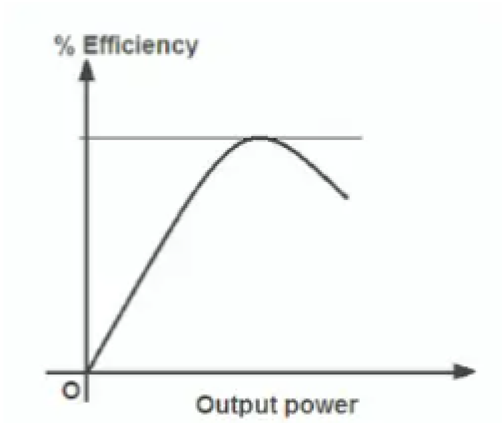
The efficiency is maximum when the denominator is minimum. According to maxima-minima theorem,

$$\frac{d}{dI}\left[1 + \left(\frac{I R_a}{V} + \frac{P_i}{VI} \right)\right] = 0$$

$$\therefore \qquad \frac{R_a}{V} - \frac{P_i}{VI^2} = 0$$

$$\therefore \qquad I^2 R_a - P_i = 0$$

$$\therefore \qquad I^2 R_a = P_i = P_{cu}$$



Hence efficiency will be maximum when variable losses are equal to constant losses.

Direct and Indirect Method of Testing of DC motor:

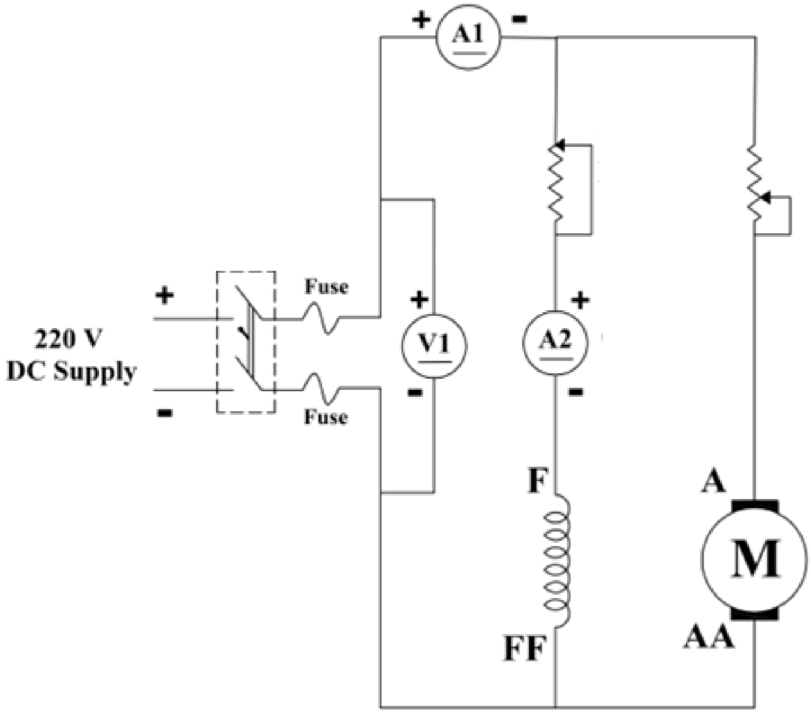
Direct Method:

- In this method, the DC machine is loaded directly using a brake applied to a water-cooled pulley coupled to the shaft of the machine.
- It is practically not possible to arrange loads for machines of large capacity. So this method is used only for testing small DC machines.
- The Brake Test is an example of a direct test.

Indirect Method :

- In this method of testing, the losses are determined without actual loading of the machine.
- If the total losses in the machine are known the efficiency can be calculated. Swinburne's Test is an example of an Indirect Test.

Swinburn's Test:



This is indirect method of testing d.c. motors in which flux remains practically constant i.e. especially in case of shunt and compound motors. Without actually loading the motor the losses and hence efficiency at different loads can be found out.

The motor is run on no load at its rated voltage. At the start some resistance is connected in series with the armature which is cut when the motor attains sufficient speed.

Now the speed of the motor is adjusted to the rated speed with the help of shunt field rheostat as shown in Fig.

The no-load armature current I_0 is measured by ammeter A1 whereas the shunt current is measured by ammeter A2.

The no-load current is

$$(I_0 - I_{sh}) \text{ or } I_{a0}.$$

Let, supply voltage $= V$ no-load input $= VI_0$ watt

$\therefore$ Power input to armature $= V(I_0 - I_{sh})$; Power input to shunt $= VI_{sh}$

No-load power input to armature supplies the following :

(i) Iron losses in core (ii) friction loss (iii) windage loss and

(iv) armature Cu loss, $(I_0 - I_{sh})^2 R_a$ or $I_{a0}^2 R_a$

In calculating armature Cu loss, the 'hot' resistance of the armature should be used. A stationary measurement of armature circuit resistance at the room-temperature of, say, 15^{0}C is made by passing current through the armature from a low voltage d.c. supply.

Then, the 'hot' resistance, allowing a temperature rise of 50ºC is found thus :

$$R_{15} = R_0(1 + 15\alpha_0) \; ; R_{65} = (1 + 65\alpha_0), R_{65} = R_{15} \times \frac{1 + 65\alpha_0}{1 + 15\alpha_0}$$

Taking $\alpha_0 = 1/234.5$, we have $R_{65} = R_{15} \times \frac{234.5 + 65}{234.5 + 15} = 1.2\, R_{15}$ (approx.*)

If we subtract from the total input the no-load armature Cu loss, then we get constant losses.

$\therefore$ Constant losses $W_c = VI_0 - (I_0 - I_{sh})^2 R_a$

Knowing the constant losses of the machine, its efficiency at any other load can be determined as given below. Let I = load current at which efficiency is required.

Then, armature current is $I_a = I - I_{sh}$ ...if machine is motoring

$= I + I_{sh}$ ...if machine is generating

Efficiency when running as a motor:

Input $= VI$, Armature Cu loss $= I_a^2 R_a = (I - I_{sh})^2 R_a$

Constant losses $= W_c$ ...found above

$$\therefore \text{Total losses} = (I - I_{sh})^2 R_a + W_c \; ; \eta_m = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{VI - (I - I_{sh})^2 R_a - W_c}{VI}$$

Efficiency when running as a Generator:

Output = VI ; Armature, Cu loss = $(I+I_{sh})^2R_a$; Constant loss = W_c ...found above

$$\therefore \quad \text{Total losses} = (I+I_{sh})^2R + W_c \; ; \; \eta_g = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{VI}{VI + (I+I_{sh})^2 R_a + W_c}$$

Advantages and Disadvantages of Swinburne's Test:

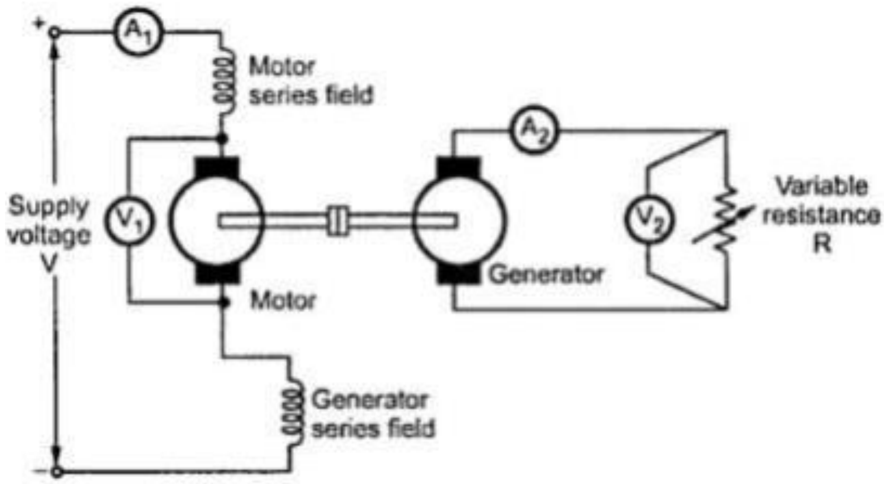
Advantages:

1. It is convenient and economical because the power required to test a large machine is small i.e. only no-load input power.
2. The efficiency can be predetermined at any load because constant losses are known.

Disadvantages:

1. No account is taken of the change in iron losses from no-load to full-load. At full load, due to armature reaction, flux is distorted which increases the iron losses m some cases by as much as 50%.
2. As the test is on no-load, it is impossible to know whether commutation would be satisfactory at full load and whether the temperature rise would be within the specified limits.

Field Test:



This test is applicable to two similar series motors. Series motors which are mainly used for traction work are easily available in pairs. The two machines are coupled mechanically.

One machine runs normally as a motor and drives a generator whose output is wasted in a variable load R (Fig.31.14). Iron and friction losses of two machines are made equal

(i) By joining the series field winding of the generator in the motor armature circuit so that both machines are equally excited and

(ii) By running them at equal speed. Load resistance R is varied till the motor current reaches its full-load value indicated by ammeter A1.

After this adjustment for full-load current, different ammeter and voltmeter readings are noted.

Let V = supply voltage; I_1 = motor current; V_2 = terminal p.d. of generator; I_2 load current.

Intake of the whole set = VI_1 ; output = V_2I_2.

Total losses in the set, $W_t = VI_1 - V_2I_2$

Armature and field Cu losses $W_{cu} = (R_a + 2R_{se})I_1^2 + I_2^2R_a$

where R_a= hot armature resistance of each machine

R_{se} = hot series field resistance of each machine

$\therefore$ Stray losses for the set $= W_t - W_{cu}$

$$\text{Stray losses per machine} \quad W_s = \frac{W_t - W_{cu}}{2}$$

Stray losses are equally divided between the machines because of their equal excitation and speed.

Motor Efficiency:

$$\begin{aligned}\text{Motor input} &= V_1I_1\\ \text{Motor losses} &= \text{armature + field Cu losses + stray losses}\\ &= (R_a + R_{se})I_1^2 + W_s = W_m \text{ (say)}\end{aligned}$$

$$\eta_m = \frac{V_1I_1 - W_m}{V_1I_1}$$

Generator Efficiency: The generator efficiency will be of little use because it is running under abnormal conditions of separate excitation. However, the efficiency under these unusual conditions can be found if desired.

$$\begin{aligned}\text{Generator output} &= V_2I_2\\ \text{Field Cu loss} &= I_1^2R_{se} \qquad (\because \text{ Motor current is passing through it.})\\ \text{Armature Cu loss} &= I_2^2R_a\text{ ; Stray losses} = W_s\\ \text{Total losses} &= I_1^2R_{se} + I_2^2R_a + W_s = W_g \text{ (say)}\end{aligned}$$

$$\eta_g = \frac{V_2I_2}{V_2I_2 + W_g}$$

ATME COLLEGE OF ENGINEERING

13th KM Stone, Bannur Road, Mysore - 560 028

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

(ACADEMIC YEAR 2024-25)

COURSE: Electric Motors

SUB CODE: BEE401

SEMESTER: Four

Vision & Mission of ATME College of Engineering

Vision

Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources.

Mission

- To keep pace with advancements in knowledge and make the students competitive and capable at the global level.
- To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torchbearers of tomorrow's society.
- To strive to attain ever-higher benchmarks of educational excellence.

Vision & Mission of Department of Electrical & Electronics Engineering

Vision of the department

To create Electrical and Electronics Engineers who excel to be technically competent and fulfill the cultural and social aspirations of the society.

Mission of the Department

- To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development.
- To offer outcome based technical education.
- To encourage faculty in training & development and to offer consultancy through research & industry interaction.

PROGRAMME EDUCATIONAL OBJECTIVES AND PROGRAMME OUTCOMES

PROGRAMME OUTCOMES:

Engineering Graduates will be able to:

PO1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of EXPERIMENTs, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one‘s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

Program Educational Objectives (PEOs):

PEO1: To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society.

PEO2: To make graduates continuously acquire and enhance their technical and socio-economic skills.

PEO3: To aspire graduates on R&D activities leading to offering solutions and excel in various career paths.

PEO4: To produce quality engineers who have the capability to work in teams and contribute to real time projects.

Electric Motors-BEE401