If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

UNIT II

DC MOTORS

Working Principle of A Dc Motor:
The DC motor is the device which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that "the current carrying conductor placed in a magnetic and electric field experience a force". And that force is called the Lorentz force. The Fleming left-hand rule gives the direction of the force.

Fleming Left Hand Rule
If the thumb, middle finger and the index finger of the left hand are displaced from each other by an angle of 90°, the middle finger represents the direction of the magnetic field. The index finger represents the direction of the current, and the thumb shows the direction of forces acting on the conductor.

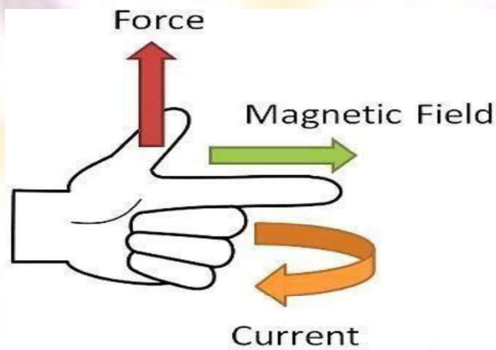


Fig: Flemings left hand rule

The formula calculates the magnitude of the force,

$$F = BIl \quad \text{newton}$$

Before understanding the working of DC motor first, we have to know about their construction. The armature and stator are the two main parts of the DC motor. The armature is the rotating part, and the stator is their stationary part. The armature coil is connected to the DC supply.

The armature coil consists the commutators and brushes. The commutators convert the AC induces in the armature into DC and brushes transfer the current from rotating part of the motor to the stationary external load. The armature is placed between the north and south pole of the permanent or electromagnet.

For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. When the DC supply is given to the armature coil the current starts flowing through it. This current develops their own field around the coil. Figure B shows the field induces around the coil.

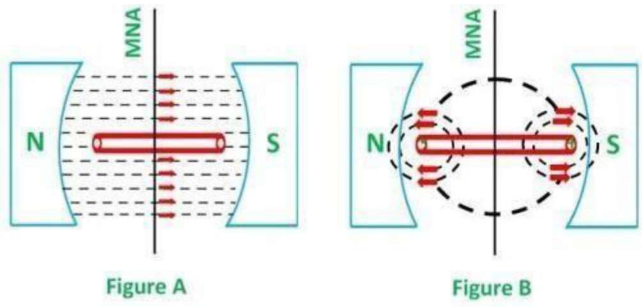


Fig: magnetic field induces around the coil.

By the interaction of the fields (produces by the coil and the magnet), resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating.

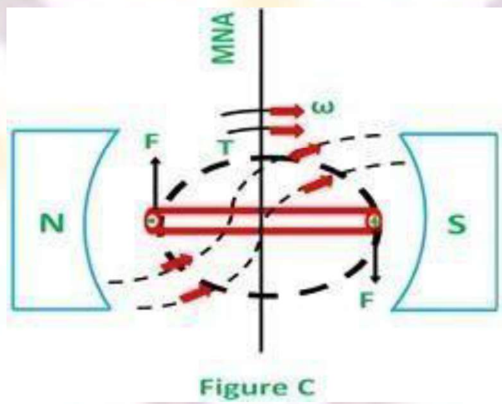


Fig: Field produced due to poles alone

Let the field produces by the main field be F_m, and this field rotates in the clockwise direction. When the current flows in the coil, they produce their own magnetic field says F_r. The field F_r tries to come in the direction of the main field. Thereby, the torque act on the armature coil.

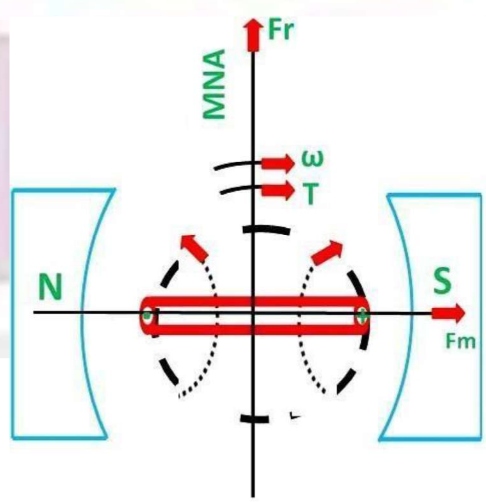


Fig: Field produced due to conductors alone

The actual DC motor consists a large number of armature coils. The speed of the motor is directly proportional to the number of coils used in the motor. These coils are kept under the impact of the magnetic field.

The one end of the conductors are kept under the influence of north pole, and the other end is kept under the influence of the South pole. The current enters into the armature coil through the north pole and move outwards through the south pole. When the coil moves from one brush to another, at the same time the polarity of the coil also changes. Thus, the direction of the force or torque acting on the coil remains same.

The torque induces in the coil become zero when the armature coil is perpendicular to the main field. The zero torque means the motor stops rotating. For solving this problem, the number of armature coil is used in the rotor. So if one of their coils is perpendicular to the field, then the other coils induce the torque. And the rotor moves continuously.

Also, for obtaining the continuous torque, the arrangement is kept in such a way that whenever the coils cut the magnetic neutral axis of the magnet the direction of current in the coils become reversed. This can be done with the help of the commutator.

Back Emf and its Significance in DC Motor:

When a dc voltage V is applied across the motor terminals, the armature starts rotating due to the torque developed in it.

As the armature rotates, armature conductors cut the pole magnetic field, therefore, as per law of electromagnetic induction, an emf called ***back emf*** is induced in them.

The back emf (also called counter emf) is given by

$$E_b = \frac{P\Phi ZN}{60A}$$

where, P=number of poles of dc

motor Φ= flux per pole

Z=total number of armature

conductors N=armature speed

A=number of parallel paths in armature winding

As all other parameters are constant, therefore, E_b a N

As per Lenz's law, "the induced emf always opposes the cause of its production”. Here, the cause of generation of back emf is the rotation of armature. Rotation of armature is due to armature torque. Torque is due to armature current and armature current is due to supply dc voltage V. Therefore, the ultimate cause of production of E_b is the supply voltage V.

Therefore, back emf is always directed opposite to supply voltage V.

Significance of back emf in dc motor:

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

It follows, therefore, that energy conversion in a dc motor is only possible due to the production of back emf.

Mechanical power developed in the armature = $E_b I_a$

(2) Back emf makes dc motor a self-regulating motor i.e Eb makes motor to adjust Ia automatically as per the load torque requirement. Let's see how.

From the motor figure,

$$I_a = \frac{V - E_b}{R_a}$$

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

(a) when the motor is running at no-load, small torque ($T_a = KI_a$) is required by the motor to overcome friction and windage. Therefore, a small current is drawn by the motor armature and the back emf is almost equal to the supply voltage.

(b) If the motor is suddenly loaded, the load torque becomes greater than the armature torque and the motor start to slow down. As motor speed decreases, back emf decreases and therefore, armature current starts increasing. With increasing Ia, armature torque increases and at some point it becomes equal to the load torque. At that moment, motor stops slowing down and keeps running at this new speed.

(c) If the load on the motor is suddenly reduced, the driving torque becomes more than the load torque and the motor starts accelerating. As the motor speed increases, back emf increases and therefore, armature current decreases. Due to this reducing armature current, armature developed torque decreases and at some point becomes equal to the load torque. That point onwards, motor will stop accelerating and will start rotating uniformly at this new slightly increased speed.

So, this shows how important is back emf in dc motor. Without back emf, the electromagnetic energy conversion would not have been possible at the first place.

Power Equation of a D.C. Motor:

The voltage equation of a d.c. motor is given by,

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

Multiplying both sides of the above equation by I_a we get,

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

This equation is called power equation of a d.c. motor.

VI_a = Net electrical power input to the armature measured in watts.

$I_a^2R_a$ = Power loss due the resistance of the armature called armature copper loss.

So difference between VI_a and $I_a^2R_a$ i.e. input - losses gives the output of the armature.

So E_bIa is called electrical equivalent of gross mechanical power developed by the armature.

This is denoted as P_m.

∴ Power input to the armature - Armature copper loss = Gross mechanical power developed in the armature.

Condition for Maximum Power:

For a motor from power equation, it is known that,

$$P_m = \text{Gross mechanical power developed} = E_b\ Ia$$

$$= VI_a - I_a^2Ra$$

For maximum P_m, $dP_m/dI_a = 0$

∴ $0 = V - 2I_aRa$

∴ $I_a = V/2Ra$ i.e.

$I_aRa = V/2$

Substituting in voltage equation,

$$V = E_b + I_aRa = E_b + (V/2)$$

∴ $\mathbf{E_b = V/2}$ is the Condition for maximum power

Key Point : This is practically impossible to achieve as for this, current required is much more than its normal rated value. Large heat will be produced and efficiency of motor will be less than 50 %.

29.6. Torque

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 metre acted upon by a circumferential force of F Newton which causes it to rotate at N r.p.m. (Fig. 29.10).

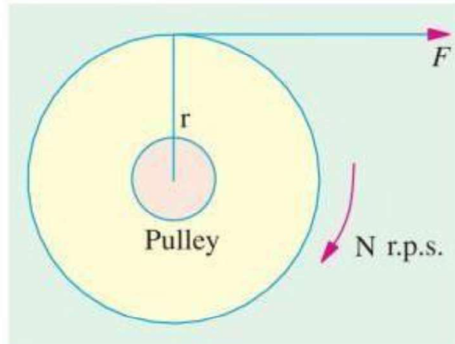


Fig. 29.10

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

Work done by this force in one revolution

$= \text{Force} \times \text{distance} = F \times 2\pi r$ Joule

Power developed $= F \times 2\,\pi r \times N$ Joule/second or Watt

$= (F \times r) \times 2\pi\, N$ Watt

Now $2\,\pi N$ = Angular velocity ω in radian/second and $F \times r$ = Torque T

$\therefore$ Power developed $= T \times \omega$ watt or $P = T\,\omega$ Watt

Moreover, if N is in r.p.m., then

$$\omega = 2\,\pi N/60 \text{ rad}/s$$

$$\therefore \quad P = \frac{2\pi N}{60} \times T \quad \text{or} \quad P = \frac{2\pi}{60}\,.\,NT = \frac{NT}{9.55}$$

29.7. Armature Torque of a 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 $= T_a \times 2\pi\, N$ watt ...(*i*)

We also know that electrical power converted into mechanical power in the armature (Art 29.4)

$= E_b I_a$ watt ...(***ii***)

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

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

$$T_a \times 2\pi N = \Phi\, ZN \left(\frac{P}{A}\right) . I_a \text{ or } T_a = \frac{1}{2\pi} . \Phi Z I_0 \left(\frac{P}{A}\right) N\text{-}m$$

$$= 0.159 \text{ N newton metre}$$

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

Note. From the above equation for the torque, we find that $T_a \propto \Phi I_a$.

(***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 $T_a \propto I_a$.

As seen from (*iii*) above

$$T_a = \frac{E_b\, I_a}{2\pi\, N} \text{ N - m - N in r.p.s.}$$

If N is in r.p.m., then

$$T_a = \frac{E_b\, I_a}{2\pi\, N/60} = 60\,\frac{E_b\, I_a}{2\pi N} = \frac{60}{2\pi}\,\frac{E_b\, I_a}{N} = 9.55\,\frac{E_b I_a}{N} \text{ N-m}$$

29.8. Shaft Torque (T_{sh})

The whole of the armature torque, as calculated above, is not available for doing useful work, because a certain percentage of it is required for supplying iron and friction losses in the motor.

The torque which is available for doing useful work is known as shaft torque T_{sh}. It is so called because it is available at the shaft. The motor output is given by

Output = $T_{sh} \times 2\pi N$ Watt provided T_{sh} is in N-m and N in r.p.s.

$$\therefore \quad T_{sh} = \frac{\text{Output in watts}}{2\pi N} \text{ N- m } -N \text{ in r.p.s}$$

$$= \frac{\text{Output in watts}}{2\pi N / 60} \text{ N-m } -N \text{ in r.p.m.}$$

$$= \frac{60}{2\pi}\frac{\text{output}}{N} = 9.55 \frac{\text{Output}}{N} \text{ N-m.}$$

The difference $(T_a - T_{sh})$ is known as lost torque and is due to iron and friction losses of the motor.

Note. The value of back e.m.f. E_b can be found from

(i) the equation, $E_b = V - I_a R_a$

(ii) the formula $E_b = \Phi ZN \times (P/A)$ volt

Brake Horse Power (B.H.P)

In the case of the motor, the mechanical power available at the shaft is known as Brake Horse Power. If T_{sh} is the shaft torque in Newton Meter and N is the speed in r.p.m then,

$$\text{Useful output power} = \omega T_{sh} = \frac{2\pi N T_{sh}}{60} \quad \text{watts}$$

$$\text{Output in B.H.P} = \frac{2\pi N T_{sh}}{60 \text{ x } 735.5} \quad \dots\dots (1)$$

The output brake horsepower is given by the equation (1) shown above.

Types Of Dc Motor:

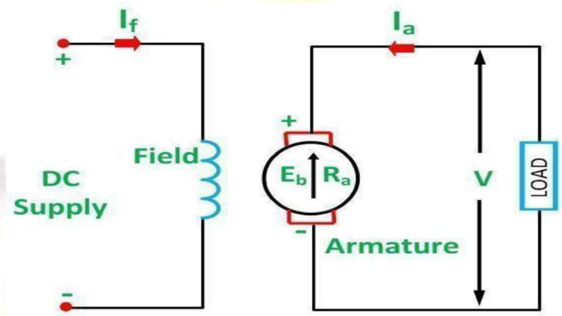
A Direct Current Motor, DC is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors. First, one is Separately Excited DC Motor and Self-excited DC Motor. The self-excited motors are further classified as Shunt wound or shunt motor, Series wound or series motor and Compound wound or compound motor.

The dc motor converts the electrical power into mechanical power is known as dc motor. The construction of the dc motor and generator are same. But the dc motor has the wide range of speed and good speed regulation which in electric traction. The working principle of the dc motor is based on the principle that the current carrying conductor is placed in the magnetic field and a mechanical force experience by it.

The DC motor is generally used in the location where require protective enclosure, for example, drip- proof, the fireproof, etc. according to the requirements. The detailed description of the various types of the motor is given below.

Separately Excited DC Motor:

As the name signifies, the field coils or field windings are energized by a separate DC source as shown in the circuit diagram shown below.



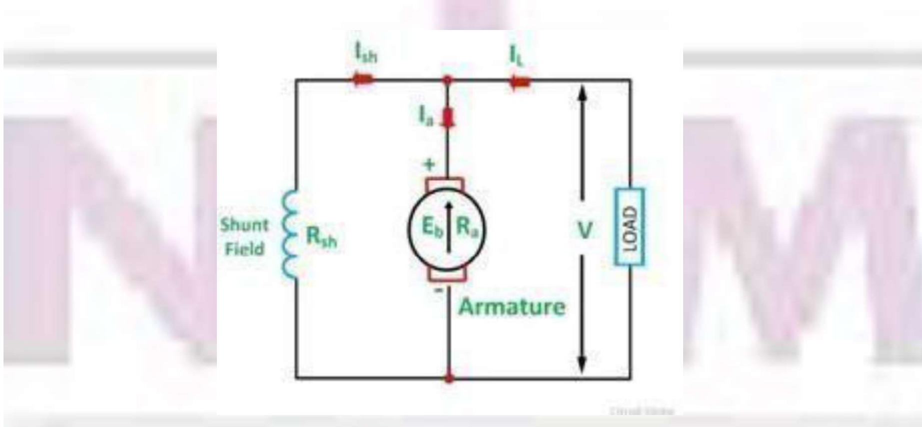
Separately Excited DC Motor

Self-Excited DC Motor:

As the name implies self-excited, hence, in this type of motor, the current in the windings is supplied by the machine or motor itself. Self-excited DC Motor is further divided into shunt wound, and series-wound motor. They are explained below in detail.

Shunt Wound Motor:

This is the most common types of DC Motor. Here the field winding is connected in parallel with the armature as shown in the figure below.



Shunt Wound DC Motor

The current, voltage and power equations for a shunt motor are written as

follows. By applying KCL at the junction A in the above figure.

The sum of the incoming currents at A = Sum of the outgoing currents at A.

$$I = I_a + I_{sh} \dots\dots\dots (1)$$

Where,

I is the input line current

I_a is the armature current

I_{sh} is the shunt field current

Equation (1) is the current equation.

The voltage equations are written by using Kirchhoff's voltage law (KVL) for the field winding circuit.

$$V = I_{sh}R_{sh} \dots\dots (2)$$

For armature winding circuit the equation will be given as

$$V = E + I_aR_a \dots\dots\dots (3)$$

The power equation is given as

Power input = mechanical power developed + losses in the armature + loss in the field.

$$VI = P_m + I_a^2R_a + I_{sh}^2R_{sh} \dots\dots\dots (4)$$

$$VI = P_m + I_a^2R_a + VI_{sh}$$

$$P_m = VI - VI_{sh} - I_a^2R_a = V(I - I_{sh}) - I_a^2R_a$$

$$P_m = VI_a - I_a^2R_a = (V - I_aR_a)I_a$$

$$P_m = EI_a \dots\dots\dots (5)$$

Multiplying equation (3) by Ia we get the following equations.

$$VI_a = EI_a + I_a^2R_a \dots\dots\dots (6)$$

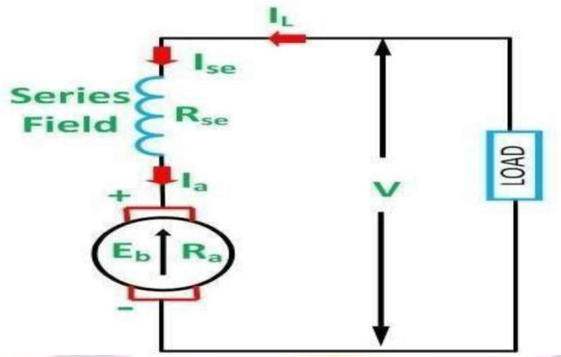
$$VI_a = P_m + I_a^2R_a \dots\dots\dots (7)$$

Where,

VI_a is the electrical power supplied to the armature of the motor.

Series Wound Motor

In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown below.



Series Wound Motor

By applying the KCL in the above figure

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

Where,

I_{se} is the series field current

The voltage equation can be obtained by applying KVL in the above figure

$$V = E + I\,(R_a + R_{se}) \ldots \ldots \ldots (8)$$

The power equation is obtained by multiplying equation (8) by I we get

$$VI = EI + I^2\,(R_a + R_{se}) \ldots \ldots \ldots (9)$$

Power input = mechanical power developed + losses in the armature + losses in the field

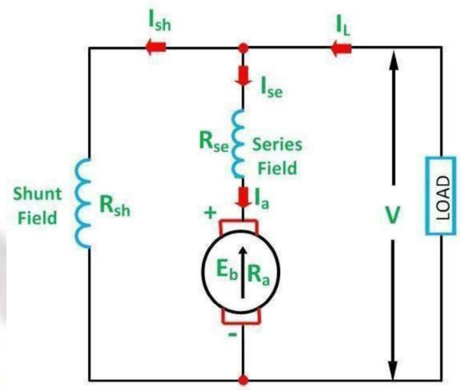
$$VI = P_m + I^2R_a + I^2R_a \ldots \ldots . . (10)$$

Comparing the equation (9) and (10), we will get the equation shown below.

$$P_m = EI \ldots\ldots\ldots (11)$$

Compound Wound Motor

A DC Motor having both shunt and series field windings is called a **Compound Motor**. The connection diagram of the compound motor is shown below.



Compound Motor

The compound motor is further subdivided as **Cumulative Compound** Motor and **Differential Compound** Motor. In cumulative compound motor the flux produced by both the windings is in the same direction, i.e. $\varphi_r = \varphi_{sh} + \varphi_{se}$

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e.

$$\varphi_r = \varphi_{sh} - \varphi_{se}$$

The positive and negative sign indicates that direction of the flux produced in the field windings.

CHARACTERISTICS OF DC MOTORS:

Generally, three characteristic curves are considered important for DC motors which are,

(i) Torque vs. armature current or Electrical Characteristics
(ii) Speed vs. armature current and
(iii) Speed vs. torque. Or Mechanical Characteristics

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

$T_a \propto \phi.I_a$ and $N \propto E_b/\phi$

These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator i.e.

$$E_b = P\phi NZ / 60A.$$

For a machine, P, Z and A are constant, therefore, $N \propto Eb/\phi$

Characteristics Of DC Series Motors

Torque Vs. Armature Current (T_a-I_a):

This characteristic is also known as electrical characteristic. We know that torque is directly proportional to the product of armature current and field flux, $Ta \propto \phi.I_a$. In DC series motors, field winding is connected in series with the armature, i.e. $I_a = I_f$. Therefore, before magnetic saturation of the field, flux $\phi$is directly proportional to Ia. Hence, before magnetic saturation Ta α Ia2. Therefore, the T_a-I_a^2 curve is parabola for smaller values of Ia.

After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to I_a only, $T \propto Ia$. Therefore, after magnetic saturation, Ta-Ia curve becomes a straight line.

The shaft torque (T_{sh}) is less than armature torque (T_a) due to stray losses. Hence, the curve T_{sh} vs I_a lies slightly lower.

In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required.

Speed Vs. Armature Current (N-I_a):

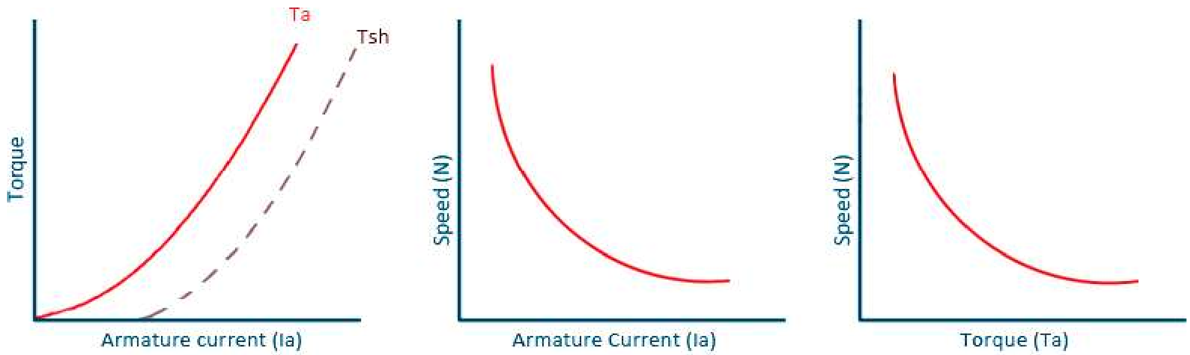
We know the relation, $N \propto Eb/\phi$

For small load current (and hence for small armature current) change in back emf Eb is small and it may be neglected. Hence, for small currents speed is inversely proportional to ϕ. As we know, flux is directly proportional to Ia, speed is inversely proportional to Ia. Therefore, when armature current is very small the speed becomes dangerously high. That is why a series motor should never be started without some mechanical load.

But, at heavy loads, armature current Ia is large. And hence, speed is low which results in decreased back emf Eb. Due to decreased Eb, more armature current is allowed.

Speed Vs. Torque (N-Ta):

This characteristic is also called as mechanical characteristic. From the above two characteristics of DC series motor, it can be found that when speed is high, torque is low and vice versa.



Characteristics of DC series motor

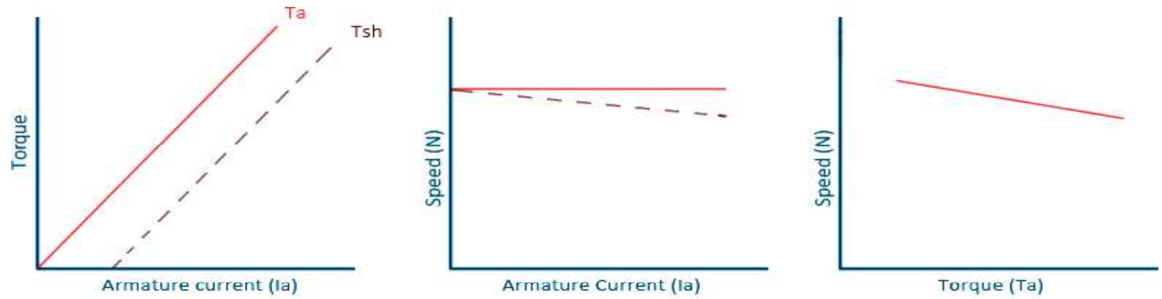
Characteristics Of DC Shunt Motors Torque Vs. Armature Current (Ta-Ia)

In case of DC shunt motors, we can assume the field flux ϕ to be constant. Though at heavy loads, ϕ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ϕ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin.

Since heavy starting load needs heavy starting current, shunt motor should never be started on a heavy load.

Speed Vs. Armature Current (N-Ia)

As flux ϕ is assumed to be constant, we can say N a Eb. But, as back emf is also almost constant, the speed should remain constant. But practically, ϕ as well as Eb decreases with increase in load. Back emf Eb decreases slightly more than ϕ, therefore, the speed decreases slightly. Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, a shunt motor can be assumed as a constant speed motor. In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.



Characteristics of DC shunt motor

Characteristics Of DC Compound Motor

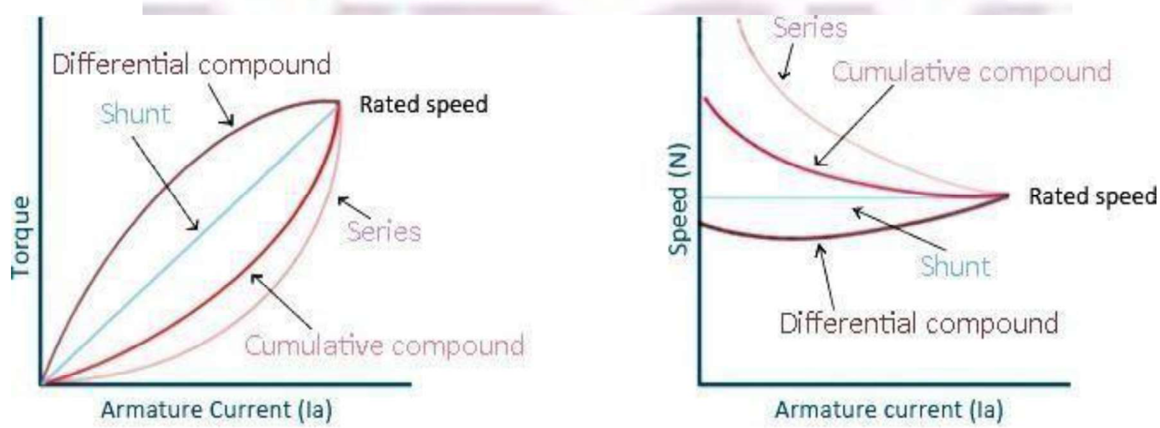
DC compound motors have both series as well as shunt winding. In a compound motor, if series and shunt windings are connected such that series flux is in direction as that of the shunt flux then the motor is said to be cumulatively compounded. And if the series flux is opposite to the direction of the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

(a) Cumulative compound motor

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

(b) Differential compound motor

Since in differential field motors, series flux opposes shunt flux, the total flux decreases with increase in load. Due to this, the speed remains almost constant or even it may increase slightly with increase in load ($N \propto E_b/\phi$). Differential compound motors are not commonly used, but they find limited applications in experimental and research work.



Characteristics of DC compound motor

29.17. Comparison of Shunt and Series Motors

(*a*) Shunt Motors

The different characteristics have been discussed in Art. 29.14. It is clear that

(*a*) speed of a shunt motor is sufficiently constant.

(*b*) for the same current input, its starting torque is not a high as that of series motor. Hence, it is used.

(*i*) When the speed has to be maintained approximately constant from N.L. to F.L. *i.e.* for driving a line of shafting etc.

(*ii*) When it is required to drive the load at various speeds, any one speed being kept constant for a relatively long period *i.e.* for individual driving of such machines as lathes. The shunt regulator enables the required speed control to be obtained easily and economically.

Shunt Motors

Summary of Applications

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

(b) Series Motors

The operating characteristics have been discussed in Art 29.13. These motors

1. have a relatively huge starting torques.
2. have good accelerating torque.
3. have low speed at high loads and dangerously high speed at low loads.

Hence, such motors are used

1. when a large starting torque is required *i.e.* for driving hoists, cranes, trams etc.
2. when the motor can be directly coupled to a load such as a fan whose torque increases with speed.
3. if constancy of speed is not essential, then, in fact, the decrease of speed with increase of load has the advantage that the power absorbed by the motor does not increase as rapidly as the torque. For instance, when torque is doubled, the power approximately increases by about 50 to 60% only. ($\therefore I_a \propto \sqrt{T_a}$).
4. a series motor should not be used where there is a possibility of the load decreasing to a very small value. Thus, it should not be used for driving centrifugal pumps or for a belt-drive of any kind.

Series Motor

SPEED CONTROL OF DC MOTOR:

The dc motor converts the mechanical power into dc electrical power. One of the most important features of the dc motor is that their speed can easily be control according to the requirement by using simple methods. Such type of control is impossible in an AC motor.

The concept of the speed regulation is different from the speed control. In speed regulation, the speed of the motor changes naturally whereas in dc motor the speed of the motor changes manually by the operator or by some automatic control device. The speed of the DC Motor is given by the relation shown below.

The equation (1) that the speed is dependent upon the supply voltage V, the armature circuit resistance R_a and the field flux ϕ, which is produced by the field current.

$$N = \frac{V - I_a R_a}{k\varphi} \quad \dots\dots\dots\dots (1)$$

For controlling the speed of DC Motor, the variation in voltage, armature resistance and field flux is taken into consideration. There are three general methods of speed control of a DC Motor.

They are as follows.

1. Variation of resistance in the armature circuit.This method is called Armature Resistance or Rheostatic control.
2. Variation in field flux. This method is known as Field Flux Control.
3. Variation in applied voltage. This method is also known as Armature Voltage Control.

The detailed discussion of the various method of controlling the speed is given below.

Armature Resistance Control of DC Motor:

Shunt Motor:

The connection diagram of a shunt motor of the armature resistance control method is shown below. In this method, a variable resistor R_e is put in the armature circuit. The variation in the variable resistance does not effect the flux as the field is directly connected to the supply mains.

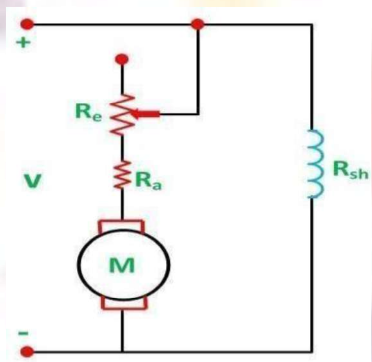


Fig: Connection diagram of a shunt motor of the armature resistance control method The **speed current characteristic** of the shunt motor is shown below.

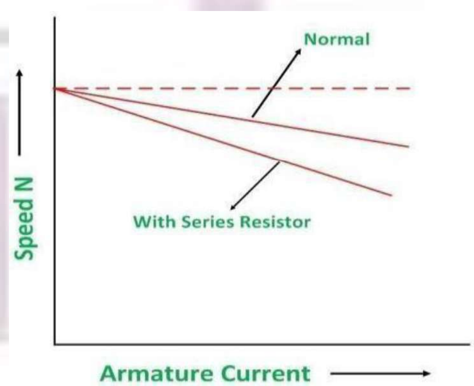
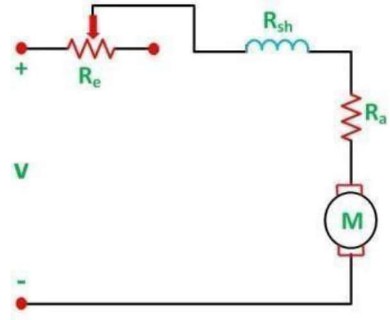


Fig: Speed current characteristic of the shunt motor

Series Motor:

Now, let us consider a connection diagram of speed control of the DC Series motor by the armature resistance control method.

Fig: Diagram of speed control of the DC Series motor



By varying the armature circuit resistance, the current and flux both are affected. The voltage drop in the variable resistance reduces the applied voltage to the armature, and as a result, the speed of the motor is reduced.

The **speed–current characteristic** of a series motor is shown in the figure below.

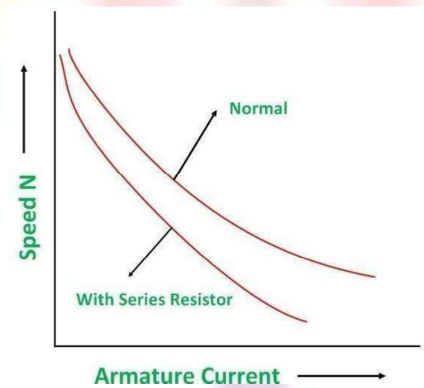


Fig: Speed–current characteristic of a series motor

When the value of variable resistance Re is increased, the motor runs at a lower speed. Since the variable resistance carries full armature current, it must be designed to carry continuously the full armature current.

Disadvantages of Armature Resistance Control Method

- A large amount of power is wasted in the external resistance Re.
- Armature resistance control is restricted to keep the speed below the normal speed of the motor and increase in the speed above normal level is not possible by this method.
- For a given value of variable resistance, the speed reduction is not constant but varies with the motor load.
- This speed control method is used only for small motors.

Field Flux Control Method of DC Motor:

Flux is produced by the field current. Thus, the speed control by this method is achieved by control of the field current.

Shunt Motor

In a Shunt Motor, the variable resistor R_C is connected in series with the shunt field windings as shown in the figure below. This resistor R_C is known as a Shunt Field Regulator.

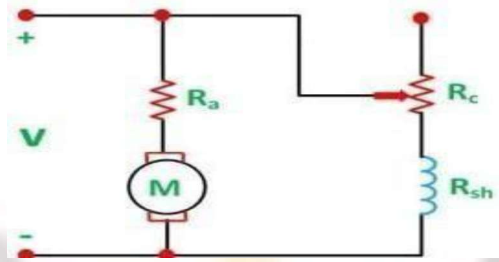


Fig: Shunt Field Regulator

The shunt field current is given by the equation shown below.

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

The connection of R_C in the field reduces the field current, and hence the flux is also reduced. This reduction in flux increases the speed, and thus, the motor runs at speed higher than the normal speed. Therefore, this method is used to give motor speed above normal or to correct the fall of speed because of the load.

The speed-torque curve for shunt motor is shown below.

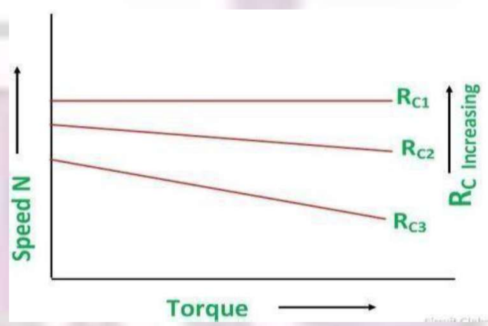


Fig: speed-torque curve for shunt motor

Series Motor

In a series motor, the variation in field current is done by any one method, i.e. either by a diverter or by a tapped field control.

By Using a Diverter:

A variable resistance R_d is connected in parallel with the series field windings as shown in figure

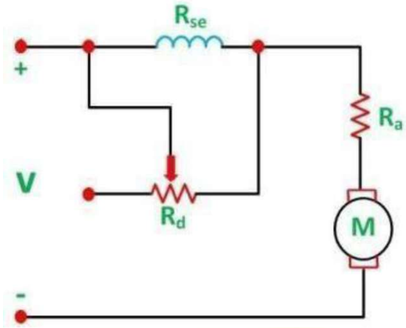


Fig: Diverter is connected in parallel with the series field windings

The parallel resistor is called a Diverter. A portion of the main current is diverted through a variable resistance R_d. Thus, the function of a diverter is to reduce the current flowing through the field winding. The reduction in field current reduces the amount of flux and as a result the speed of the motor increases.

Tapped Field Control:

The second method used in a series motor for the variation in field current is by tapped field control. The connection diagram is shown below.

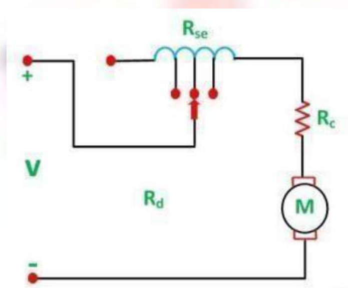


Fig: Tapped Field Control

Here the ampere turns are varied by varying the number of field turns. This type of arrangement is used in an electric traction system. The speed of the motor is controlled by the variation of the field flux. The speed-torque characteristic of a series motor is shown below.

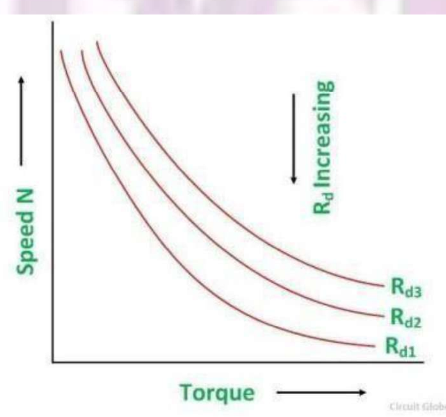


Fig: Speed-torque characteristic

Advantages of Field Flux Control
The following are the advantages of the field flux control method.

- This method is easy and convenient.
- As the shunt field is very small, the power loss in the shunt field is also small.

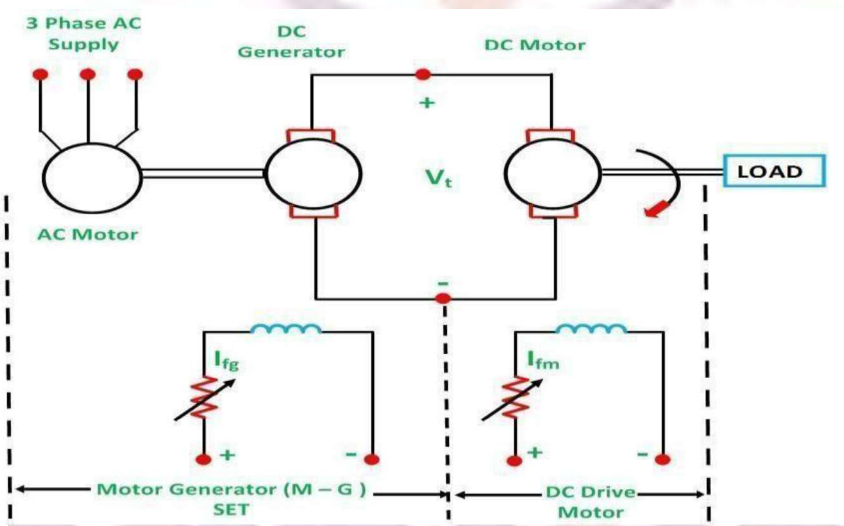
The flux cannot usually be increased beyond its normal values because of the saturation of the iron. Therefore, speed control by flux is limited to the weakening of the field, which gives an increase in speed. This method is applicable over only to a limited range because if the field is weakened too much, there is a loss of stability.

Armature Voltage Control of DC Motor:

In armature voltage control method, the speed control is achieved by varying the applied voltage in the armature winding of the motor. This speed control method is also known as **Ward Leonard Method**, which is discussed in detail under the topic Ward Leonard Method or Armature Voltage Control.

Ward Leonard Method of Speed Control or Armature Voltage Control:

Ward Leonard Method of speed control is achieved by varying the applied voltage to the armature. This method was introduced in 1891. The connection diagram of the Ward Leonard method of speed control of a DC shunt motor is shown in the figure below.

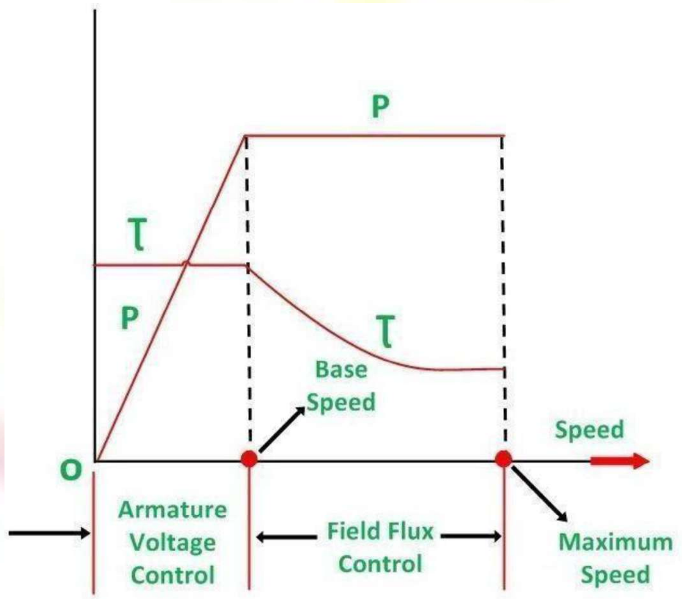


- In the above system, M is the main DC motor whose speed is to be controlled, and G is a separately excited DC generator. The generator G is driven by a 3-phase driving motor which may be an induction motor or a synchronous motor. The combination of AC driving motor and the DC generator is called the Motor-Generator (M-G) set.
- The voltage of the generator is changed by changing the generator field current. This voltage when directly applied to the armature of the main DC motor, the speed of the motor M changes. The motor field current I_{fm} is kept constant so that the motor field flux

ϕ_m also remains constant. While the speed of the motor is controlled, the motor armature current I_a is kept equal to its rated value.

- The generated field current I_{fg} is varied such that the armature voltage V_t changes from zero to its rated value. The speed will change from zero to the base speed. Since the speed control is carried out with the rated current Ia and with the constant motor field flux, a constant torque is directly proportional to the armature current, and field flux up to rated speed is obtained. The product of torque and speed is known as power, and it is proportional to speed. Thus, with the increase in power, speed increases automatically.

The Torque and Power Characteristic is shown in the figure below.



- Hence, with the armature voltage control method, constant torque and variable power drive is obtained from speed below the base speed. The Field flux control method is used when the speed is above the base speed. In this mode of operation, the armature current is maintained constant at its rated value, and the generator voltage Vt is kept constant.
- The motor field current is decreased and as a result, the motor field flux also decreases.This means that the field is weakened to obtain the higher speed. Since VtIa and EIa remain constant, the electromagnetic torque is directly proportional to the field flux ϕm and the armature current Ia. Thus, if the field flux of the motor is decreased the torque decreases.
- Therefore, the torque decreases, as the speed increases. Thus, in the field control mode, constant power and variable torque are obtained for speeds above the base speed. When the speed control over a wide range is required, a combination of armature voltage control and field flux control is used. This combination permits the ratio of maximum to minimum speed available speeds to be 20 to 40. For closed loop control, this range can be extended up to 200.
- The driving motor can be an induction or synchronous motor. An induction motor operates at a lagging power factor. The synchronous motor may be operated at a leading power factor by over-excitation of its field. Leading reactive power is generated by over

excited synchronous motor. It compensates for the lagging reactive power taken by other inductive loads. Thus, the power factor is improved.

- A Slip ring induction motor is used as p prime mover when the load is heavy and intermittent. A flywheel is mounted on the shaft of the motor. This scheme is known as Ward Leonard-Ilgener scheme. It prevents heavy fluctuations in supply current.
- When the Synchronous motor is acting as a driving motor, the fluctuations cannot be reduced by mounting a flywheel on its shaft, because the synchronous motor always operates at a constant speed. In another form of Ward Leonard drive, non-electrical prime movers can also be used to drive the DC generator.
- For example – In DC electric locomotive, DC generator is driven by a diesel engine or a gas turbine and ship propulsion drives. In this system, Regenerative braking is not possible because energy cannot flow in the reverse direction in the prime mover.

Advantages of Ward Leonard Drives:

The main advantages of the Ward Leonard drive are as follows: -

- Smooth speed control of DC motor over a wide range in both the direction is possible.
- It has an inherent braking capacity.
- The lagging reactive volt-amperes are compensated by using an overexcited synchronous motor as the drive and thus, the overall power factor improves.
- When the load is intermittent as in rolling mills, the drive motor is an induction motor with a flywheel mounted to smooth out the intermittent loading to a low value.

Drawbacks of Classical Ward Leonard System:

The Ward Leonard system with rotating Motor Generator sets has following drawbacks.

- The Initial cost of the system is high as there is a motor generator set installed, of the same rating as that of the main DC motor.
- Larger size and weight.
- Requires large floor area
- Costly foundation
- Maintenance of the system is frequent.
- Higher losses.
- Lower efficiency.
- The drive produces more noise.

Applications of Ward Leonard Drives:

The Ward Leonard drives are used where a smooth speed control of the DC motors over a wide range in both the directions is required. Some of the examples are as follows:-

- Rolling mills
- Elevators
- Cranes
- Paper mills
- Diesel-electric locomotives
- Mine hoists

Solid State Control or Static Ward Leonard System:

Now a days Static Ward Leonard system is mostly used. In this system, the rotating motor-generator (M-G) set is replaced by a solid-state converter to control the speed of the DC motor. Controlled Rectifiers and choppers are used as a converter.
In the case of an AC supply, controlled rectifiers are used to convert fixed AC supply voltage into a variable AC supply voltage. In the case of DC supply, choppers are used to obtain variable DC voltage from the fixed DC voltage.

STARTING OF DC MOTORS:

A starter is a device to start and accelerate a motor. A controller is a device to start the motor, control and reverse the speed of the DC motor and stop the motor. While starting the DC motor, it draws the heavy current which damages the motor. The starter reduces the heavy current and protects the system from damage.

Need of Starters for DC Motors:
The dc motor has no back EMF. At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor.

Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine is cut out of the circuit when the machine gains it speeds. The armature current of a motor is given by

$$I_a = \frac{V - E}{R_a} \quad \dots\dots\dots \quad (1)$$

Thus, I_a depends upon E and R_a, if V is kept constant. When the motor is first switched ON, the armature is stationary. Hence, the back EMF E_b is also zero. The initial starting armature current I_{as} is given by the equation shown below.

$$I_{as} = \frac{V - 0}{R_a} = \frac{V}{R_a} \quad \dots\dots\dots\dots \quad (2)$$

Since, the armature resistance of a motor is very small, generally less than one ohm. Therefore, the starting armature current I_{as} would be very large. For example – if a motor with the armature resistance of 0.5 ohms is connected directly to a 230 V supply, then by putting the values in the equation (2) we will get.

$$I_{as} = \frac{V}{R_a} = \frac{230}{0.5} = 460 \quad \text{Ampere}$$

This large current would damage the brushes, commutator and windings.

As the motor speed increases, the back EMF increases and the difference (V – E) go on decreasing. This results in a gradual decrease of armature current until the motor attains its stable speed and the corresponding back EMF. Under this condition, the armature current reaches its desired value. Thus, it is found that the back EMF helps the armature resistance in limiting the current through the armature.

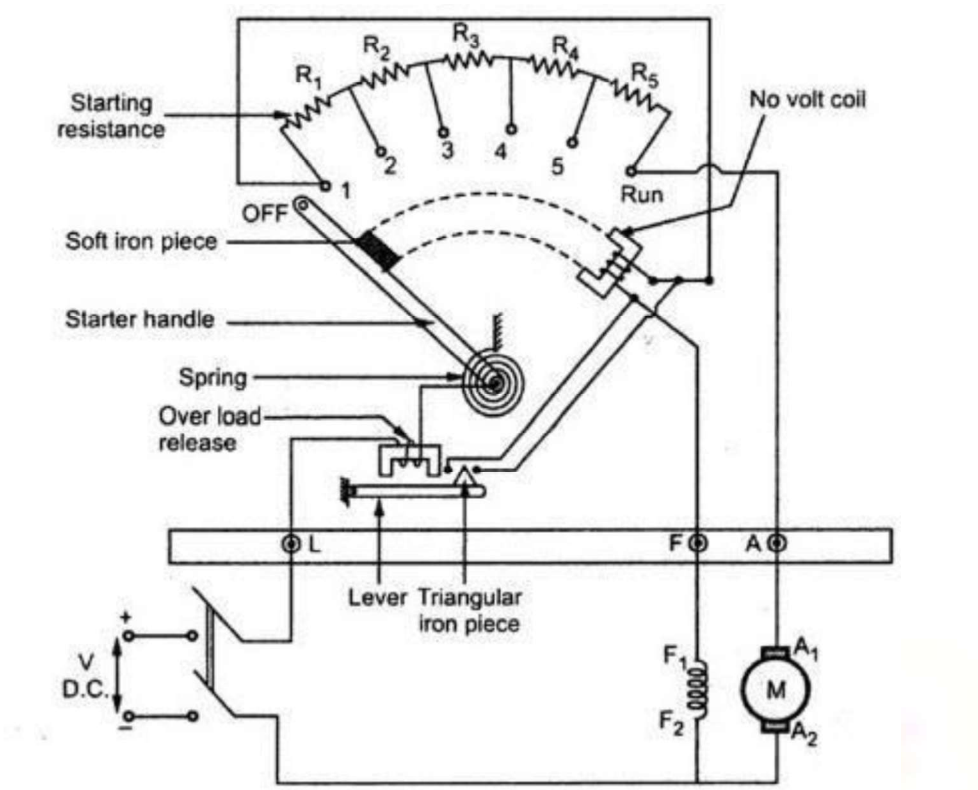
Since at the time of starting the DC Motor, the starting current is very large. At the time of starting of all DC Motors, except for very small motors, an extra resistance must be connected in series with the armature. This extra resistance is added so that a safe value of the motor is maintained and to limit the starting current until the motor has attained its stable speed.

The series resistance is divided into sections which are cut out one by one, as the speed of the motor rises and the back EMF builds up. The extra resistance is cut out when the speed of the motor builds up to its normal value.

THREE POINT STARTER:

3 Point Starter is a device whose main function is starting and maintaining the speed of the DC shunt motor. The 3-point starter connects the resistance in series with the circuit which reduces the high starting current and hence protects the machines from damage.

The 3 Point DC Shunt Motor Starter is shown in the figure below



Construction of 3 Point Starter:

Construction wise a starter is a variable resistance, integrated into the number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as **OFF, 1, 2, 3, 4, 5, RUN**. Other than that there are three main points, referred to as

1. 'L' Line terminal (Connected to positive of supply)
2. 'A' Armature terminal (Connected to the armature winding)
3. 'F' Field terminal (Connected to the field winding)

And from there it gets the name 3-point starter. Now studying the construction of 3-point starter in further details reveals that the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is also attached with it, and the starter handle also contains a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F.' The starting resistance at starting is entirely in series with the armature. The OLR and NVC act as the two protecting devices of the starter.

Working of Three Point Starter:

Having studied its construction, let us now go into the working of the 3-point starter**.** To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting the resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes:

$$I_a = \frac{E}{(R_a + R_{st})}$$

As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.
So the external electrical resistance is not required anymore and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with the development of speed. Now the obvious question is once the handle is taken to the RUN position how it is supposed to stay there, as long as the motor is running.

To find the answer to this question let us look into the working of No Voltage Coil.

Working of No Voltage Coil of 3 Point Starter:

The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized. Now when the handle is in the 'RUN' position, a soft iron piece is connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it. The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus, NVC holds the handle in the 'RUN' position and hence also called hold on coil**.**
Now when there is any kind of supply failure, the current flow through NVC is affected and it immediately loses its magnetic property and is unable to keep the soft iron piece on the handle, attracted. At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor. So due to the combination of NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problem. Thus it also acts as a protective device safeguarding the motor from any kind of abnormality.

Drawbacks of a 3 Point Starter:

The following drawbacks of a 3-point starter are as follows: -

- The 3-point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat.
- To increase the speed of the motor, the field resistance should be increased. Therefore,

the current through the shunt field is reduced.

- The field current may become very low because of the addition of high resistance to obtain a high speed.
- A very low field current will make the holding electromagnet too weak to overcome the force exerted by the spring.
- The holding magnet may release the arm of the starter during the normal operation of the motor and thus, disconnect the motor from the line. This is not a desirable action.

Hence, to overcome this difficulty, the 4 Point Starter is used.

Four Point Starter:

Working Principle of 4 Point Starter

A 4 point starter protects the armature of a DC shunt motor or compound wound DC motor against the initially high starting current of the DC motor.
The 4 point starter has a lot of constructional and functional similarity to a 3 point starter, but this special device has an additional point and coil in its construction (as the name suggests). This brings about some difference in its functionality, though the basic operational characteristic remains the same. The basic difference in the circuit of a 4 point starter as compared to 3 point starter is that the holding coil is removed from the shunt field current and is connected directly across the line with current limiting resistance in series.
Now to go into the details of the operation of 4 point starter, let's have a look at its construction diagram. This will help demonstrate the difference between a 4 vs 3 point starter.

Construction and Operation of Four Point Starter:

A 4-point starter as the name suggests has 4 main operational points, namely

1. 'L' Line terminal (Connected to positive of supply.)
2. 'A' Armature terminal (Connected to the armature winding.)
3. 'F' Field terminal. (Connected to the field winding.)
4. Like in the case of the 3-point starter, and in addition to it there is, a 4th point N (Connected to the No Voltage Coil NVC)

The remarkable difference in case of a 4-point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called 'N' in addition to the 'L', 'F' and 'A'. As a direct consequence of that, any change in the field supply current does not bring about any difference in the performance of the NVC. Thus it must be ensured that no voltage coil always produce a force which is strong enough to hold the handle in its 'RUN' position, against the force of the spring, under all the operational conditions. Such a current is adjusted through No Voltage Coil with the help of fixed resistance R connected in series with the NVC using fourth point 'N' as shown in the figure below.

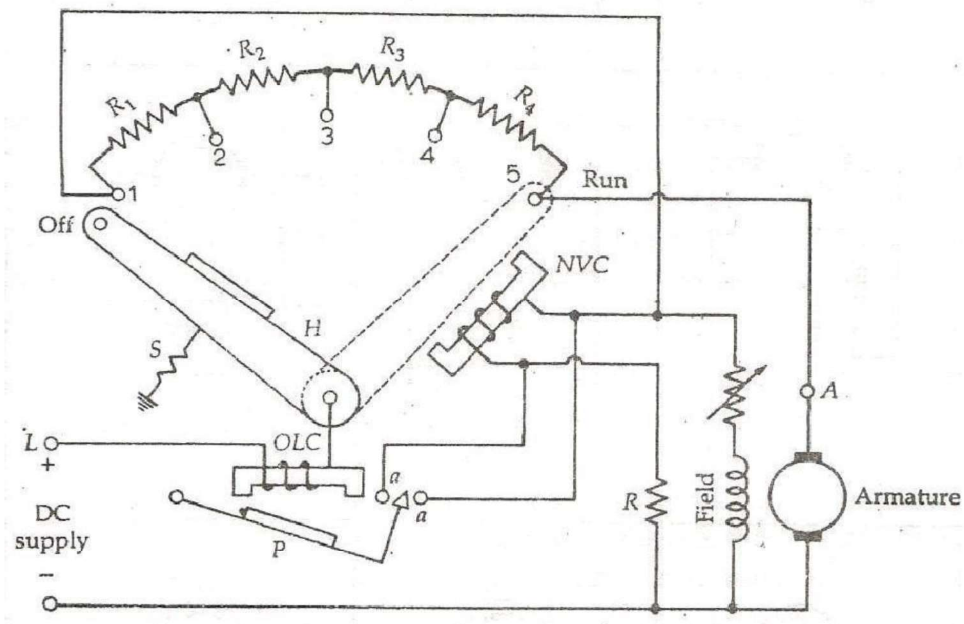


Fig: 4 Point Starter

Apart from this above mentioned fact, the 4 point and 3 point starters are similar in all other ways like possessing is a variable resistance, integrated into number of sections as shown in the figure above. The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN, over which the handle is free to be maneuvered manually to regulate the starting current with gathering speed.

Now to understand its way of operating let's have a closer look at the diagram given above. Considering that supply is given and the handle is taken stud No.1, then the circuit is complete and the line current that starts flowing through the starter. In this situation we can see that the current will be divided into 3 parts, flowing through 3 different points.

1. 1 part flows through the starting resistance (R_1+ R_2 + R_3…..) and then to the armature.
2. A 2^{nd} part flowing through the field winding F.
3. And a 3^{rd} part flowing through the no voltage coil in series with the protective resistance R.

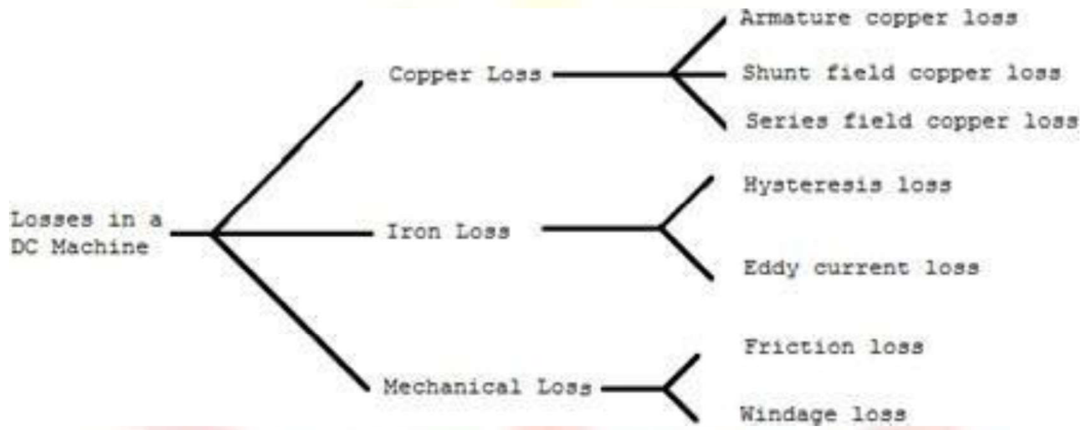
So the point to be noted here is that with this particular arrangement any change in the shunt field circuit does not bring about any change in the no voltage coil as the two circuits are independent of each other.

This essentially means that the electromagnet pull subjected upon the soft iron bar of the handle by the no voltage coil at all points of time should be high enough to keep the handle at its RUN position, or rather prevent the spring force from restoring the handle at its original OFF position, irrespective of how the field rheostat is adjusted.

This marks the operational difference between a 4-point starter and a 3-point starter. As otherwise both are almost similar and are used for limiting the starting current to a shunt wound DC motor or compound wound DC motor, and thus act as a protective device.

Losses in DC Machine:

As we know "Energy neither can be created nor it can be destroyed, it can only be transferred from one form to another". In DC machine, mechanical energy is converted into the electrical energy. During this process, the total input power is not transformed into output power. Some part of input power gets wasted in various forms. The form of this loss may vary from one machine to another. These losses give in the rise in temperature of the machine and reduce the efficiency of the machine. In DC Machine, there are broadly four main categories of energy loss.



Copper Losses or Electrical Losses in DC Machine or Winding Loss:

The copper losses are the winding losses taking place during the current flowing through the winding. These losses occur due to the resistance in the winding. In a DC machine, there are only two windings, armature and field winding.
Thus copper losses categories in three parts; armature loss, the field winding loss, and brush contact resistance loss. The copper losses are proportional to the square of the current flowing through the winding.

Armature Copper Loss in DC Machine

Armature copper loss = $I_a^2R_a$
Where, I_a is armature current and Ra is armature resistance.
These losses are about 30% of the total full load losses.

Field Winding Copper Loss in DC Machine:

Field winding copper loss = $I_f^2R_f$
Where, I_f is field current and R_f is field resistance.
These losses are about 25% theoretically, but practically it is constant.

Brush Contact Resistance Loss in DC Machine:

Brush contact loss attributes to resistance between the surface of brush and commutator. It is not a loss which could be calculated separately as it is a part of variable losses. Generally, it contributes to both the types of copper losses. So, they are factors in the calculation of the above losses.

Core Losses or Iron Losses in DC Machine or Magnetic Losses:

As iron core of the armature is rotating in magnetic field, some losses occurs in the core which is called core losses. Normally, machines are operated with constant speed, so these losses are almost constant. These losses are categorized in two form; Hysteresis loss and Eddy current loss.

Hysteresis Loss in DC Machine:

Hysteresis losses occur in the armature winding due to reversal of magnetization of the core. When the core of the armature exposed to the magnetic field, it undergoes one complete rotation of magnetic reversal. The portion of the armature which is under S-pole, after completing half electrical revolution, the same piece will be under the N-pole, and the magnetic lines are reversed in order to overturn the magnetism within the core. The constant process of magnetic reversal in the armature, consume some amount of energy which is called hysteresis loss. The percentage of loss depends upon the quality and volume of the iron.

Eddy Current Loss in DC Machine:

According to Faraday's law of electromagnetic induction, when an iron core rotates in the magnetic field, an emf is also induced in the core. Similarly, when armature rotates in the magnetic field, the small amount of emf induced in the core which allows the flow of charge in the body due to the conductivity of the core. This current is useless for the machine. This loss of current is called eddy current. This loss is almost constant for the DC machines. It could be minimized by selecting the laminated core.

Mechanical Losses in DC Machine:

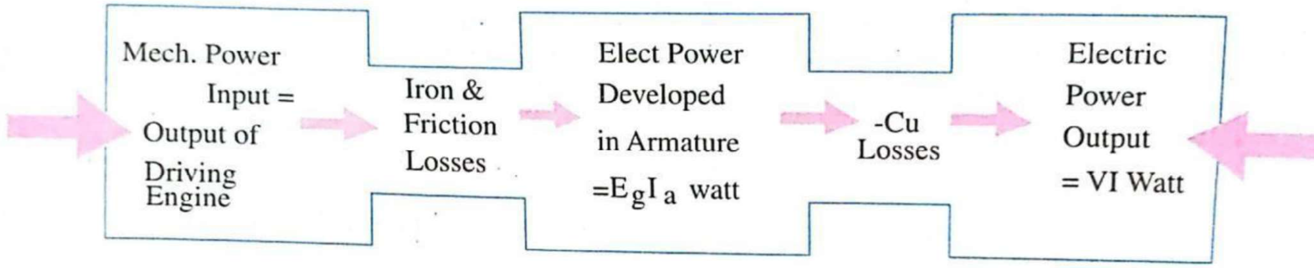
The losses associated with mechanical friction of the machine are called mechanical losses. These losses occur due to friction in the moving parts of the machine like bearing, brushes etc, and windage losses occur due to the air inside the rotating coil of the machine. These losses are usually very small about 15% of full load loss.

Stray Load Losses in DC Machine:

There are some more losses other than the losses which have been discussed above. These losses are called stray-load losses. These miscellaneous losses are due to the short-circuit current in the coil undergoing commutation, distortion of flux due to the armature and many more losses which are difficult to find. These losses are difficult to determine. However, they are taken as 1% of the whole load power output.

26.38. Power Stages

Various power stages in the case of a d.c. generator are shown below :



Following are the three generator efficiencies :

1. Mechanical Efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

2. Electrical Efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

3. Overall or Commercial Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

It is obvious that overall efficiency $\eta_c = \eta_m \times \eta_e$. For good generators, its value may be as high as 95%.

29.19. Power Stages

The various stages of energy transformation in a motor and also the various losses occurring in it are shown in the flow diagram of Fig. 29.26.

Overall or commercial efficiency $\eta_c = \frac{C}{A}$, Electrical efficiency $\eta_e = \frac{B}{A}$, Mechanical efficiency $\eta_m = \frac{C}{B}$.

The efficiency curve for a motor is similar in shape to that for a generator (Art. 24.35).

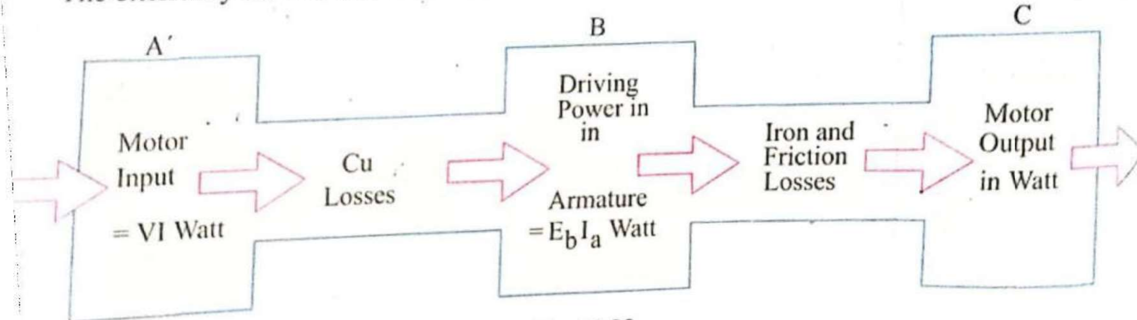


Fig. 29.26

It is seen that $A - B$ = copper losses and $B - C$ = iron and friction losses.

26.39. Condition for Maximum Efficiency

Generator output = VI

Generator input = output + losses

$$= VI + I_a^2 R_a + W_c = VI + (I + I_{sh})^2 R_a + W_c \qquad (\because I_a = I + I_{sh})$$

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

$$\therefore \quad \eta = \frac{\text{output}}{\text{input}} = \frac{VI}{VI + I_a^2 R_a + W_c} = \frac{VI}{VI + I^2 R_a + W_c} \qquad (\because I_a = I)$$

$$= \frac{1}{1 + \left(\frac{IR_a}{V} + \frac{W_c}{VI}\right)}$$

Now, efficiency is maximum when denominator is minimum *i.e.* when

$$\frac{d}{dI}\left(\frac{IR_a}{V} + \frac{W_c}{VI}\right) = 0 \text{ or } \frac{R_a}{V} - \frac{W_c}{VI^2} = \quad \text{or} \quad I^2 R_a = W_c$$

Hence, generator efficiency is maximum when

Variable loss = constant loss.

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

$$I^2 R_a = W_c \quad \text{or} \quad I = \sqrt{\frac{W_c}{R_a}}.$$

UNIT-III

TESTING OF DC MACHINES

BRAKE TEST:

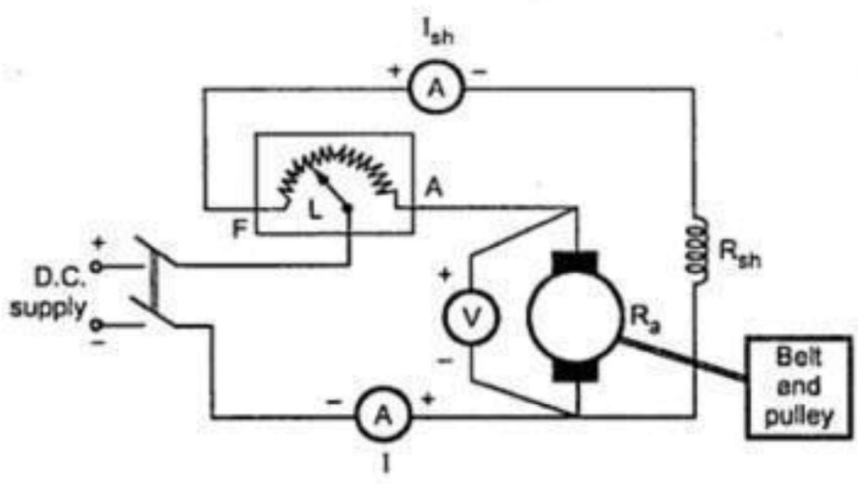
Brake test is a method of finding efficiency of dc motors. We took dc shunt motor as running machine. Brake test also called as direct loading test of testing the motor because loading will be applied directly on shaft of the motor by means of a belt and pulley arrangement.

Test Requirements:

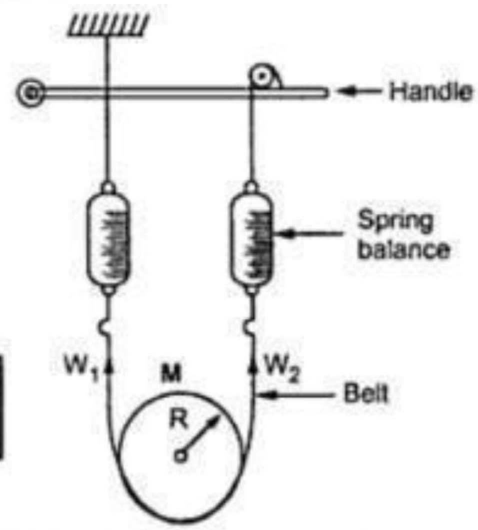
1. DC shunt motor
2. Water-cooled pulley
3. Spring balance

Procedure of Brake Test on DC Shunt Motor:

1. By adjusting the handle of the pulley take different readings of the spring balance.
2. The tension in the belt can be adjusted using the handle. The tension in kg can be obtained from the spring balance readings.
3. Adjusting the load step by step till full load, number of readings can be obtained. By increasing the load is slowly, adjust to get rated load current.
4. The power developed gets wasted against the friction between belt and shaft. Due to the braking action of belt the test is called brake test.
5. The speed can be measured by tachometer. Thus, all the motor characteristics can be plotted.



(a) Experimental setup



(b) Belt and pulley arrangement

Calculation of Brake Test on DC Shunt Motor

Let R (or) r= Radius of pulley in meters

N = Speed in R.P.S.

W_1 = spring balance reading on tight side in kg

W_2 = spring balance reading on slack side in kg

So, net pull on the belt due to friction at the pulley is the difference between the two spring balance readings.

Net pull on the rope,

$$\mathbf{F = (W_1 - W_2)\ kg = (W_1 - W_2) \times 9.81\ newtons} \qquad (1)$$

As radius R and speed N are known, the shaft torque developed can be obtained as,

$$\mathbf{T_{sh} = F \times R = (W_1 - W_2) \times 9.81 \times R} \qquad (2)$$

Now let, V = Voltage applied in volts

I = Total line current drawn in amps.

As we know V and I are input parameters of dc motors in brake test. Then,

$$\mathbf{P_{in} = V.I\ Watts}$$

Motor Efficiency (η)=Output/Input

Now,

$$\textbf{Output power } \mathbf{P_{out} = T_{sh} \times 2\Pi N = 2\Pi N \times (W_1 - W_2) \times 9.81 \times R}$$

When N is in RPM,

$$\textbf{Output power } \mathbf{P_{out} = T_{sh} \times 2\Pi N/60 = 2\Pi N/60 \times (W_1 - W_2) \times 9.81 \times R}$$

Hence, from above equations, we can calculate the efficiency of the motor.

Advantages of Brake Test on DC Shunt Motor:

1. Actual efficiency of the motor under working conditions can be found out.
2. Brake test is simple and easy to perform.
3. It is not only for dc shunt motor, also can be performed on any type of D.C. motor.

Disadvantages of Brake Test on DC Shunt Motor:

1. In brake test due the belt friction lot of heat will be generated and hence there is large dissipation of energy.
2. Cooling arrangement is necessary to minimize the heat. Mostly in our laboratories we use

water as cooling liquid.

3. Convenient only for small rated machines due to limitations regarding heat dissipation arrangements.

4. Power developed gets wasted hence brake test method is little expensive.

5. The efficiency observed is on lower side.

Example 31.1. *In a brake test the effective load on the branch pulley was 38.1 kg, the effective diameter of the pulley 63.5 cm and speed 12 r.p.s. The motor took 49 A at 220 V. Calculate the output power and the efficiency at this load.*

Solution. Effective load $(W_1 - W_2) = 38.1$ kg. wt ; radius $= 0.635/2 = 0.3175$ m

Shaft torque $= 38.1 \times 0.3175$ kg-m $= 9.81 \times 38.1 \times 0.3175 = 118.6$ N-m

Power output = torque × angular velocity in rad/s $= 118.6 \times 2\pi \times 12 =$ **8,945 W**

Now, motor input $= 49 \times 220$ W $\quad \therefore \quad$ Motor $\eta = \dfrac{8,945}{49 \times 220} =$ **0.83** or **83%**

Example 31.2(*a*). *The following readings are obtained when doing a load test on a d.c. shunt motor using a brake drum :*

Spring balance reading	*10 kg and 35 kg*	*Diameter of the drum*	*40 cm*
Speed of the motor	*950 r.p.m.*	*Applied voltage*	*200 V*
Line current	*30 A*		

Calculate the output power and the efficiency. **(Electrical Engineering, Madras Univ. 1986)**

Solution. Force on the drum surface $F = (35 - 10) = 25$ kg wt $= 25 \times 9.8$ N

Drum radius $\quad R = 20$ cm $= 0.2$ m ; Torque $T_{sh} = F \times R = 25 \times 9.8 \times 0.2 = 49$ N

$N = 950/60 = 95/6$ r.p.s. ; $\omega = 2\pi\,(95/6) = 99.5$ rad/s

Motor output $= T_{sh} \times \omega$ watt $= 49 \times 99.5 = 4,876$ W

Motor input $= 200 \times 30 = 6000$ W ; $\eta = 4876/6000 = 0.813$ or **81.3%**

Example 31.2(*b*). *In a brake-test, on a d.c. shunt motor, the tensions on the two sides of the brake were 2.9 kg and 0.17 kg. Radius of the pulley was 7 cm. Input current was 2 amp at 230 volts. The motor speed was 1500 rpm. Find the torque, power-output and efficiency.*

Solution. Net force on pulley $= 2.90 - 0.17 = 2.73$ kg

$= 2.73 \times 9.81 = 26.78$ Nw

Net torque = Force × Radius $= 26.78 \times 7/100$

$= 1.8746$ Nw-m

Power output = Torque × Radians/sec.

$= 1.8746 \times 2\pi\ 1500/60$

$= 294$ watts

Efficiency $= 294/(230 \times 2) = 0.639$

% efficiency $= 63.9\%$

SWINBURNE'STEST:

Swinburne's Test is an indirect method of testing of DC machines. In this method the losses are measured separately and the efficiency at any desired load is predetermined. Machines are tested for finding out losses, efficiency and temperature rise. For small machines direct loading test is performed. For large shunt machines, indirect methods are used like Swinburne's or Hopkinson's test.

The machine is running as a motor at rated voltage and speed. The connection diagram for DC shunt machine is shown in the figure below.

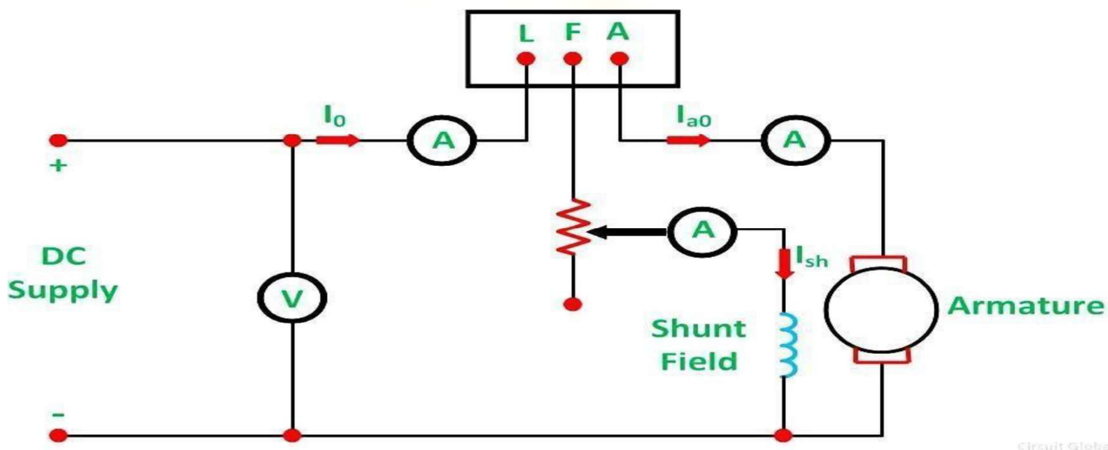


Fig: Swinburne's Test

Let

V be the supply voltage
I_0 is the no-load current
I_{sh} is the shunt field current

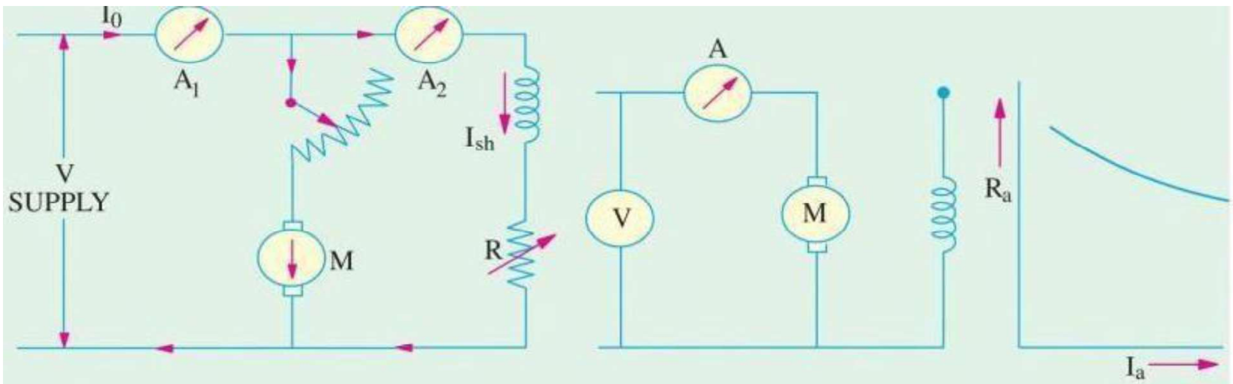
Therefore, no load armature current is given by the equation shown below.

$$I_{a0} = I_0 - I_{sh}$$

No-load input = VI_0
Power input to the armature = $V(I_o-I_{sh})$
Power input to the shaft = $V\,I_{sh}$
The no-load power input to the machine supplies the following, as given below.

- Iron loss in the core
- Friction losses in the bearings and commutators.
- Windage loss
- Armature copper loss at no load.

When the machine is loaded, the temperature of the armature winding and the field winding increases due to I^2R losses. For calculating I^2R losses hot resistances should be used. A stationary measurement of resistances at room temperature of 15 degree Celsius is made by passing current through the armature and then field from a low voltage DC supply. Then the heated resistance, allowing a temperature rise of 50ºC is found. The equations are as follows:



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 $\quad R_{65} = R_{15} \times \dfrac{234.5 + 65}{234.5 + 15} = 1.2\, R_{15}$ (approx.*)

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

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

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 $\quad I_a = I - I_{sh}$ ...if machine is motoring

$\quad = I + I_{sh}$ ...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 = $(I + I_{sh})^2 R_a$; Constant loss = W_c ...found above

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

31.3. Advantages of Swinburne's Test

1. It is convenient and economical because 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.

31.4. Main 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 in 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.

Limitations of Swinburne's Test:

- Machines having a constant flux are only eligible for Swinburne's test. For examples – shunt machines and level compound generators.
- Series machines cannot run on light loads, and the value of speed and flux varies greatly. Thus, the Swinburne's Test are not applicable for series machines

Example 31.3. *A 220 V, d.c. shunt motor at no load takes a current of 2.5 A. The resistances of the armature and shunt field are 0.8 Ω and 200 Ω respectively. Estimate the efficiency of the motor when the input current is 20 A. State precisely the assumptions made.*

(Electrical Technology, Kerala Univ. 1986)

Solution. No-load input = $220 \times 2.5 = 550$ W

This input meets all kinds of no-load losses *i.e.* armature Cu loss and constant losses.

$I_{sh} = 220/200 = 1.1$ A. No-load arm current, $I_{a0} = 2.5 - 1.1 = 1.4$ A

No-load armature Cu loss = $I_{a0}^2 R_a = 1.4^2 \times 0.8 = 1.6$ W

Constant losses = $550 - 1.6 = 548.4$ W

When Input Current is 20A

$I_a = 20 - 1.1 = 18.9$A ; Armature copper loss = $(18.9)^2 \times 0.8 = 285.7$ Watts

Total loss = $548.4 + 285.7 = 834.1$ Watts

Input = $220 \times 20 = 4400$ Watts

Output = $4400 - 834.1 = 3565.9$ Watts

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$$

$$\eta = \frac{3565.9}{4400} \times 100 = 81.04\%$$

In the above calculations, it has been assumed that :

1. mechanical losses remain constant even through motor speed changes from no-load to the given load.

2. effect of armature reaction on main pole flux with a consequent change in iron losses has been neglected.

3. decrease in flux due to increase in shunt resistance by heating has been neglected.

Example 31.4. *When running on no-load, a 400-V shunt motor takes 5 A. Armature resistance is 0.5 Ω and field resistance 200 Ω. Find the output of the motor and efficiency when running on full-load and taking a current of 50 A. Also, find the percentage change in speed from no-load to full-load.* **(Electro Mechanics, Allahabad Univ. 1991)**

Solution. No-load input $= 400 \times 5 = 2{,}000$ W

This input goes to meet all kinds of no-load losses *i.e.* armature Cu loss and constant losses.

$$I_{sh} = 400/200 = 2 \text{ A} ; \text{No-load } I_a = 5 - 2 = 3 \text{ A}$$

$$\text{No-load arm. Cu loss} = 3^2 \times 0.5 = 4.5 \text{ W} ; \text{Constant losses} = 2{,}000 - 4.5 = \mathbf{1{,}995.5 \text{ W}}$$

When line current is 50 A

$$I_a = 50 - 2 = 48 \text{ A} ; \text{Arm. Cu loss} = 48^2 \times 0.5 = 1{,}152 \text{ W}$$

$$\text{Total loss on F.L.} = 1{,}152 + 1{,}995.5 = 3{,}147.5 \text{ W} ; \text{Input} = 50 \times 400 = 20{,}000 \text{ W}$$

$$\text{Output} = 20{,}000 - 3{,}147.5 = \mathbf{16{,}852.5 \text{ W} = 16.8 \text{ kW}}$$

$$\text{F.L. efficiency} = 16{,}852.5/20{,}000 = 0.8426 \text{ or } \mathbf{84.26\%}$$

Now,
$$E_{b1} = 400 - (3 \times 0.5) = 398.5 \text{ V} ; E_{b2} = 400 - (48 \times 0.5) = 376 \text{ V}$$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} = \frac{398.5}{376} \quad \therefore \quad \frac{N_1 - N_2}{N_2} = \frac{22.5}{376} = 0.0598$$

$\therefore$ percentage change in speed = **5.98**

Example 31.5. *The no-load test of a 44.76 kW, 220-V, d.c. shunt motor gave the following figures:*

Input current = 13.25 A ; field current = 2.55 A ; resistance of armature at 75°C = 0.032 Ω and brush drop = 2 V. Estimate the full-load current and efficiency.

(Electrical Engineering, Madras Univ. 1987)

Solution. No-load Condition

No-load input $= 220 \times 13.25 = 2915$ W ; Armature current $= 13.25 - 2.55 = 10.7$ A

$$\text{Armature Cu loss} = 10.7^2 \times 0.032 = 3.6 \text{ W}$$

$$\text{Loss due to brush drop} = 2 \times 10.7 = 21.4 \text{ W}$$

Variable loss $= 21.4 + 3.6 = 25\ W_e$, Constant losses $W_c = 2915 - 25 = 2890$ W

Full-load Condition

If I_a is the full-load armature current, then full-load motor input current is $(I_a + 2.55)$ A.

F.L. motor power input $= 220\ (I_a + 2.55)$ W

This input must be equal to the sum of

(*i*) output $= 44.76$ kW $= 44{,}760$ W (*ii*) $W_c = 2{,}890$ W

(*iii*) brush loss $= 2I_a$ watt (*iv*) Arm. Cu loss $= 0.032\ I_a^2$

$$\therefore \quad 220\ (I_a + 2.55) = 44{,}750 + 2{,}890 + 2I_a + 0.032\ I_a^2$$

$$0.032 I_a^2 - 218 I_a + 47{,}079 = 0$$

$$I_a = \frac{218 \pm \sqrt{(218)^2 - 4 \times 0.032 \times 47{,}079}}{2 \times 0.032}$$

$$I_a = 223.2 \text{ A}$$

$$\text{Line input current } I = I_a + I_{sh} = 223.5 + 2.55 = \mathbf{226\ A}$$

$$\text{F.L. power input} = 226 \times 220 = 49{,}720 \text{ W}$$

$$\therefore \quad \text{F.L. efficiency} = 44{,}760/49{,}720 = 0.9 \text{ or } \mathbf{90\%}.$$

Example 31.6. *A 200-V, shunt motor develops an output of 17.158 kW when taking 20.2 kW. The field resistance is 50 Ω and armature resistance 0.06 Ω. What is the efficiency and power input when the output is 7.46 kW ?* **(Elect. Machines-I, Aligarh Muslim Univ. 1989)**

Solution. In the first case :

Output = 17,158 W Input = 20,200 W

Total losses = 20,200 − 17,158 = 3,042 W ; Input current = 20,200/200 = 101 A

I_{sh} = 200/50 = 4 A ; I_a = 101 − 4 = 97 A

∴ Armature Cu loss = $97^2 \times 0.06 = 564.5$ W

∴ Constant losses = 3,042 − 564.5 = 2,477.5 = 2478 W (approx.)

In the second case :

Let, I_a = armature current Input current = $(I_a + 4)$ A

Now, input power = output + $I_a^2 R_a$ + constant losses

$$\therefore \quad 200(I_a + 4) = 7{,}460 + 0.06\, I_a^2 + 2{,}478$$

$$\text{or} \quad 0.06 I_a^2 - 200 I_a + 9{,}138 = 0$$

$$\therefore \quad I_a = \frac{200 \pm \sqrt{200^2 - 4 \times 0.06 \times 9{,}138}}{2 \times 0.06} = \frac{200 \pm 194}{0.12} = 3{,}283.3 \text{ A or } 46 \text{ A}$$

We will reject the larger value because it corresponds to unstable operation of the motor. Hence, take $I_a = 46$ A.

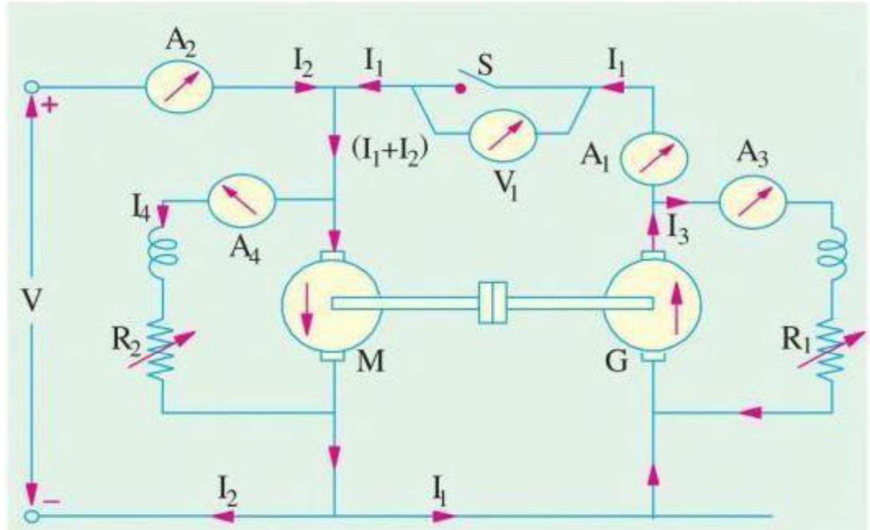
∴ Input current $I = I_a + I_{sh} = 46 + 4 = 50$ A

$$\text{Power input} = \frac{50 \times 200}{1000} = \mathbf{10\ kW} \quad \therefore \quad \eta = \frac{7{,}460 \times 100}{10{,}000} = \mathbf{74.6\%}$$

31.5. Regenerative or Hopkinson's Test (Back-to-Back Test)

By this method, ***full-load test*** can be carried out on two shunt machines, preferably identical ones, without wasting their outputs. The two machines are mechanically coupled and are so adjusted electrically that one of them runs as a motor and the other as a generator. The mechanical output of the motor drives the generator and the electrical output of generator is used in supplying the greater part of input to the motor. If there were no losses in the machines, they would have run without any external power supply. But due to these losses, generator output is not sufficient to drive the motor and ***vice-versa***. The losses are supplied either by an extra motor which is belt-connected to the motor-generator set or as suggested by Kapp, electrically from the supply mains.

Essential connections for the test are shown in Fig. 31.6. The two shunt machines are connected in parallel. They are, to begin with, started as unloaded motors. Then, the field of one is weakened and that of the other is strengthened so that the former runs as a motor and the latter as a generator. The usual method of procedure is as follows :



Machine M is started up from the supply mains with the help of a starter (not shown) whereas main switch S of the other machine is kept open. Its speed is adjusted to normal value by means of its shield regulator. Machine M drives machine G as a generator and its voltage is read on voltmeter V_1. The voltage of G is adjusted by its field regulator until voltmeter V_1 reads zero, thereby showing that its voltage is the same, both in polarity and magnitude as that of the main supply. Thereafter, S is closed to parallel the machines. By adjusting the respective field regulators, any load can now be thrown on to the machines. Generator current I_1 can be adjusted to any desired value by increasing the excitation of G or by reducing the excitation of M and the corresponding values of different ammeters are read.

Motor-cum generator set

The electrical output of the generator ***plus*** the small power taken from the supply, is taken by the motor and is given out as a mechanical power ***after*** supplying the motor losses.

If supply voltage is V, then

$$\text{Motor input} = V(I_1 + I_2), \text{ where } I_2 \text{ is the current taken from the supply.}$$

$$\text{Generator output} = VI_1 \quad \text{...}(i)$$

Assuming that both machines have the same efficiency η,

$$\text{Output of motor} = \eta \times \text{input} = \eta\, V(I_1 + I_2) = \text{generator input}$$

$$\text{Output of generator} = \eta \times \text{input} = \eta \times \eta\, V(I_1 + I_2) = \eta^2\, V(I_1 + I_2) \quad \text{...}(ii)$$

Hence, from (i) and (ii), we get

$$\eta^2 V(I_1 + I_2) = VI_1 \quad \text{or} \quad \eta = \sqrt{\frac{I_1}{I_1 + I_2}}$$

However, it is not quite correct to assume equal efficiencies for two machines because their armature currents as well as excitations are different. We will not find the efficiencies separately.

Let R_a = armature resistance of each machine
I_3 = exciting current of the generator
I_4 = exciting current of the motor

Armature Cu loss in generator = $(I_1 + I_3)^2 R_a$; Armature Cu loss in motor = $(I_1 + I_2 - I_4)^2 R_a$

Shunt Cu loss in generator = VI_3 ; Shunt Cu loss in motor = VI_4

But total motor and generator losses are equal to the power supplied by the mains.

Power drawn from supply = VI_2

If we subtract the armature and shunt Cu losses from this, we get the stray losses of *both* machines.

∴ Total stray losses for the set

$$= VI_2 - [(I_1 + I_3)^2 R_a + (I_1 + I_2 - I_4)^2 R_a + VI_3 + VI_4] = \text{W (say)}$$

Making one assumption that stray losses are equally divided between the two machines, we have

Stray loss per machine = W/2

For Generator

Total losses $= (I_1 + I_3)^2 R_a + VI_3 + W/2 = W_g$ (say)

Output $= VI_1 \quad \therefore \quad \eta_g = \dfrac{VI_1}{VI_1 + W_g}$

For Motor,

Total losses $= (I_1 + I_2 - I_4)^2 R_a + I_4 + W/2 = W_m$ (say)

Input $= V(I_1 + I_2) \quad \therefore \quad \eta_m = \dfrac{V(I_1 + I_2) - W_m}{V(I_1 + I_2)}$

31.6. Alternative Connections for Hopkinson's Test

In Fig. 31.7 is shown in slightly different method of connecting the two machines to the supply. Here, the main difference is that the shunt windings are directly connected across the lines. Hence, the line input current is I_1 ***excluding the field currents.*** The efficiencies can be calculated as detailed below :

Motor armature Cu loss = $(I_1 + I_2)^2 R_a$; Generator armature Cu loss = $I_2^2 R_a$

Power drawn from the supply = $V I_1$

∴ Total stray losses *i.e.* iron, friction and windage losses for the two machines are

$$= VI_1 - [(I_1 + I_2)^2 R_a - I_2^2 R_a] = \text{W (say)}$$

∴ stray loss for each machine = W/2

Motor Efficiency

$$\text{Motor input} = \text{armature input} + \text{shunt field input} = V(I_1 + I_2) + VI_3$$

$$\text{Motor losses} = \text{armature Cu loss} + \text{shunt Cu loss} + \text{stray losses}$$

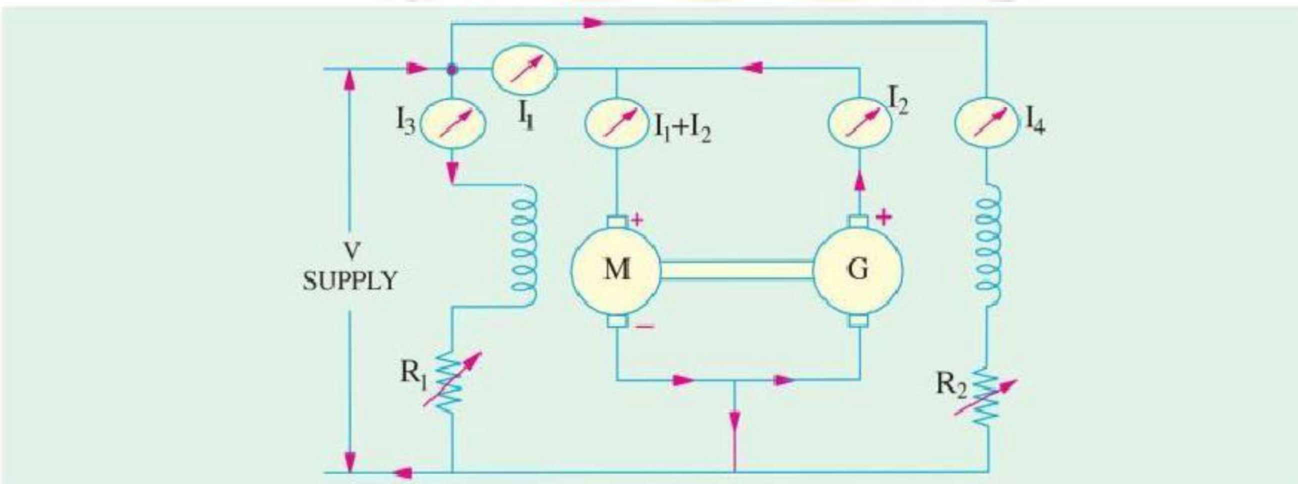
$$= (I_1 + I_2)^2 R_a + VI_3 + W/2 = W_m \text{ (say)}$$

$$\text{Motor} \quad \eta = \frac{W_{input} - W_m}{W_{input}} \times 100$$

Generator Efficiency

$$\text{Generator output} = VI_2 \text{ ; Generator losses} = I_2^2 R_a + V I_4 + W/2 = W_g \text{ (say)}$$

$$\therefore \quad \text{Generator} \quad \eta = \frac{VI_2}{VI_2 + W_g}$$



31.7. Merits of Hopkinson's Test

1. Power required for the test is small as compared to the full-load powers of the two machines.
2. As machines are being tested under full-load conditions, the temperature rise and the commutation qualities of the machines can be observed.
3. Because of full-load conditions, any change in iron loss due to flux distortion at full-load, is being taken into account.

The only disadvantage is with regard to the availability of two identical machines.

Example 31.10 (*a*). *In a Hopkinson's test on two 220-V, 100-kW generators, the circulating current is equal to the full-load current and, in addition, 90 A are taken from the supply. Obtain the efficiency of each machine.*

Solution. Output current of the generator

$$I_1 = \frac{100,000}{220} = \frac{5,000}{11} = 454.4 \text{ A}, I_2 = 90 \text{ A}$$

Assuming equal efficiencies, from Art. 29.5, we have

$$\eta = \sqrt{\frac{I_1}{I_1 + I_2}} = \sqrt{\frac{454.5}{454.5 + 90}} = 0.914 \text{ or } \mathbf{91.4\%}$$

Example 31.10 (*b*). *In the Hopkinson's test on two d.c. machines, machine A has a field current of 1.4 A and machine B has a field current of 1.3 A. Which machine acts as a generator ?*

Solution. In Hopkinson's test (on two identical d.c. shunt machines), since the two machines are coupled, the speed is common and is decided by the field current of the motor. The field windings of both the machines are in parallel with a separate D.C. source.

Since the machines are identical and are running at the ***same speed***, their e.m.fs are in proportion to their field currents.

$$\frac{\text{E.M.F. induced in the armature of machine A}}{\text{E.M.F. induced in the armature of machine B}} = \frac{1.4}{1.3}$$

$$E_A = (1.4/1.3) \times E_B = 1.077\ E_B$$

Since E_A is larger than E_B, Machine A supplies power to Machine B. It means, A is working as a generator, and B is motoring.

Example 31.12. *The Hopkinson's test on two similar shunt machines gave the following full-load data :*

Line voltage	*= 110 V*	*Field currents are 3 A and 3.5 A*
Line current	*= 48 A*	*Arm. resistance of each is 0.035 Ω*
Motor arm. current	*= 230 A*	

Calculate the efficiency of each machine assuming a brush contact drop of 1 volt per brush.

Solution. The motor-generator set is shown in Fig. 31.8. It should also be noted that the machine with lesser excitation is motoring. We will find the total armature Cu losses and brush contact loss for both machines.

Motor

Arm. Cu loss $= 230^2 \times 0.035 = 1{,}851.5$ W

Brush contact loss $= 230 \times 2 = 460$ W

Total arm. Cu loss $= 1851.5 + 460 = 2{,}312$ W

Shunt Cu loss $= 110 \times 3 = 330$ W

Total Cu loss $= 2{,}312 + 330 = 2{,}642$ W

Generator

Generator arm. current $= 233 - 48 + 3.5$

$= 188.5$ W

Arm. Cu loss $= 188.5^2 \times 0.035 = 1{,}244$ W

Brush contact Cu loss $= 188.5 \times 2 = 377$ W

Total arm. Cu loss $= 1{,}244 + 377 = 1{,}621$ W

Shunt Cu loss $= 110 \times 3.5 = 385$ W ;

Total Cu loss $= 1{,}621 + 385 = 2{,}006$ W

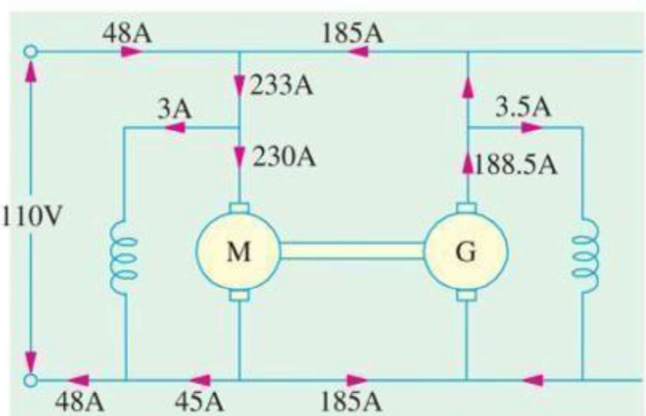


Fig. 31.8

For the Set

Total arm. and shunt Cu loss for the set

$= 2{,}642 + 2{,}006 = 4{,}648$ W

Total input $= 110 \times 48 = 5{,}280$ W ; Stray losses for the set $= 5{,}280 - 4{,}648 = 632$ W

Stray losses per machine $= 632/2 = 316$ W

Motor Efficiency

Arm. Cu + brush drop loss = 2,312 W   Shunt Cu loss = 330 W

Stray losses = 316 W   Total loss = 2,312 + 330 + 316 = 2,958 W

Motor input = 110×233 = 25,630 W ; Motor output = 25,630 − 2,958 = 22,672

$\therefore \quad \eta = 22,672 \times 100/25,630 =$ **88.8%**

Generator Efficiency

Total losses = 2,006 + 316 = 2,322 W ; Output = 110×185 = 20,350 W

Generator input = 20,350 + 2,322 = 22,672 W = motor input

$\eta = 20,350/22,672 = 0.894$ or **89.4%**

Example 31.13. *In a Hopkinson's test on a pair of 500-V, 100-kW shunt generators, the following data was obtained :*

Auxiliary supply, 30 A at 500 V : Generator output current, 200 A

Field currents, 3.5 A and 1.8 A

Armature circuit resistances, 0.075 Ω each machine. Voltage drop at brushes, 2 V (each machine).

Calculate the efficiency of the machine acting as a generator.

Solution. Motor arm. current = 200 + 30 = 230 A, as shown in Fig. 31.9.

Motor arm. Cu loss $= 230^2 \times 0.075 + 230 \times 2 = 4,428$ W

Motor field Cu loss $= 500 \times 1.8 = 900$ W

Generator arm. Cu loss $= 200^2 \times 0.075 + 200 \times 2 = 3,400$ W

Geneator field Cu loss = $500 \times 3.5 = 1,750$ W

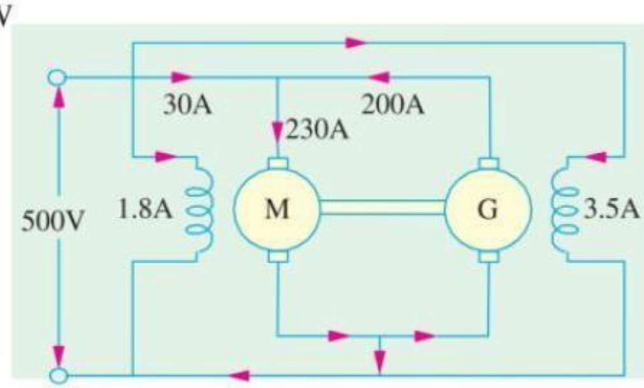


Fig. 31.9

Total Cu loss for two machines

= 4,428 + 900 + 3400 + 1750

= 10,478 W

Power taken from auxiliary supply

$= 500 \times 30 = 15,000$ W

Stray losses for the two machines

= 15,000 − 10,478 = 4,522 W

Stray loss per machine = 4,522/2 = 2,261 W

Total losses in generator = 3400 + 1750 + 2261 = 7,411 W

Generator output $= 500 \times 200 = 100,000$ W

$$\therefore \quad \eta_g = \frac{\text{output}}{\text{output + losses}} = \frac{100,000}{107,411} \times 100 = \mathbf{93.09\%}$$

Example 31.14. *Explain the Hopkinson's test on a pair of shunt motors.*

In such a test on 250-V machines, the line current was 50 A and the motor current 400 A not including the field currents of 6 A and 5 A. The armature resistance of each machine was 0.015 Ω. Calculate the efficiency of each machine. **(Adv. Elect. Machines, A.M.I.E. Sec. B, 1991)**

Solution. The connections are shown in Fig. 31.10.

Motor armature Cu loss

$= 400^2 \times 0.015 = 2{,}400$ W

Generator armature Cu loss

$= 350^2 \times 0.015 = 1{,}838$ W

Power drawn from supply

$= 250 \times 50 = 12{,}500$ W

$\therefore$ Iron, friction and windage losses for the two machines

$= 12{,}500 - (2{,}400 + 1{,}838)$

$= 8{,}262$ W

Iron, friction and windage loss per machine

$= 8.262/2 = 4{,}130$ W* (approx.)

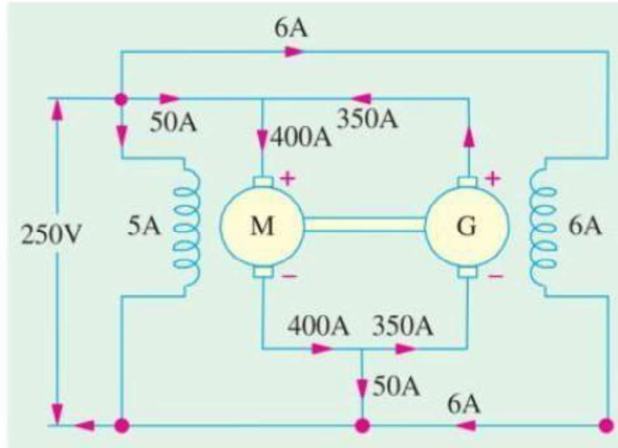


Fig. 31.10

Motor Losses and Efficiency

Motor arm. Cu loss = 2,400 W ; Motor field Cu loss = $250 \times 5 = 1{,}250$ W

Iron, friction and windage losses = 4,130 W

Total motor losses $= 2{,}400 + 1{,}250 + 4{,}130 = 7{,}780$ W

Motor input $= 250 \times 400 + 250 \times 5 = 101{,}250$ W

$\therefore$ Motor efficiency $= (101{,}250 - 7{,}780)/101{,}250 = 0.923$ or **92.3%**

Generator Losses and Efficiency

Generator arm. Cu loss = 1,838 W ; Generator field Cu loss = $250 \times 6 = 1{,}500$ W

Iron, friction and windage loss = 4,130 W

Total losses $= 1{,}838 + 1{,}500 + 4{,}130 = 7.468$ W

Generator output $= 250 \times 350 = 87{,}500$ W

$\therefore$ Generator efficiency $= (87{,}500 - 7.468)/87{,}500 = 0.915$ or **91.5%**

Example 31.15. *The Hopkinson's test on two shunt machines gave the following results for full-load :*

Line voltage = 250 V ; current taken from supply system excluding field currents = 50 A ; motor armature current = 380 A ; field currents 5 A and 4.2 A. Calculate the efficiency of the machine working as a generator. Armature resistance of each machine is 0.2 Ω.

(Electrical Machinery-I Mysore Univ. 1988)

Solution. The connections are shown in Fig. 31.11.

Motor arm. Cu loss $= 380^2 \times 0.02 = 2{,}888$ W

Generator arm. Cu loss $= 330^2 \times 0.02 = 2{,}178$ W

Power drawn from supply $= 250 \times 50 = 12{,}500$ W

Stray losses for the two machines

$= 12{,}500 - (2{,}888 + 2{,}178) = 7.434$ W

Stray losses per machine $= 7{,}434/2 = 3{,}717$ W

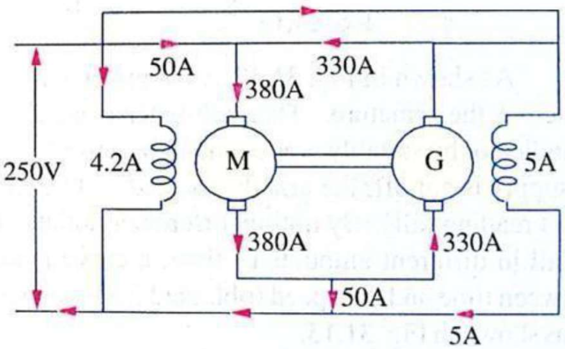


Fig. 31.11

Motor Efficiency

$$\begin{aligned}
\text{Arm. Cu loss} &= 2{,}888 \text{ W} \\
\text{Field Cu loss} &= 250 \times 4.2 = 1050 \text{ W} \\
\text{Stray losses} &= 3{,}717 \text{ W} \\
\text{Total loss} &= 2{,}888 + 1050 + 3{,}717 \\
&= 7{,}655 \text{ W} \\
\text{Motor input} &= 250 \times 380 + 250 \times 4.2 \\
&= 96{,}050 \text{ W} \\
\text{Motor output} &= 96{,}050 - 7{,}655 \\
&= 88{,}395 \text{ W} \\
\therefore \quad \eta &= 88{,}395/96{,}050 = 0.9203 \text{ or } \mathbf{92.03\%}
\end{aligned}$$

Generator Efficiency

$$\begin{aligned}
\text{Arm. Cu loss} &= 2{,}178 \text{ W} ; \text{Field Cu loss} = 250 \times 5 = 1250 \text{ W} \\
\text{Stray losses} &= 3{,}717 \text{ W} ; \text{Total losses} = 7{,}145 \text{ W} \\
\text{Generator output} &= 250 \times 330 = 82{,}500 \text{ W} \\
\text{Generator input} &= 82{,}500 + 7{,}145 = 89{,}645 \text{ W} \\
\eta &= 82{,}500/89{,}645 = 0.9202 \text{ or } \mathbf{92.02\%}
\end{aligned}$$

31.9. Field's Test for Series Motor

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.

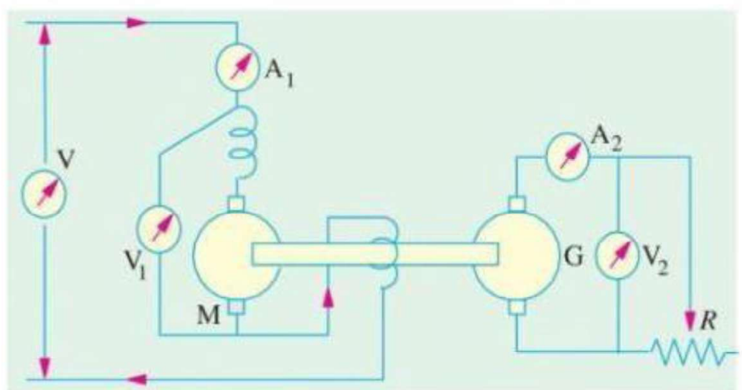


Fig. 31.14

One machine runs normally as a motor and drives 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

Micro series motors

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 A_1. 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.

$\therefore$ 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

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

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

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

Motor Efficiency

$$\text{Motor input} = V_1I_1$$

$$\text{Motor losses} = \text{armature + field Cu losses + stray losses}$$

$$= (R_a + R_{se})I_1^2 + W_s = W_m \text{ (say)}$$

$$\eta_m = \frac{V_1 I_1 - W_m}{V_1I_1}$$

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.

$$\text{Generator output} = V_2I_2$$

$$\text{Field Cu loss} = I_1^2R_{se} \quad (\because \text{ Motor current is passing through it.})$$

$$\text{Armature Cu loss} = I_2^2R_a \text{ ; Stray losses} = W_s$$

$$\text{Total losses} = I_1^2R_{se} + I_2^2R_a + W_s = W_g \text{ (say)}$$

$$\eta_g = \frac{V_2 I_2}{V_2I_2 + W_g}$$

It should be noted that although the two machines are mechanically coupled yet it is not a regenerative method, because the generator output is wasted instead of being fed back into the motor as in Hopkinson's (back-to-back) test.

Example 31.20. *A test on two coupled similar tramway motors, with their fields connected in series, gave the following results when one machine acted as a motor and the other as a generator.*

Motor : *Armature current* = *56 A ; Armature voltage = 590 V*

Voltage drop across field winding = *40 V*

Generator :

Armature current = *44 A ; Armature voltage = 400 V*

Field voltage drop = *40 V ; Resistance of each armature = 0.3 Ω*

Calculate the efficiency of the motor and gearing at this load.

Solution. The connection for the two machines are shown in Fig. 31.15.

$$\text{Total input} = 630 \times 56 = 35{,}280 \text{ W}$$

$$\text{Output} = 400 \times 44 = 17{,}600 \text{ W}$$

Total losses in the two machines are

$$= 35{,}280 - 17{,}600 = 17{,}680 \text{ W}$$

Series field resistance

$$R_{se} = 40/56 = 0.714\ \Omega$$

Total Cu loss $= (0.3 + 2 \times 0.714) \times 56^2 + 44^2 \times 0.3 = 5{,}425 + 581 = 6{,}006$ W

Stray losses of the set $= 17{,}680 - 6{,}006 = 11{,}674$ W

$\therefore$ Stray losses/machine $= 11{,}674/2 = 5{,}837$ W

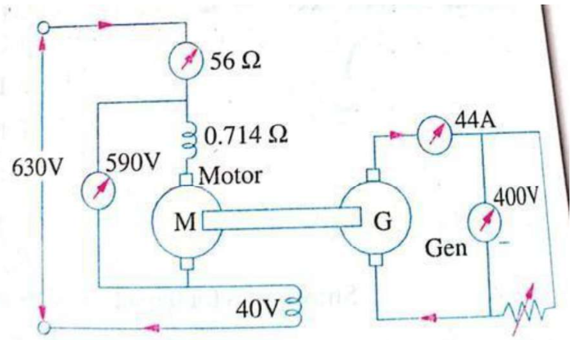


Fig. 31.15

Motor Efficiency

Motor armature input = arm. voltage × motor current $= 590 \times 56 = 33{,}040$ W

Armature circuit Cu loss

Armature circuit Cu loss

$$= (0.3 + 0.714) \times 56^2 = 3{,}180 \text{ W}$$

Stray loss = 5,837 W – found above

Total losses $= 3{,}180 + 5{,}837 = 9{,}017$ W, Output $= 33{,}040 - 9{,}017 = 24{,}023$ W

$\therefore \quad \eta_m = 24{,}023/33{,}040 = 0.727$ or **72.7%**

Generator Efficiency

Armature Cu loss $= 44^2 \times 0.3 = 581$ W, Series field Cu loss $= 40 \times 56 = 2{,}240$ W

Stray losses $= 5{,}837$ W ; Total losses $= 581 + 2{,}240 + 5{,}837 = 8{,}658$ W

Output $= 400 \times 44 = 17{,}600$ W

$\therefore \quad \eta_g = 17{,}600/(17{,}600 + 8{,}658) = 0.67$ or 67%

Retardation Test or Running Down Test:

This method is generally employed to shunt generators and shunt motors. From this method we can get stary losses. Thus, if armature and shunt copper losses at any given load current are known then efficiency of a machine can be easily estimated.

The machine whose test is to be taken is run at a speed which is slightly above its normal speed. The supply to the motor is cut off while the field is kept excited. The armature consequently slows down and its kinetic energy is used in supplying the rotational or stray losses which includes iron, friction and winding loss.

If I is the amount of inertia of the armature

ω is the angular velocity

Kinetic energy of armature = (½) $I\omega^2$

∴ Rotational losses, W = Rate of change of kinetic energy

$$= \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = I\omega\frac{d\omega}{dt}$$

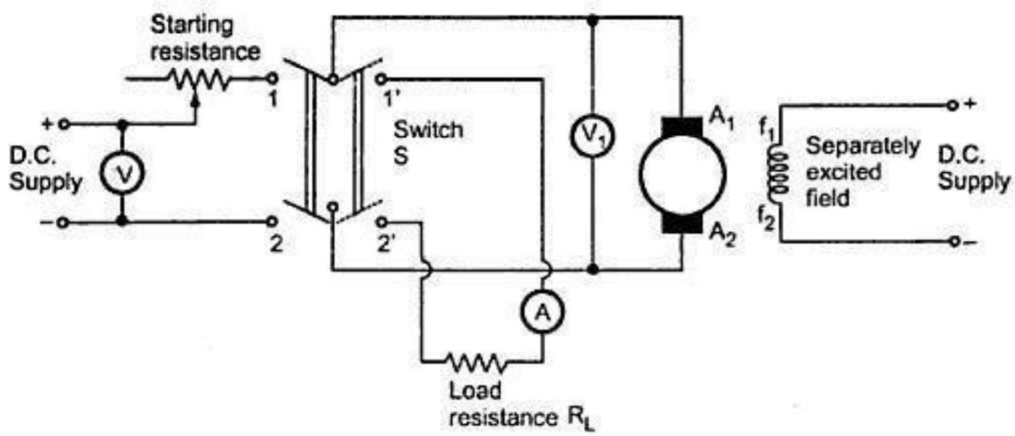


Fig 1:

Angular velocity, $\omega = (2\pi N)/60$

$$W = I\left(\frac{2\pi N}{60}\right)\frac{d}{dt}\left(\frac{2\pi N}{60}\right) = I\left(\frac{2\pi N}{60}\right)\left(\frac{2\pi}{60}\right)\frac{dN}{dt}$$

$$\therefore \quad \boxed{W = \left(\frac{2\pi}{60}\right)^2 I N \frac{dN}{dt}}$$

Thus, to find the rotational losses, the moment of inertia I and (dN/dt) must be known. These quantities can be found as follows;

Determination of dN/dt:

The voltmeter V_1 which is connected across the armature will read the back e.m.f. of the motor. We know that back e.m.f. is proportional to speed so that voltmeter is calibrated to read the speed directly.

When motor is cut off from the supply, the speed decrease in speed is noted with the help of stop watch. A curve showing variation between time and speed which is obtained from voltmeter which is suitably calibrated is shown in the Fig. 3.

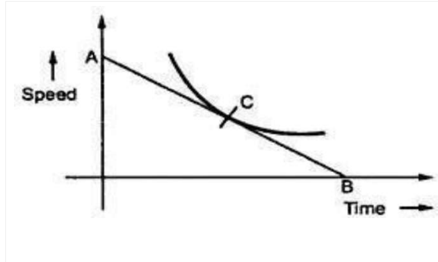


Fig. 3 Determination of dN/dt

At any point C corresponding to normal speed, a tangent AB is drawn. Then

$$\frac{dN}{dt} = \frac{OA \text{ (in r.p.m.)}}{OB \text{ (in seconds)}}$$

The value obtained from above can be substituted in the expression for W which can give the rotational losses.

Determination of moment of inertia (I):

Method 1: Using Flywheel

The armature supply is cut off and time required for definite change in speed is noted to draw the corresponding curve as we have drawn in previous case. This curve is drawn considering only armature of the machine. Now a flywheel with known moment of the inertia say is I_1 keyed onto the shaft and the same curve is drawn again. The slowing down time will be extended as combined moment of inertia of the two is increased.

For any given speed (dN/dt_1) and (dN/dt_2) are determined same as previous case. It can be seen that the losses in both the cases are almost same as addition of flywheel will not make much difference to the losses.

In the first case where flywheel is not there then,

$$W = \left(\frac{2\pi}{60}\right)^2 I\, N \frac{dN}{dt_1}$$

Adding the flywheel to the motor armature in second case we get,

$$W = \left(\frac{2\pi}{60}\right)^2 (I + I_1)\; N \frac{dN}{dt_2}$$

$$\therefore \quad I\, N \frac{dN}{dt_1} = (I + I_1)\, N \frac{dN}{dt_2}$$

$$\therefore \quad \frac{I + I_1}{I} = \frac{(dN/dt_1)}{(dN/dt_2)}$$

$$\therefore \quad I = \left[(I+I_1)\frac{dN}{dt_2}\right] \Big/ \left(\frac{dN}{dt_1}\right)$$

$$\therefore \quad I = I_1 \times \frac{dN/dt_2}{(dN/dt_1)-(dN/dt_2)} = I_1 \times \frac{dt_1}{dt_2 - dt_1}$$

$$\therefore \quad \boxed{I = I_1 \cdot \frac{t_1}{t_2 - t_1}}$$

Method 2: without using Flywheel

In this method time is noted for the machine to slow down by say 5 % considering the armature alone. Thus retarding torque either mechanical or electrical is applied. Preferably electrical retarding torque is applied and time required to slow down by 5% is noted again. The method by which electrical torque can be provided as shown in the Fig. 1 in which the switch S after disconnecting from the supply is thrown to terminals 1'2'. The machine then gets connected to a non-inductive load resistance R_L. The power drawn by this resistance will acts as a retarding torque on the armature which will make it slow more quickly.

The additional loss in the resistance will be equal to product of ammeter reading and the average reading of the voltmeter (for a fall of 5% of voltmeter reading, the time is noted.) The ammeter reading is also changing so its average reading is taken. Thus, the additional losses are $I_a^2 (R_a + R)$. Let t_1 be the time when armature is considered alone and t_2 be the time when armature is connected across a load resistance, V be average voltage across R and I_a be the average current and W' is additional retarding electrical torque supplied by motor.

$$W = \left(\frac{2\pi}{60}\right)^2 I N \frac{dN}{dt_1}$$

$$W + W' = \left(\frac{2\pi}{60}\right)^2 I N \frac{dN}{dt_2}$$

If dN i.e. change in speed is same in two cases then

$$\frac{W+W'}{W} = \frac{1/dt_2}{1/dt_1} = \frac{dt_1}{dt_2} = \frac{t_1}{t_2}$$

$$\therefore \quad (W + W')\, t_2 = W\, t_1$$

$$\therefore \quad W\,(t_1 - t_2) = W' t_2$$

$$\therefore \quad \boxed{W = W' \frac{t_2}{t_1 - t_2}}$$

Here dN/dt_1 is rate of change in speed without extra load whereas dN/dt_2 is rate change in speed with extra electrical load which provides retarding torque