ELECTRICAL MACHINES(EE 554)

Chapter-4(DC Motors)

Basic Concepts of DC Motors

- DC machines Converts Electrical Energy into Mechanical Energy
- When we apply certain field current (I_f), then field Poles will gets magnetized and Poles will be created.
- Now, when the current is given to armature conductors then , the current carrying conductors lie in the magnetic field. Hence, Force will developed on the conductors and under the action of this force, whole armature rotates.
- The direction of force is given by Fleming's Left hand rule.
- In case of DC motors, Both the field and armature windings are supplied by DC current.

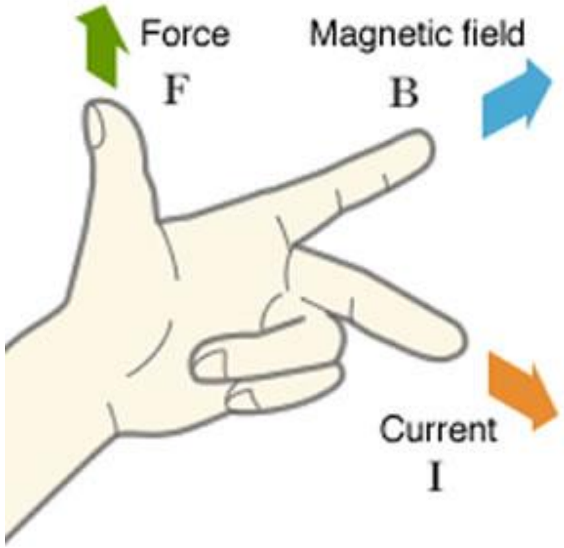
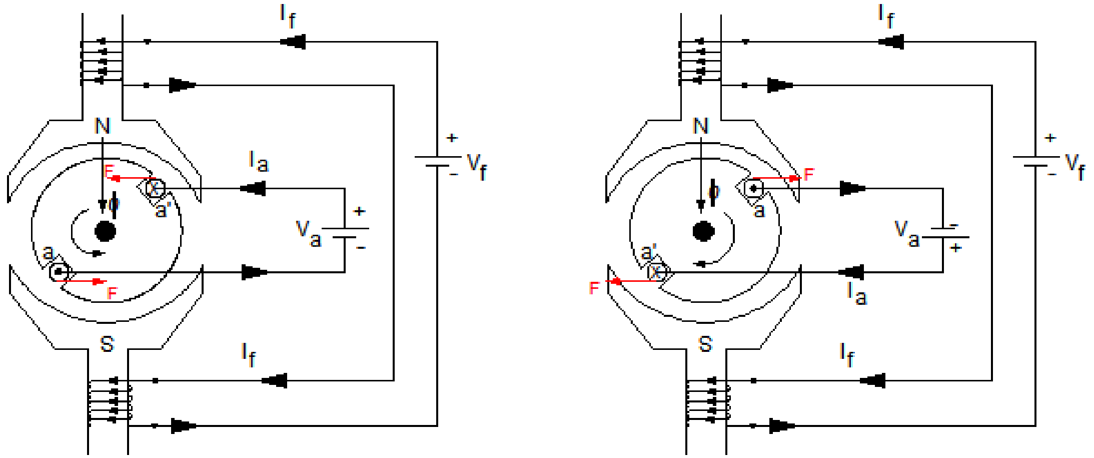


Fig: Fleming Left Hand Rule

Operating Principle of DC Motor:

Let us consider an elementary two pole DC machine as shown in fig1 where carbon brushes and commutator segments are not provided. The field current (If) produced magnetic field whose polarity is fixed as shown in Fig.1. In the initial position, armature current (Ia) passing IN through conductor a' and coming out through the conductor a. The direction of magnetic flux (ϕ) is N-pole to S-pole. Here, the current carrying conductors (a and a') are lying in the magnetic filed. Therefore, force will develop on the both conductors whose direction as determined by Fleming Left Hand Rule are shown by red color arrow in the figure. Hence, the armature rotates in anti-clock wise direction.

After 180^0 rotation, the situation will be as shown in Fig.1(b). The direction of current in armature conductors remains same. Now the direction of force will be opposite with respect to case (a). Hence, the armature tries to rotate in clock-wise direction. Therefore, the armature just oscillates and can not rotates continuously in a direction. The other problem is that the battery of armature has to be rotated along with the armature.



(a) Initial position (b) After 180^0 rotation

Fig1. Operation of DC motor without carbon brushes and commutator segments

The arrangement of carbon brushes and commutator segments helps to give continuous rotation as explained below:

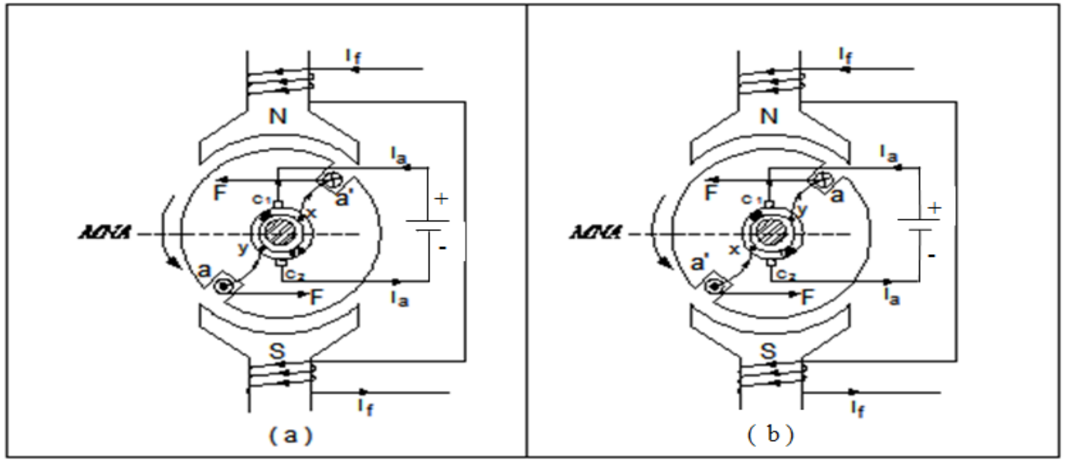


Fig. 2 Operation of DC motor

Fig.2 shows an elementary two pole DC machine with carbon brushes and commutator segments. Coil a-a’ rotates along with the commutator segments. The carbon brushes C_1 and C_2 are fixed and they are touching over the surface of commutator segments. Hence, the supply for the armature coil need not to be rotated along with the armature. Here, the armature winding is supplied by dc current I_a through the carbon brushes and commutator segments. The field winding is also supplied by dc current I_f. In Fig.2(a), the armature current I_a flows through the path: C_1-x-a’-a-y-C_2. The direction of force develop on the conductors a and a’ are shown in Fig.3.32(a). Hence, the armature rotates in the anti-clockwise direction.

After 180^0 rotation, the situation will be as shown in Fig.2(b). Here, the carbon brush C1 comes in contact with the commutator segment ‘x’. Therefore the armature current (I_a) flows IN through the conductor ‘a’. That means the direction of current through the conductor ‘a’ has reversed due to the action of carbon brushes and commutator arrangement. Here, the direction of force developed is in the same direction as in case of Fig.(a). Therefore the armature continuously in anti-clockwise direction.

Torque Developed by Armature

When the armature conductors a and a' rotates, they continuously cut magnetic flux, therefore, according to Faraday's law of Electromagnetic induction, emf will induce in the conductor a-a'. According to lenz law, the direction of this induce emf will be opposing to the direction of applied voltage V_{dc} as in fig.2. This induced emf is known as back emf and is given by:

$$E_b = \frac{Z\phi N}{60} * \frac{P}{A}$$

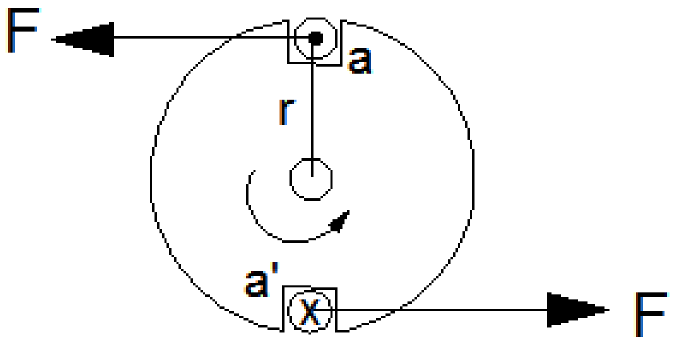
Where, Z= no. of conductor (armature)

N = Speed of the armature in RPM

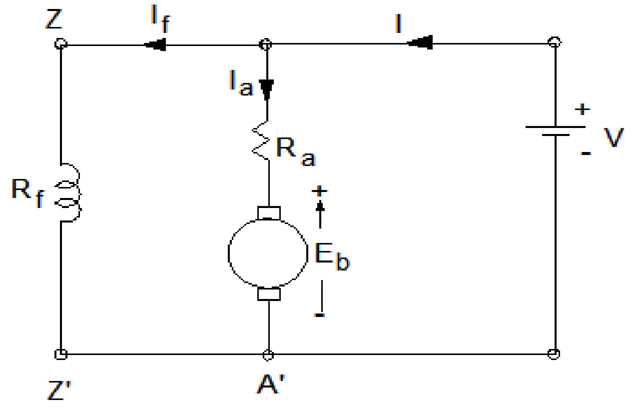
ϕ = Flux per pole

P = No. of Magnetic Pole

A = No. of Parallel Paths in armature in armature wir



Here, $I_a = \frac{V_{dc} - E_b}{R_a}$



Power Developed by the armature,

$P_a = E_b * I_a$

Work done by conductors in one revolution = $F \times 2\pi r$

Time for N revolution = 60 Sec

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

Mechanical power developed by the armature(P_m) = Rate of doing work = $\frac{Work\ Done}{Time}$

$$\text{Or,}\quad P_m = \frac{F \times 2\pi . r}{\frac{60}{N}} = \frac{F \times 2\pi . r.N}{60}$$

$$\text{Now, } P_m = P_a$$

$$\frac{F * 2\pi rN}{60} = E_b * I_a$$

$$\frac{F * 2\pi rN}{60} = \frac{Z\phi N}{60} * \frac{P}{A} * I_a$$

$$F * 2\pi r = \frac{Z\phi P}{A} * I_a$$

If, r = Radius of the armature coil

then, Torque developed by armature, Ta = F × r (N-m)

$$= \frac{1}{2\pi} * \frac{Z\phi P}{A} * I_a$$

Therefore, $\mathbf{T_a \propto \phi \times I_a}$

Back EMF in DC Motor:

When the armature rotates, the armature conductors cut the magnetic flux produced by the field poles. Hence, according to Faraday's law of electromagnetic induction, emf will induce across the armature winding. According to lenz's law, the direction of emf induced across the armature winding is opposite to the applied voltage to the armature. This opposing induced emf is known as back emf.

Fig.1 shows the circuit diagram of a DC motor. The applied voltage V pushes current I_a through the armature winding against the opposition offered by back emf E_b. Hence, the magnitude of armature current is given by:

$$I_a = \frac{V - E_b}{R_a} \qquad (1)$$

Where, V = Applied voltage to armature

R_a = Resistance of armature winding

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

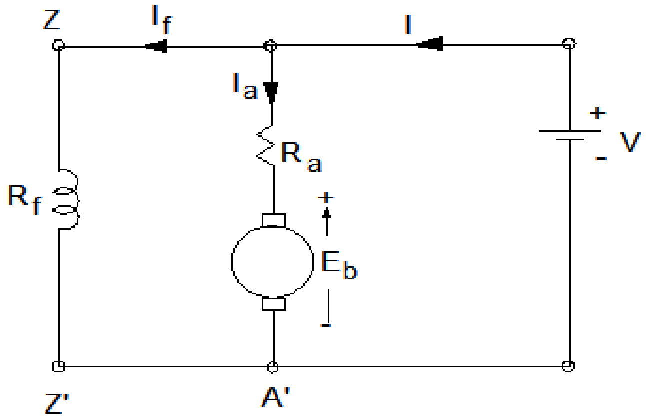


Fig.1 Back emf in DC motor

Equation (1) can be re-write as : $I_a.R_a = V - E_b$

Multiplying this equation by I_a gives:

$I_a^2.R_a = V\,I_a - E_b\,I_a$ Or $V\,I_a - I_a^2.R_a = E_b\,I_a$

i.e. (Input power to armature) – (Copper loss in armature) = (Power developed by armature)

Roles of Back EMF in DC Motor:

The back emf has very important role in the operation of dc motor. If back emf weren't developed, the motor wouldn't have developed. Followings are the three major roles of back emf in DC motor.

1. Back emf helps to protect the armature circuit from short circuit during the normal running condition.

If there were no back emf during normal running condition, the armature current will be:

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

Let us take a typical practical example of 5 kW motor with R_a = 0.1 ohm and V = 200 volt

$$\text{Full load current of motor} = \frac{\text{Power}}{\text{voltage}} = \frac{5 \times 1000}{200} = 25 \text{ amp}$$

In the absence of back emf, $I_a = \frac{V - 0}{R_a} = \frac{200 - 0}{0.1} = 2000$ amp, Which is like short circuit.

If back emf E_b = 198 V, then $I_a = \frac{V - Eb}{R_a} = \frac{200 - 198}{0.1} = 20$ amp(Safe)

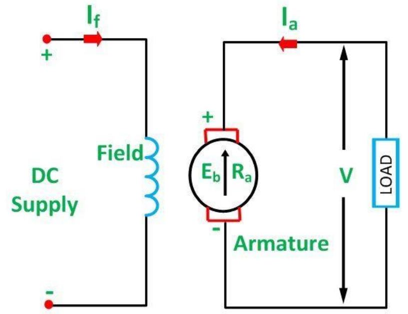
This current is less than its full load current. In this way, back emf helps to protect the armature from short circuit.

2. Back emf helps to produced required amount of torque according to mechanical load on the shaft of the motor.

$$E_b = \frac{Z.\phi.N}{60} \times \frac{P}{A} \qquad (1)$$

$$I_a = \frac{V - E_b}{R_a} \qquad (2)$$

$$T_a \propto \phi \times I_a \qquad (3)$$



Suppose, the armature was rotating without load at speed, N_1. The armature will produce very small amount of torque to overcome the frictional loss. If the mechanical load on the shaft is increased, it is natural that the speed decreases. When the speed decreases, the back emf E_b will decrease according to (1). At reduced value of E_b armature current I_a, will increase according to (2). Then, the torque developed by the armature increases by equation (3).
Similarly, When the load on the shaft decreases, motor will develop less torque.
In this way, back emf is helping to develop required torque according to increase or decrease in load of shaft.

3. In every energy converting process, there must be an opposing force otherwise, the energy conversion process will not be successful. In case of DC motor, the back emf is playing the role of opposing force.

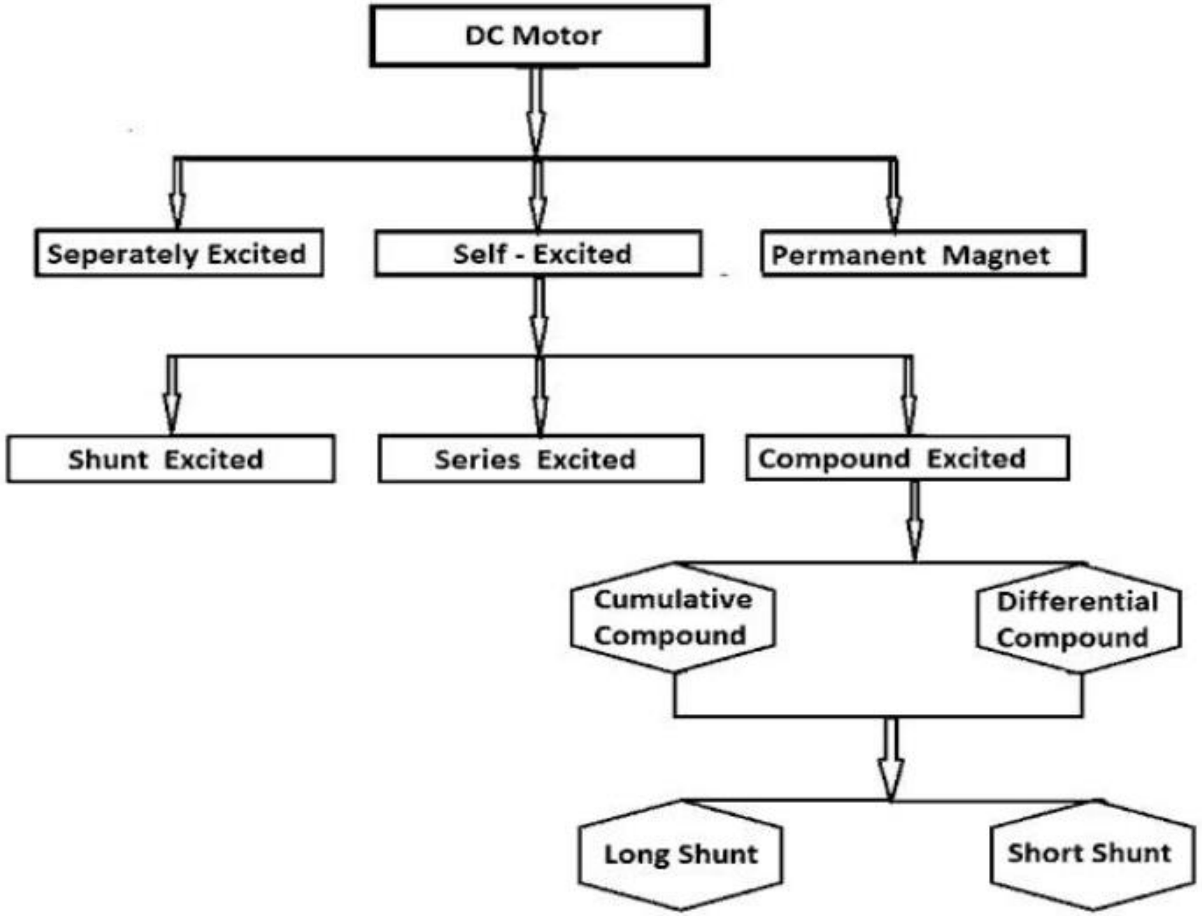
In case of dc motor, the supply voltage V_{dc} push the current into armature and back emf opposes the flow of armature current. The magnitude of back emf will be little less than input V_{dc} therefore some limited amount of current will flow into the armature circuit against the back pressure of E_b and energy conversion takes place. If there were no back emf, very high amount of armature current will flow damaging the armature circuit and energy conversion process fails.

Methods of Excitation, Types of DC Motors

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

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

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



Permanent Magnet DC Motor

- Permanent magnet is used for field system.
- Smaller in size and chepaer in cost.
- Excessive current in the armature winding demagnetizes permanent magnet.
- Mostly used in automobiles as starter motors and for windshield wipers and washers in personal computer disc drives etc.

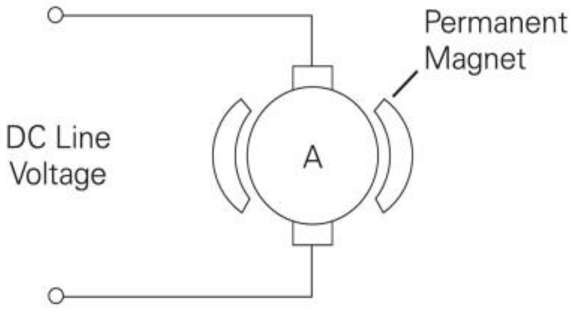


Fig : PMDC

Separately Excited DC Motor

It is the dc motor, whose field winding is excited by an independent external DC voltage source as shown in Fig.1. There is no electrical connection between field winding and armature winding.

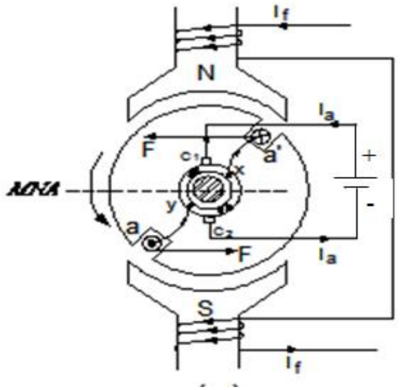


Fig1: Separately excited DC Motor

Self Excited DC Motor

It is the motor, whose field winding is excited by the DC current supplied from source to the armature of the machine itself. No external DC source is required for such motor. The field winding and armature winding have electrical connection. The field coils may be connected either in series with the armature, in parallel with the armature or partly in series and partly in parallel with the armature.

DC Motors and their characteristics :

These different types of motor have different characteristics and accordingly they are used in various applications. The characteristics of DC motors are distinguished by the following characteristics curves.

i) Torque – armature current characteristic (Electrical characteristic)
ii) Speed – torque characteristic (Mechanical characteristic)

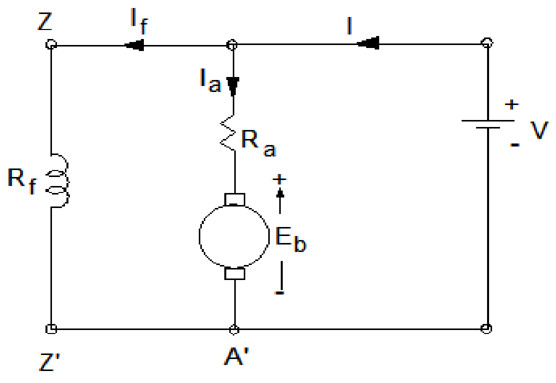
Characteristics of DC shunt motor:

a) Torque – armature current characteristic:
It is a curve showing the armature torque developed at different values of armature current.
It was derived in the earlier section that $T_a \propto \phi . I_a$ and $\phi \propto I_f$.

In case of dc shunt motor, the field winding is connected across the fixed DC voltage. Therefore, the field current (I_f) is constant and hence the air-gap magnetic flux (ϕ) is constant.

Therefore, $T_a \propto I_a$

Hence, T_a-I_a characteristic of DC shunt motor is a straight line as shown in Fig.1. It shows that the armature torque changes proportionately with armature current. However, the net shaft torque is always less that the armature toque due to friction loss. The net shaft torque is shown by the dotted line in the Fig.1



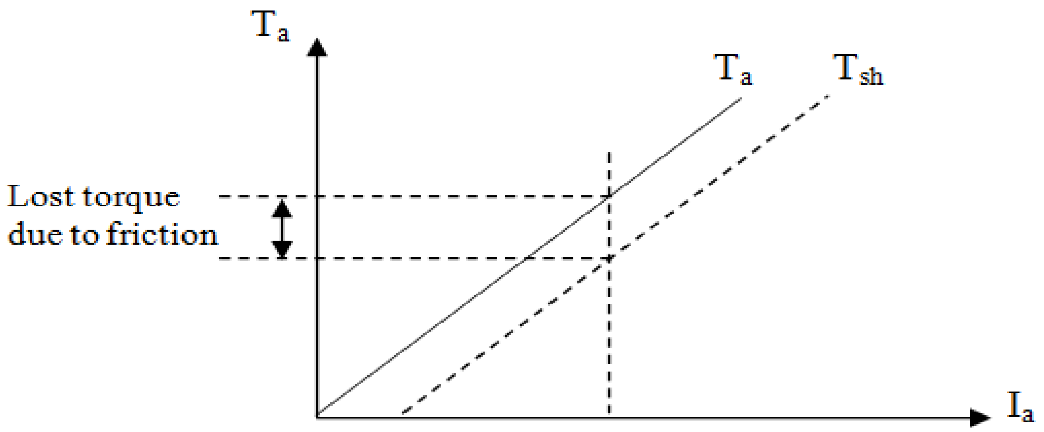


Fig.1 Torque – armature current characteristic Of DC shunt motor

b) <u>Speed – torque characteristic</u>:

It is a curve showing the speed of the motor at different values of armature torque. The nature of this characteristic curve can be explained as follow:

The back emf developed by the armature is given by: $E_b = \frac{Z.\varphi.N}{60} \times \frac{P}{A}$ Or $N = \frac{E_b}{\varphi} \times \frac{60 \times A}{Z \times P}$ Or $N \, \alpha \frac{E_b}{\varphi}$

Since ϕ is constant for DC shunt motor, $N \propto E_b$ And $I_a = \frac{V - E_b}{R_a}$

When the speed of the motor decreases, back emf (E_b) decreases, the armature current (I_a) increases and the armature torque (Ta) increases. Hence, the speed-torque characteristic has the shape of drooping curve as shown in Fig.2.

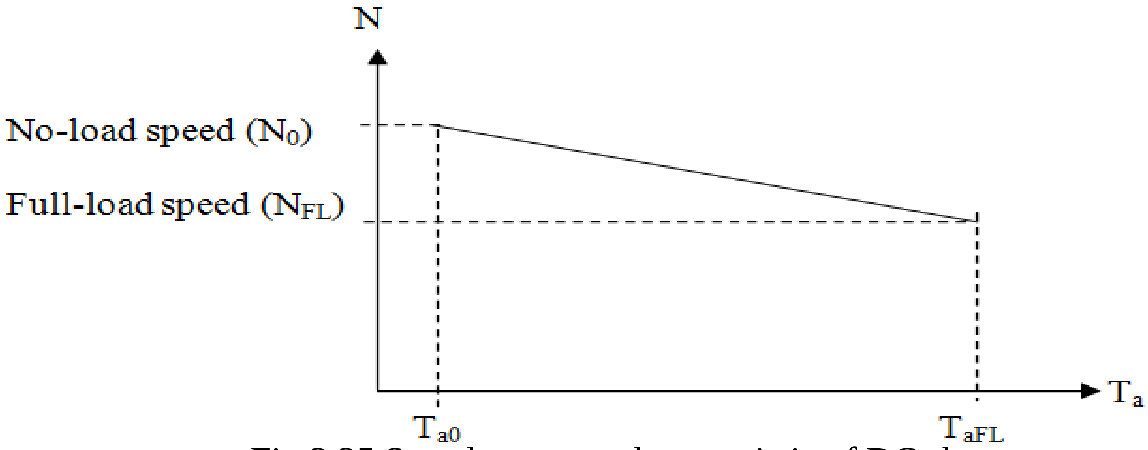


Fig.3.35 Speed – torque characteristic of DC shunt motor

It can be seen from the characteristic that there is no appreciable change in speed from no-load to full-load. Hence, shunt motor is called as a constant speed motor and it is suitable to drive a load which is totally and suddenly thrown off so that there is no fair of excessive speed. Due to its constancy in speed, it also suitable for driving the shaft of lathe machine, drilling machine, Grinders, Blowers, Compressers etc, where approximate constant speed is required.

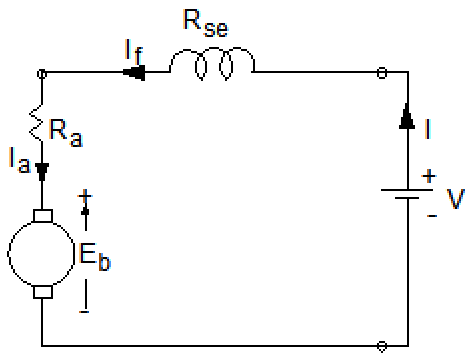
Characteristics of DC series motor:

a) Torque – armature current characteristic:

In case of DC series motor, armature current flows through the field winding and field current and armature current are same.

Here, $T_a \propto \phi . I_a$ and $\phi \propto I_f = I_a$

Therefore, $T_a \propto I_a^2$



Hence, Ta- Ia characteristic of DC series motor is parabolic in nature as shown in Fig.3. However, after saturation of field pole, the magnetic flux does not increase with increase in armature current. Therefore, $T_a \propto I_a$ after saturation. Hence, the Ta- Ia characteristic is a straight line after the saturation.

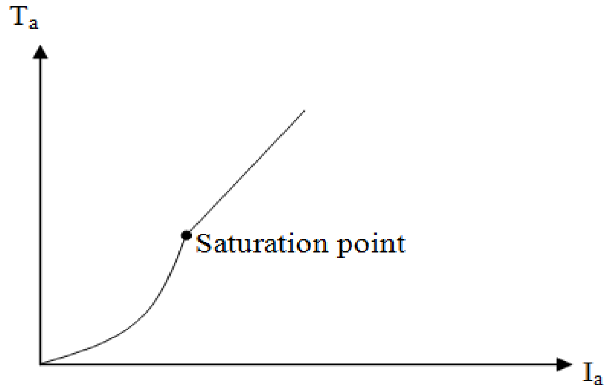


Fig.3 Torque-armature current characteristic of DC series motor

b) <u>Speed – torque characteristic</u>:

Here, $N \propto \frac{E_b}{\phi}$, $E_b = V - I_a(R_a+R_{se})$, and $T_a \propto I_a^2$

At heavy torque (T_a), the armature current is high. Therefore, the back emf will be less to allow high armature current. Therefore, the flux per pole will be very high. Hence speed will be very low at high torque due to low back emf and high flux.

On the other hand at light torque, the armature current is low. Therefore, the back emf will be high to allow low armature current. Therefore, the flux per pole will be very low. Hence speed will be very high at light torque due to high back emf and low flux. Therefore, the torque- speed characteristic will be as shown in Fig.4.

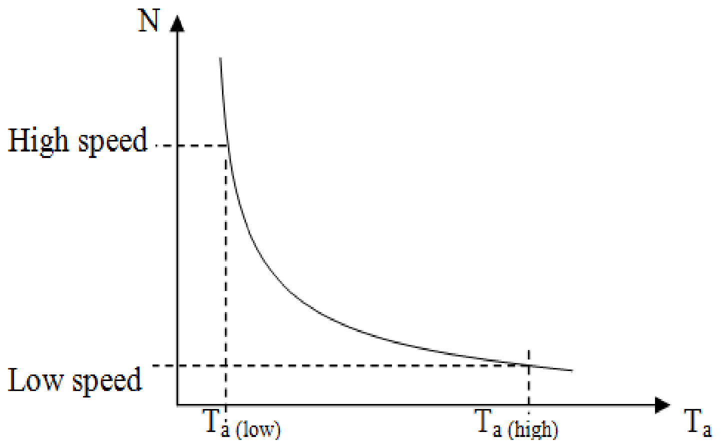
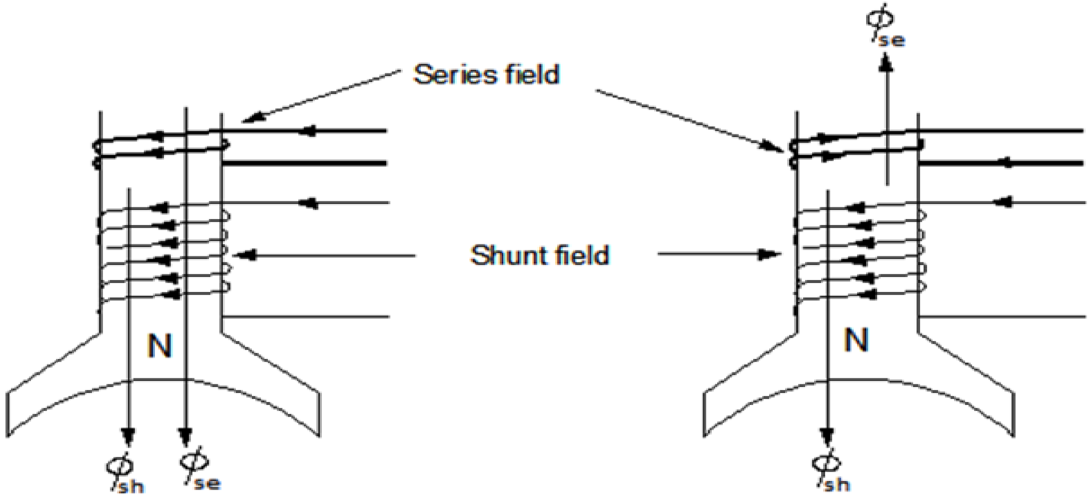


Fig.4 Speed-torque characteristic of DC series motor

From the characteristic, it is clear that at starting (when the speed is very low), the motor develops a high starting torque. On the other hand, at no-load, the speed is dangerously high. Hence, a DC series shall not be operated without load on the shaft. Due to its characteristics of high starting torque, it is suitable for electric train, trolley bus, lifting hoist, crane, Rolling mills, Conveyors etc.

Characteristics of DC compound motor:

A DC compound motor has both series and shunt field windings. If the series field winding produces the magnetic flux in the same direction as produced by the shunt field winding (as shown in Fig.5a), then such a motor is known as cumulative compound motor. On the other hand, if the series field winding produces the magnetic flux in the opposite direction as produced by the shunt field winding (as shown in Fig.5b), then such a motor is known as differential compound motor.



(a) Cumulative compound (b) Differential Compound

Fig.5 Field windings in DC compound motors

<u>Cumulative compound motor</u>: In a cumulative compound motor, the series field flux supports the shunt field flux. Therefore, the increase in flux per pole with the armature current is more severe with compare to that in shunt motor. Hence, the T_a-I_a characteristic of cumulative compound motor will be above the characteristic of shunt motor as shown in Fig.6 and the speed-torque characteristic will be as shown in Fig.7. Due to cumulative action of series field, at a particular value of torque, the flux per pole will be more with compare to a shunt motor. Hence, the speed-torque characteristic is more sloping than the characteristic of shunt motor but less sloping than a series motor.

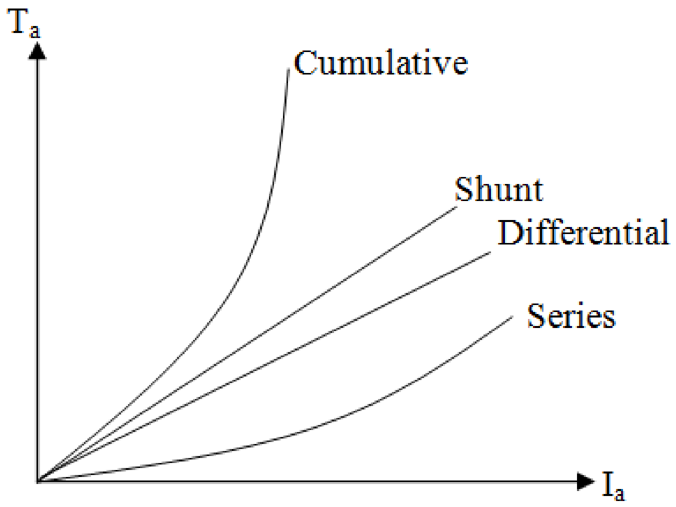


Fig.6 T_a-I_a Characteristics

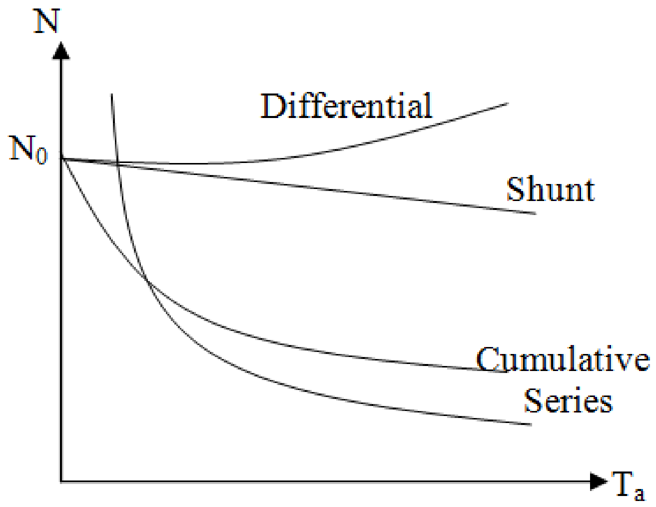


Fig.7 Speed- torque characteristic

Differential compound motor: In a cumulative compound motor, the series field flux opposes the shunt field flux. Therefore, the flux per pole decreases with increase in armature current. Hence, T_a-I_a characteristic of differential compound motor lies below the characteristic of shunt motor as shown in Fig.6. Due to differential action of series field, at a particular value of torque, the flux per pole will be less with compare to a shunt motor. Hence, the speed-torque characteristic lies above the characteristic of shunt motor as shown in Fig.7.

The speed of these motors increases with increases in the load which leads to an unstable operation. So, we can not use this motor for any practical applications.

DC motor starter

Current drawn by the armature and the back emf generated by the armature during normal operation is given by:

$$I_a = \frac{V - E_b}{R_a} \quad \text{and} \quad E_b = \frac{Z.\varphi.N}{60} \times \frac{P}{A}$$

If we start a dc motor directly closing a normal switch with full rated voltage V_{dc}, the motor will draw very high starting current. Due to this high starting current, the motor may get damaged.

At the instant of starting, the motor starts from zero speed and after some time it runs at normal speed. Therefore, at starting back emf E_b=0 and motor draws a starting current $I_{a(st)}$ and it is given by:

$$I_{a(st)} = \frac{V - 0}{R_a}$$

This starting current will be very high.

When the armature rotates, it generates back emf and the armature current decreases. When speed reaches to its normal value, the armature current also decreases to its normal value. The starting current will be very high just for few seconds.

Even though the high starting current is only for few seconds, it is harmful for the dc motor operation in the following aspect:

i) It may blow out the fuse which is used to protect the motor.

ii) It may damage the commutator segments and carbon brushes

To avoid these problem, DC motor shall be started using a **starter** which helps to reduce the starting current to a safe value

Basically a DC motor starter is a variable high resistance connected in series with the armature circuit as shown in Fig.1.

At starting, the pointer 'P' is at the end-1 of the starting resistance R_S so that whole value of R_S is connected in series with R_a and starting current drawn by the armature is given by:

$$I_{a(st)} = \frac{V - 0}{R_a + R_s}$$

By selecting the proper value of R_S, the value of $I_{a(st)}$ can be reduced to safe value. Once the motor rotates, back emf increases and it helps to reduce armature current. So, the value of R_S shall be reduce accordingly by sliding the pointer 'P' towards '0'. When the motor rotates at normal speed, full back emf will develop. Therefore, R_s is no more required. So, at normal Speed, the pointer P has to be at point '0'

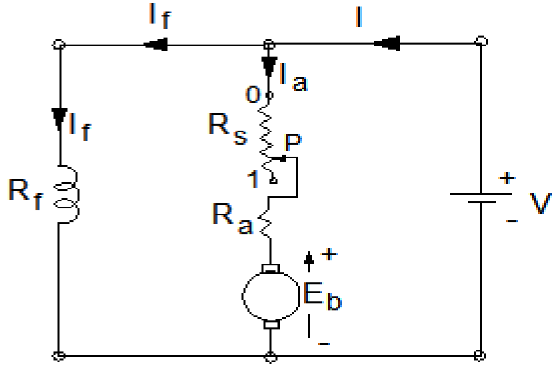


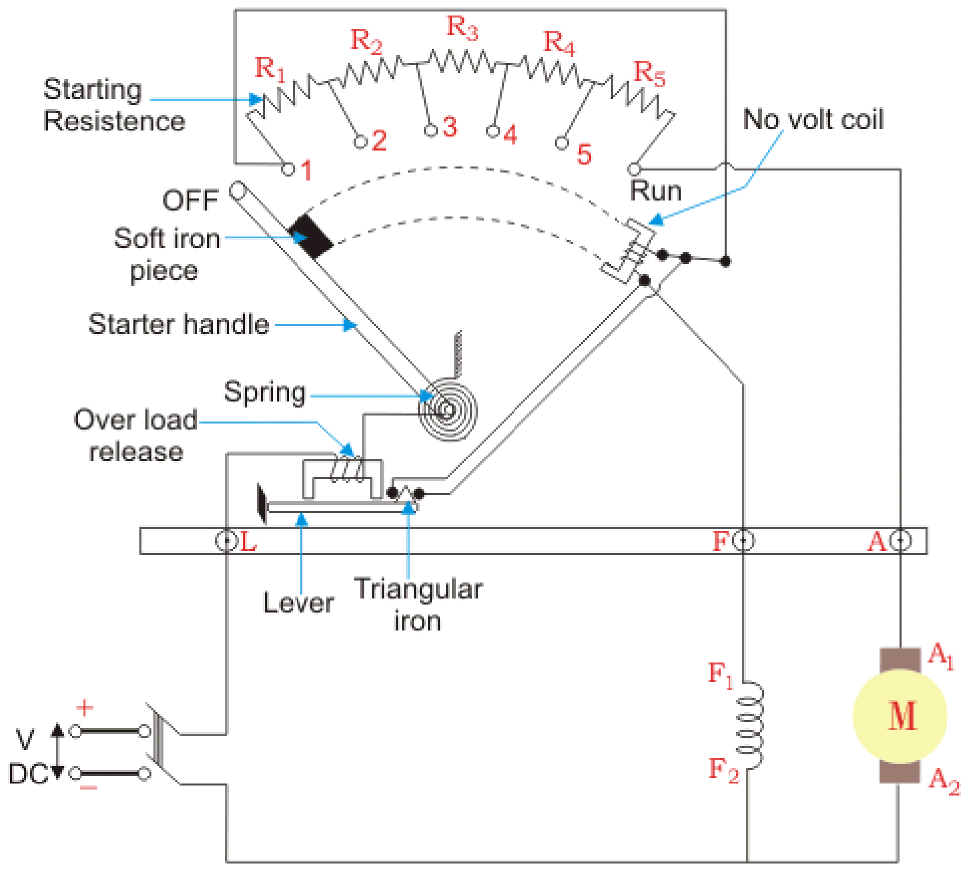
Fig.1 Basic circuit of DC motor starter

A commercial DC motor starter will have some additional protection features in addition to starting resistance R_S.

3-point Starter:

The three terminals of the starter are marked as L, F and A. Th negative terminal of supply source is directly connected to the armatu which is also connected to the negative terminal of the field windin The positive terminal of the supply source is connected to the termin marked ‘L’ of the starter, which is further connected to the start handle through the overload release magnet .

When the supply is turned on by closing main switch, the handle is kep at stud1, then whole external resistance is connected in series with armature. So, small current starts to flow through armature winding. A the same time, field coil is supplied by whole of the applied voltage through the no volt coil. Motor starts to rotate with small speed at this condition. Now, handle should be moved slowly towards the Run position which results in higher speed of armature and also back emf will be in increasing order. When the handle reached to ‘Run’ position, back emf should reach to max. value and rated speed must be attained. Now, the handle is at ‘Run’ position but due to spring force it tries to comeback to ‘OFF’ Position. But there is a soft iron piece ‘S’ on the arm which in the ON position is attracted and hold by the no volt coil. When the motor is switched off by turning off the main switch, the hold-ON magnet(No volt coil) will get demagnetized and the starter handle will be thrown back to OFF position under the action of spring force.

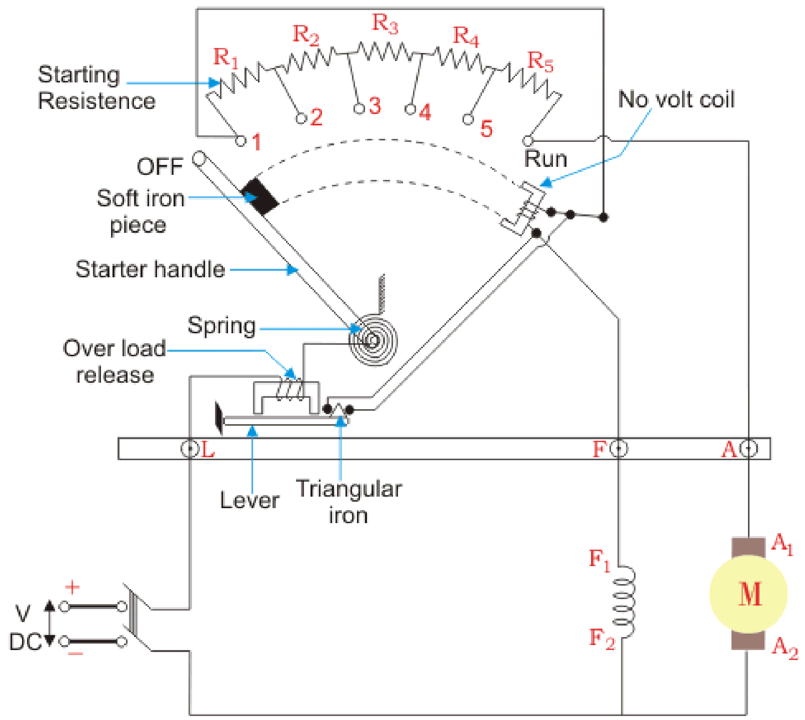


Three Point Starter

Fig.2 Detail circuit diagram of a commercial 3-point starter

If the motor is overloaded, the motor will draw high armature current and the overload release electromagnet becomes strong enough to pull up the liver and it will short circuit the no volt coil (electromagnet). Then the electromagnet(no volt coil) will get de-magnetized and it will release the starter handle to OFF position thus by protecting the motor from over-loading.

If the field winding of a running motor breaks, there will be zero current through the field winding. However, there will be some residual magnetic flux in the core of field poles. Hence, at lower value of magnetic flux , the motor runs at dangerously high speed. The no volt coil (electromagnet) is connected in series with the field winding. Therefore, when the field winding breaks, the current through the no volt coil also becomes zero and it gets de-magnetized thus by releasing the handle to OFF position. In this way motor gets protected from running to high speed. This is also known as protection against the loss of field.

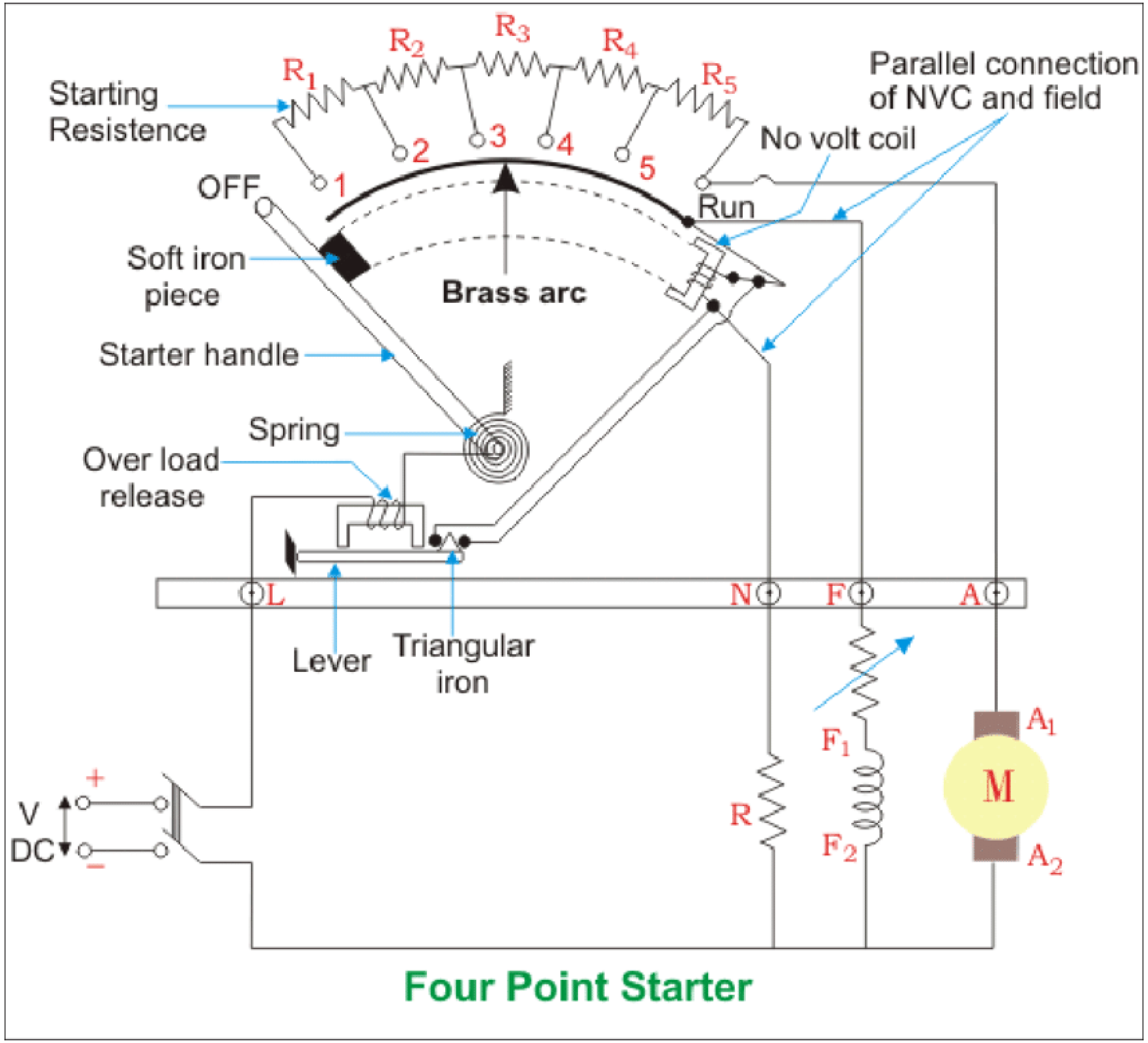


Three Point Starter

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 field resistance can be increased. Therefore current through the shunt field is reduced.
Field current becomes very low which results in 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 desirable. A 4 point starter is thus used instead, which does not have this drawback.

4-point Starter:

Assignment



Speed Control DC motor

In practical application, a DC motor may have to operated at different speed under the different loading conditions. Therefore, it is necessary to adopt some methods to control the speed as per requirement. There are various methods available for speed control of DC motor.

Factors affecting the speed of DC motor:

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

Therefore the factors affecting the speed are:

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

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

Speed Control of DC shunt motor

i) Field Control Method:

In this method, the speed is varied by changing the magnetic flux. A variable resistance R_S is connected in series with the field winding to regulate the field current there by regulates the magnetic flux as shown in Fig.1.

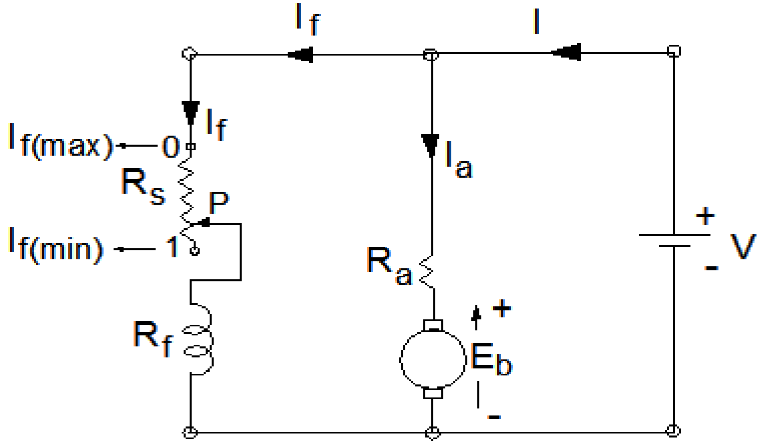
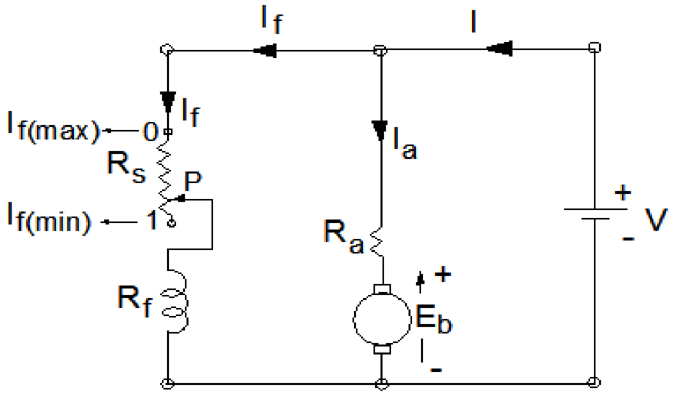


Fig.1 Circuit diagram for field control method

The variable resistance R_S can only reduce the field current below its rated value. Therefore, this method is only suitable to control the speed above the rated speed. When the value of R_S is increased, the field current will decrease and magnetic flux per pole will decrease.

When the value of R_S is increased, the field current will decrease and magnetic flux per pole will decrease.



Since $N \alpha \frac{E_b}{\varphi}$

Speed will increase. By varying the value of R_S, speed can be controlled above its rated speed.

When, the pointer 'P' is at end-0 of the R_S, R_S= 0, field current will be maximum and given by: $I_{f1} = \frac{V}{R_f}$

Let us say motor runs at a speed of N_1 rpm and corresponding back emf is E_{b1} and $E_{b1} = V-I_{a1}.R_a$
The value of I_{a1} depends on load on the shaft of the motor.

Armature torque at this condition $T_{a1} \alpha I_{a1} \times I_{f1}$

When the pointer 'P' is moved toward the end-1 of R_S keeping the load torque on the shaft constant, the value of R_S increases. Field current decreases to:

$$I_{f2} = \frac{V}{R_f + R_S}$$

Since the load torque is constant, the armature has to develop same amount of torque as before.

Therefore, $T_{a2} = I_{a2} \times I_{f2} = I_{a1} \times I_{f1}$. OR, $I_{a2} = \frac{I_{a1} \times I_{f1}}{I_{f2}}$

Since I_{f2} has decreases, I_{a2} will increase to produce same amount of torque.

Back emf at this condition $Eb_2 = V - I_{a2}.R_a$.

Therefore, motor runs at a new speed : $N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{I_{f1}}{I_{f2}} \times N_1$

ii) Armature Control Method:

In this method, the speed is varied by changing the armature resistance by adding a variable resistance 'R_S' in series with R_a as shown in Fig.2. When R_S is added, there will be some voltage drop in R_S. Therefore, voltage across the armature circuit decreases and accordingly the speed of the motor decreases. By varying the value of R_S, the speed of the motor can be varied. Here, it shall be noted that this method is only suitable to control the speed below its rated speed.

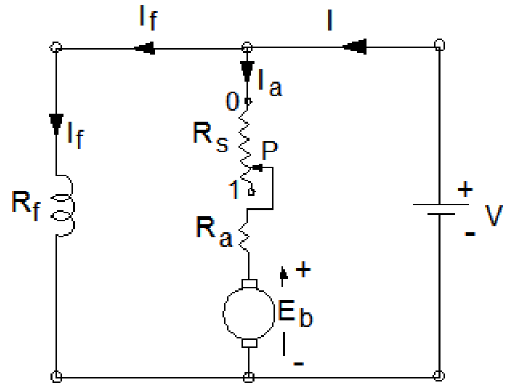


Fig.2 Circuit diagram for armature control method

When, the pointer 'P' is at end-0 of the R_S, $R_S = 0$, There will be no voltage drop in R_S and the voltage across the armature will be maximum. The armature current depends on the load on the shaft.

Let I_{a1} = armature current at this condition

Then back emf at this condition is given by: $E_{b1} = V - I_{a1}.R_a$.

Here, it shall be noted that the filed current I_f remains constant, because R_f is connected across the fixed supply voltage 'V'

When the pointer 'P' is moved toward the end-1 of R_S keeping the load torque on the shaft constant, the value of R_S increases. Field current remains constant. Therefore, $I_{f1} = I_{f2}$.

Since the load torque is constant, the armature has to develop same amount of torque as before.

Therefore, $T_{a2} = I_{a2} \times I_{f2} = I_{a1} \times I_{f1}$. Since $I_{f2} = I_{f1}$, I_{a2} will be equal to I_{a1} to produce same amount of torque.

Back emf at this condition $E_{b2} = V - I_{a2}.(R_a + R_S)$

Therefore, motor runs at a new speed $N_2 = \dfrac{E_{b2}}{E_{b1}} \times \dfrac{I_{f1}}{I_{f2}} \times N_1$

ii) Applied Voltage Changing Method:

In this method, the speed is varied by changing the applied voltage as shown in Fig.3.

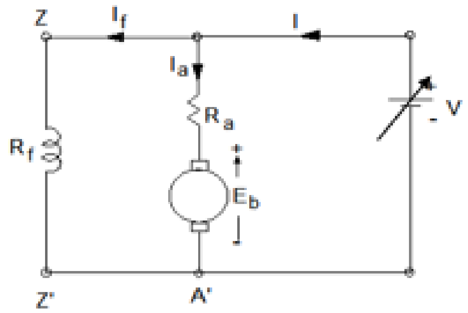


Fig. 3. circuit diagram for voltage changing method

- ❖ This method requires a variable source of voltage separate from the source supplying the field current.
- ❖ This method provides better speed regulation and efficiency but is expensive initial cost.
- ❖ Adjustable voltage for the armature is obtained from an adjustable voltage generator or electronic rectifier.
- ❖ Provides large speed range with any desired number of speed points.

Speed Control of DC series motor

Speed of a DC series motor can be controlled by various methods.

i) Field diverter method:

In this method a variable resistance (R_S) is connected across the series field winding as shown in Fig.3.

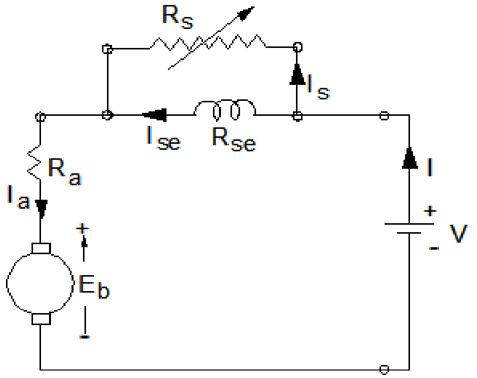


Fig.3 Circuit diagram for field control method

When R_S is connected across the field winding, the total line current (I) gets diverted through R_S and I_{se} decreases. With reduce value of Ise, magnetic flux per pole decreases and the speed of the motor increases (because, speed is inversely proportional to flux per pole). Desired amount of I_{se} current can be passed through the field winding by varying R_S and accordingly speed can be controlled above the rated speed.

Let I_{se1} = current through the field winding without $R_S = I_1 = I_{a1}$

The magnitude of I_{a1} depends on load on the shaft.

Torque developed by the armature $T_{a1} \propto I_{a1} \times I_{se1} = I_{a1}^2$ (because, $I_{a1} = I_{se1}$)

Let N_1 = speed at this condition and corresponding back emf is given by: $E_{b1} = V - I_{a1}(R_{se} + R_a)$

If R_S is connected keeping the load on the shaft constant, the total current (I_2) divides into two parallel path according to current division rule: Let $I_{a2} = I_{se2} + I_S$, then, $T_{a2} \propto I_{a2} \times I_{se2}$ Since the load torque constant, $I_{a2} \times I_{se2} = I_{a1}^2$ $\therefore I_{a2} = \frac{I_{a1}^2}{I_{se2}}$

Then back emf at this condition $E_{b2} = V - I_{a2}.R_a - I_{se2}.R_{se}$

Therefore, motor runs at a new speed $N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{I_{se1}}{I_{se2}} \times N_1$

ii) **Armature diverter method**:

In this method a variable resistance (R_S) is connected across the armature circuit as shown in Fig.4.

When R_S is connected across the armature winding keeping the load torque constant, the total line current (I) gets diverted through R_S and I_a decreases. In order to produce same amount of armature torque, I_{se} will increase to produce more magnetic flux at reduced value of I_a. When the magnetic flux increases, speed decreases. By varying the value of R_S, the magnitude of Ise can be varied and accordingly speed will vary.

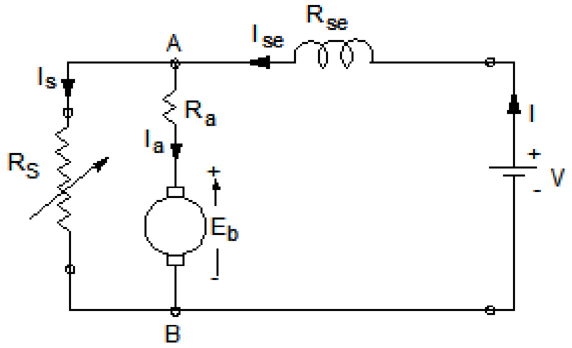


Fig.4 Circuit diagram for armature diverter method

Let I_{se1} = current through the field winding without $R_S = I_1 = I_{a1}$

The magnitude of I_{a1} depends on load on the shaft.

Torque developed by the armature $T_{a1} \propto I_{a1} \times I_{se1} = I_{a1}^2$ (because, $I_{a1} = I_{se1}$)

Let N_1 = speed at this condition and corresponding back emf is given by: $E_{b1} = V - I_{a1}(R_{se} + R_a)$

If R_S is connected keeping the load on the shaft constant, the total current (I_2) divides into two parallel path according to current division rule.

Let $I_2 = I_{a2} + I_{S2}$ Then, $T_{a2} \propto I_{a2} \times I_{se2}$ Since the load torque constant, $I_{a2} \times I_{se2} = I_{a1} \times I_{se1}$ $\therefore I_{a2} = \dfrac{I_{a1} \times I_{se1}}{I_{se2}}$

Then back emf at this condition $E_{b2} = V - I_{a2}.R_a - I_{se2}.R_{se}$

Therefore, motor runs at a new speed: $N_2 = \dfrac{E_{b2}}{E_{b1}} \times \dfrac{I_{se1}}{I_{se2}} \times N_1$

ii) Tapped field control method

In this method, the series field winding is provided with number of tapings as shown in Fig..

The magnetic flux produced by the field winding is given by:

$$\varphi = \frac{\mathrm{N} \times \mathrm{I}}{\mathrm{Reluctance}}$$

By shifting the contact pointer ‘P’, the effective number of turns field winding can be changed and magnetic flux will change accordingly. Then speed of the motor will vary.

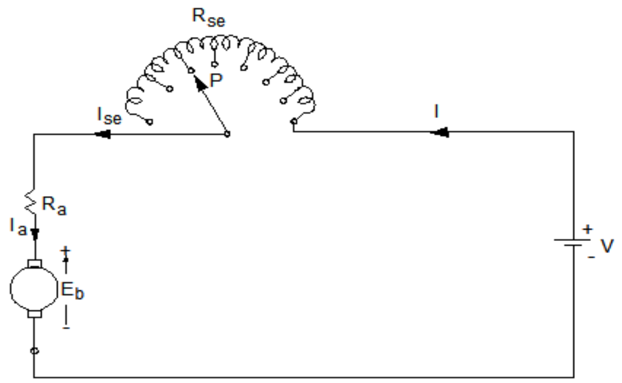


Fig.5 Circuit diagram for tapped field control method

Losses in a D.C. Motor

The losses occurring in a d.c. motor are the same as in a d.c. generator .These are:

(i) copper losses (ii) Iron losses or magnetic losses & (ii) mechanical losses

As in generator, these losses cause
(a) increase in temperature of machine
(b) Reduction in the efficiency of the d.c. motor.

Copper Losses:

- Armature copper loss = Ia^2Ra
- Shunt Field copper loss = Ish^2Rsh
- Series field copper loss = Ise^2Rse
- Brush Contact loss = Ia^2Rb [generally included in armature copper loss]

Iron losses:

- Hysteresis loss : Occurs in the rotating armature. It's expression is given as:

$P_h = \eta(Bmax)^{1.6} fV$ (watt)

Where, P_h = Hysteresis loss in watts
η = Steinmetz's constant
Bmax =Maximum flux density in core
f =number of cycles of magnetization made per second
V=Volume of magnetic material in m^3

- To minimise this loss, armature core is made of silicon steel which has low Steinmetz's constant or hysteresis constant.

- **Eddy Current loss:** Occurs in the armature core. Expressed as:

$$\mathbf{P_e = KB_m^2 f^2 t^2.Vol \quad (Watts)}$$

Where, B_m = Peak value of magnetic flux density in the core (Wb/m^2)
f = Frequency of the applied voltage (Hz)
t = Thickness of each lamination (in mm)
Vol = Volume of iron core (m^3)
K = Constant depending upon the grade of iron core

- To minimise eddy current loss armature core is laminated into thin sheets(0.3-0.5 mm)

Mechanical Losses:
- Air friction of rotating armature (windage loss).
- Friction at the bearing and friction between brushes and commutator (friction loss)
- Lubrication is done at the bearing to reduce this loss.

Efficiency of DC Motor

$$\text{Efficiency} = \frac{\text{output power}}{\text{output power} + \text{Total Losses}}$$

Power Stages

- The power stages in a d.c. motor are represented diagrammatically in Figure below.
- A - B = Copper losses
- B - C = Iron and friction losses
- Overall efficiency, ηc = C/A
- Electrical efficiency, ηe = B/A
- Mechanical efficiency, ηm = C/B

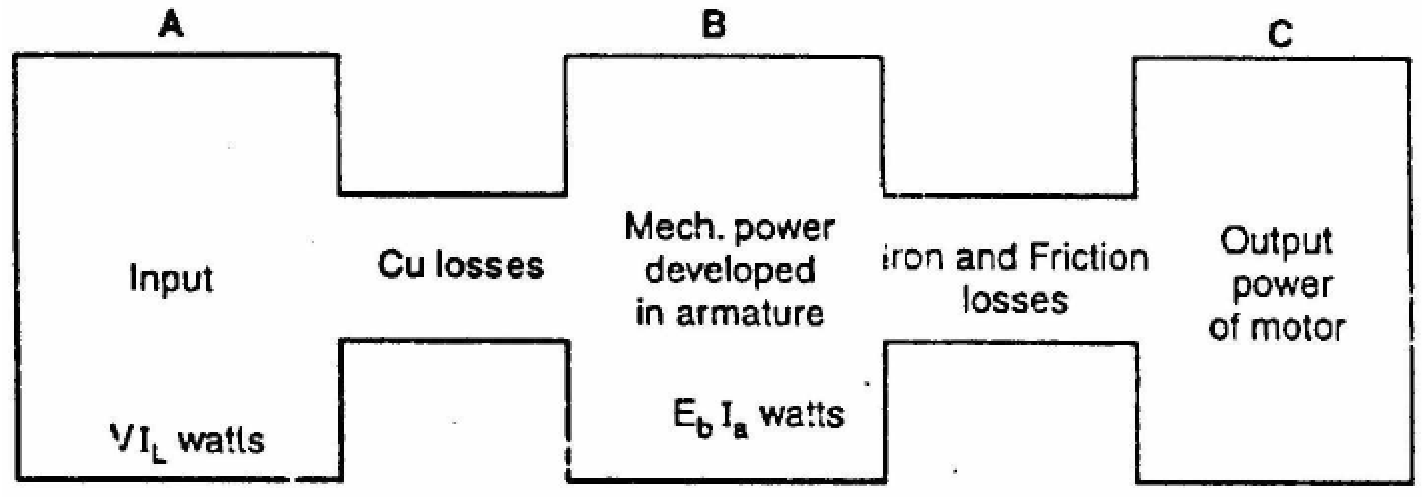


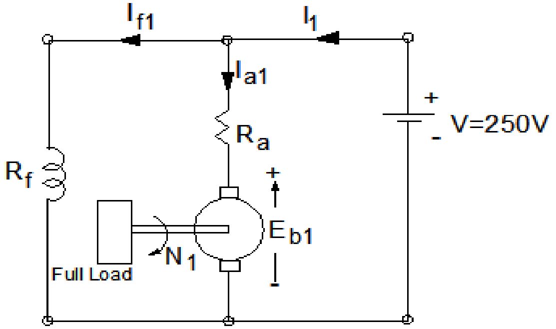
Figure: Power Stages

Illustrative Example #1

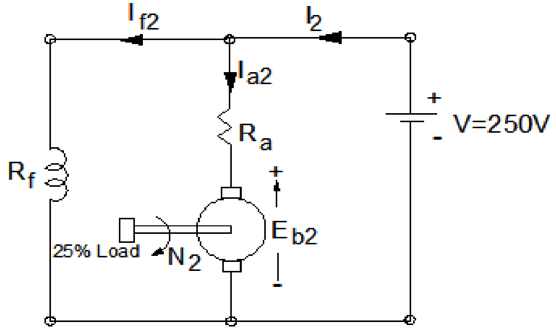
A 250V DC shunt motor has armature and field windings resistances of 0.05 Ω and 125 Ω respectively. When the motor is fully loaded, the motor draws a current of 30 amp and runs at a speed of 1500 rpm. When the 75% of load is taken off, the motor current reduces to 10A. Calculate the new speed.

Solution:

Since, $N \propto \frac{E_b}{\varphi} \propto \frac{E_b}{I_f}$ $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{f1}}{I_{f2}}$ OR $N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{I_{f1}}{I_{f2}} \times N_1$



Case-1 : Fully Loaded



Case-2 : 25% Load

When the motor is fully loaded: $I_1 = 30A$, $I_{f1} = \frac{V}{R_f} = \frac{250}{125} = 2A$ $I_{a1} = I_1 - I_{f1} = 30 - 2 = 28A.$

$E_{b1} = V - I_{a1}(R_a) = 250 - 28(0.05) = 248.6\ V$ $N_1 = 1500$ rpm

When 75% of load is taken off:

$I_2 = 10A$, I_{f2} is same as before = 2A. $I_{a2} = I_2 - I_{f2} = 10 - 2 = 8A.$

$E_{b2} = V - I_{a2}(R_a) = 250 - 8(0.05) = 249.6\ V$

Then $N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{I_{f1}}{I_{f2}} \times N_1 = \frac{249.6}{248.6} \times \frac{2}{2} \times 1500 = 1506$ rpm

Assignment

- A 250V dc shunt motor has armature winding resistance of 0.5 ohm and field winding resistance of 125 ohms. It draws a current of 25 amp at a speed of 900 rpm. It is required to increase the speed to 1100 rpm keeping the load torque constant. Calculate the value of additional resistance to be connected in series with the field winding to achieve this speed. **[30]**

- A dc series motor runs at speed of 500 rpm and draws a current of 60 A from 460 volt Source given R_a=0.2 ohms and R_{se} = 0.1 ohms. Calculate the new speed that when a resistance of 0.15 ohms is connected across the series field winding keeping the load torque constant**.(642rpm)**