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وزارة التعليم العالي والبحث العلمي
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DC Machine

مكائن التيار المستمر

المرحلة الثانية

المحاضرة (4)

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I. DC Motor

An electro-mechanical energy conversion device (electrical machine) that converts DC electrical energy or power (E I) into mechanical energy or power (ω T) is called a DC motor.

Electric motors are used for driving industrial machines, e.g., hammers, presses, drilling machines, lathes, rollers in paper and steel industry, blowers for furnaces, etc., and domestic appliances, e.g., refrigerators, fans, water pumps, toys, mixers, etc. The block diagram of energy conversion, when the electro-mechanical device works as a motor, is shown in **Fig. 1**.

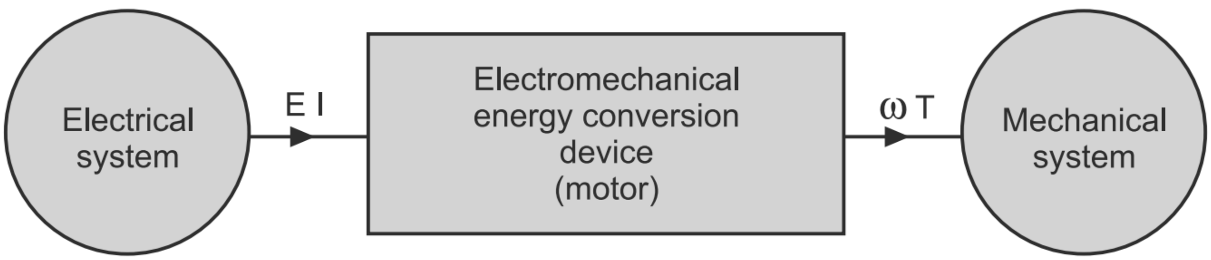


Figure 1. Block diagram of electromagnetic energy conversion (motor action).

II. Working Principle of DC Motors

The operation of a DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, a mechanical force is experienced by it. The direction of this force is determined by Fleming's Left Hand Rule and its magnitude is given by the relation:

$$F = Bil \quad \text{Newten}$$

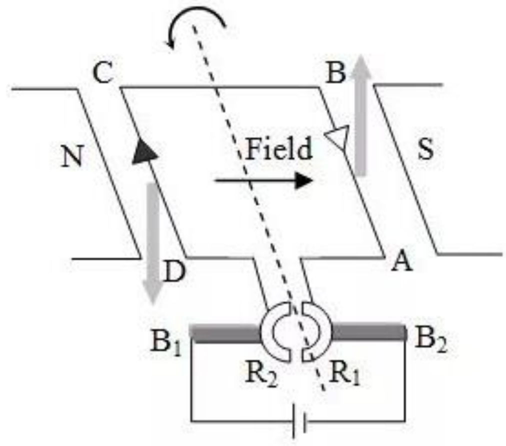


Figure 2. DC Motor.

For simplicity, consider only one coil of the armature placed in the magnetic field produced by a bipolar machine [see **Fig. 3(a)**]. When DC supply is connected to the coil, current flows through it which sets up its own field as shown in **Fig. 3(b)**. By the interaction of the two fields (i.e., field produced by the main poles and the coil), a resultant field is set up as shown in **Fig. 3(c)**. The tendency of this is to come to its original position i.e., in straight line due to which force is exerted on the two coil sides and torque develops which rotates the coil.

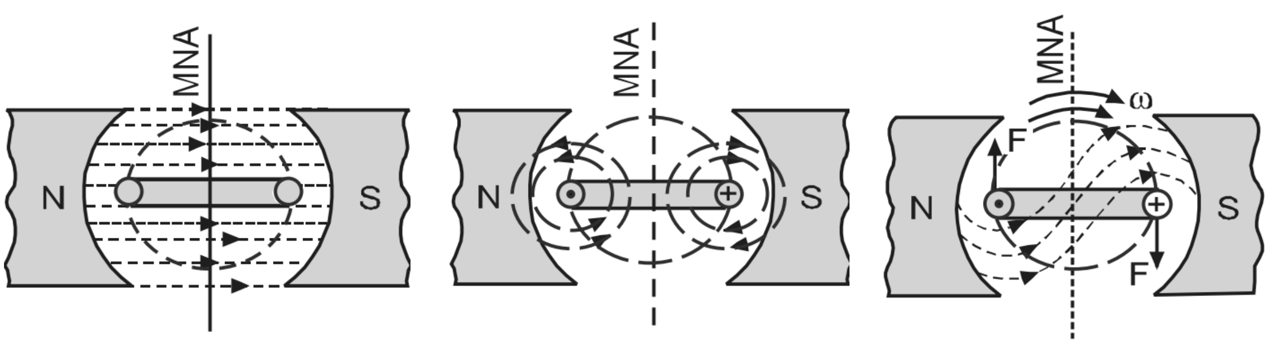


Figure 3. Working principle of a motor (a) Main field (b) Field due to current carrying coil (c) Resultant field.

Alternately, it can be said that the main poles produce a field F_m. Its direction is marked in **Fig. 4**. When current is supplied to the coil (armature conductors), it produces its own field marked as F_r. This field tries to come in line with the main field and an electromagnetic torque develops in clockwise direction as marked in **Fig. 5**.

In actual machine, a large number of conductors are placed on the armature. All the conductors, placed under the influence of one pole (say, North pole) carry the current in one direction (outward). Whereas the other conductors placed under the influence of other pole i.e., south pole, carry the current in opposite direction as shown in **Fig. 5**. A resultant rotor field is produced. Its direction is marked by the arrow-head F_r. This rotor field Fr tries to come in line with the main field F_m and torque (T_e) develops. Thus, rotor rotates.

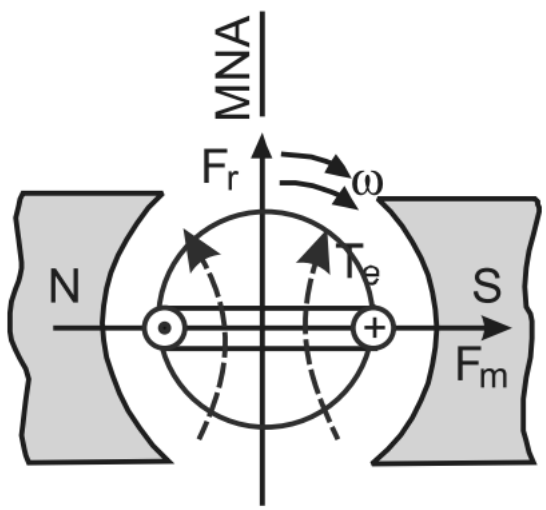


Figure 4. Position of main field F_m and rotor field F_r.

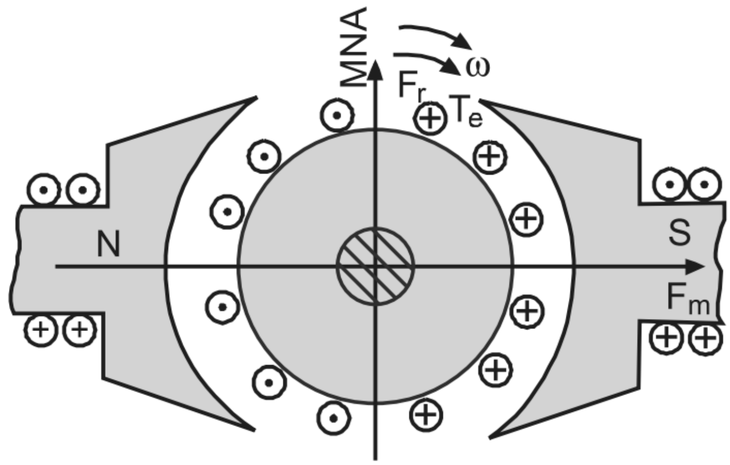


Figure 5. Motor action.

It can be seen that to obtain a continuous torque, the direction of flow of current in each conductor or coil side must be reversed when it passes through the magnetic neutral axis (*M.N.A*). This is achieved with the help of a commutator.

- *Function of a Commutator*

The function of a commutator in DC motors is to reverse the direction of flow of current in each armature conductor when it passes through the *M.N.A.* to obtain continuous torque.

III. Back emf

It has been seen that when current is supplied to the armature conductors, as shown in **Fig. 6(a)**, placed in the main magnetic field, torque develops, and armature rotates. Simultaneously, the armature conductors cut across the magnetic field and an emf is induced in these conductors. The direction of this induced emf in the armature conductors is determined by Fleming's Right Hand Rule and is marked in **Fig. 6(b)**.

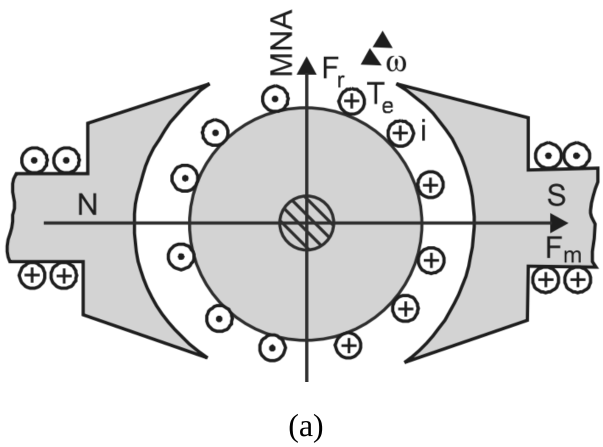


Figure 6. Back emf (a) Torque development due to alignment of rotor field with main field (b) Production Back emf.

It can be seen that the direction of this induced emf is opposite to the applied voltage. That is why this induced emf is called back emf (E_b). The magnitude of this induced emf is given by the relation;

$$E_b = \frac{PZ\phi N}{60A}$$

$N \propto \frac{E_b}{\phi}$ shows that speed of motor is inversely proportional to magnetic field or flux.

A simple conventional circuit diagram of the machine working as motor, is shown in Fig. 7. In this case, the supply voltage is always greater than the induced or back emf (i.e., V > Eb). Therefore, current is always supplied to the motor from the mains and the relation among the various quantities will be; $E_b = V - I_a R_a$

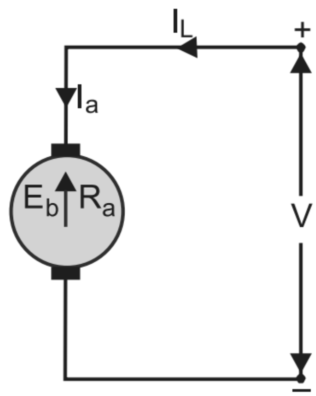


Figure 7. Circuit diagram ($E_b < V$).

- *Significance of Back emf*

The current flowing through the armature is given by the relation:

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

When mechanical load applied on the motor increases, its speed decreases which reduces the value of E_b. As a result, the value $(V - E_b)$ increases which consequently increases I_a. Hence, motor draws extra current from the mains.

IV. Electro-magnetic Torque Developed in DC Motor

The electrical power which is supplied to a DC motor is converted into mechanical power. The conversion of power takes place in the armature as stated below:

The power developed in the armature is given as

$$EI_a = \omega T_e \text{ or } EI_a = \frac{2\pi N}{60} \times T_e$$

$$\text{or } \frac{\phi ZNP}{60\text{A}} \times I_a = \frac{2\pi N}{60} \times T_e \text{ or } T_e = \frac{PZ\phi I_a}{2\pi A} \text{Nm}$$

For a particular machine, the number of poles (P), number of conductors per parallel path (Z/A) are constant.

$$\therefore T = K\frac{\phi I_\alpha}{2\pi} \text{ where } K = \frac{PZ}{A} \text{ is a constant}$$

The constant K for a given machine is the same for the emf equation as well as the torque equation.

As well as $T = K_2\phi I_a$ where $K_2 = \frac{PZ}{2\pi A}$ is another constant or $T \propto \phi \mathrm{I}_a$

Thus, it is concluded that torque produced in the armature of a DC machine is directly proportional to flux per pole and armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the direction of flux or magnetic field and the direction of flow of current in the armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed the direction of torque (or rotation) does not change.

V. Shaft Torque

In DC motors whole of the electromagnetic torque (T_e) developed in the armature is not available at the shaft. A part of it is lost to overcome the iron and mechanical (friction and windage) losses. Therefore, shaft torque (T_{sh}) is somewhat less than the torque developed in the armature. Thus, in case of DC motors, the actual torque available at the shaft for doing useful mechanical work is known as shaft torque.

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

$$= \frac{60}{2\pi}\frac{\text{output}}{N} = 9.55\frac{\text{Output}}{N} \text{ Nm}$$

- *Brake Horsepower (B.H.P.)*

In case of motors, the mechanical power (H.P.) available at the shaft is known as brake horsepower (B.H.P.). If T_{sh} is the shaft torque in Nm and N is speed in rpm then,

$$\text{Output in B.H.P.} = \frac{2\pi N T_{sh}}{60 \times 735.5}$$

Example

A 50 HP, 400 V, 4 pole, 1000 rpm, DC motor has flux per pole equal to 0.027 Wb. The armature having 1600 conductors is wave connected. Calculate the gross torque when the motor takes 70 ampere.

Solution:

$$\text{Torque developed, } T = \frac{P\varphi Z I_a}{2\pi A}$$

Where, $P = 4$; $\phi = 0.027$ Wb; $Z = 1600$; $I_a = 70$A; $A = 2$ (wave connected)

$$T = \frac{4 \times 0 \cdot 027 \times 1600 \times 70}{2 \times \pi \times 2} = \mathbf{963\ Nm}\ (Ans.)$$

Example

The induced emf in a DC machine is 200 V at a speed of 1200 rpm. Calculate the electromagnetic torque developed at an armature current of 15 A.

Solution:

Here, $E_b = 200$ V; $N = 1200$ rpm; $I_a = 15$ A

Now power developed in the armature,

$$\omega T_e = E_b I_a$$

or

$$T_e = \frac{E_b I_a}{\omega} = \frac{E_b I_a}{2\pi N} \times 60 \qquad \left(\because \omega = \frac{2\pi N}{60}\right)$$

$$= \frac{200 \times 15}{2\pi \times 1200} \times 60 = \mathbf{23.87\ Nm}\ (Ans.)$$

Example

A DC motor has 6-poles with lap wound armature. What will be its brake horse power when it draws a current of 340 A and rotates at 400 rpm. The flux per pole is 0.05 Wb and the armature carries 864 turns, Neglect mechanical losses.

Solution:

Here, $P = 6$; $A = P = 6$ (lap wound); $I_L = 340$ A; $N = 400$ rpm,

$$\phi = 0.05 \text{ Wb; No. of turns} = 864$$

$$Z = 864 \times 2 = 1728$$

$$\text{Back emf, } E_b = \frac{\phi Z N P}{60A} = \frac{0.05 \times 1728 \times 400 \times 6}{60 \times 6} = 576 \text{ V}$$

$$\text{Armature current, } I_a = I_L = 340 \text{ A}$$

$$\text{Power developed} = E_b \times I_a = 576 \times 340 = 195840 \text{ W}$$

$$\text{Neglecting losses, brake } HP = \frac{E_b I_a}{735.5} = \frac{195840}{735.5} = \mathbf{266.27} \ (Ans.)$$

VI. Types of DC Motors

On the basis of the connections of armature and their field winding, DC motors can be classified as;

1. **Separately excited DC motors:** The conventional diagram of a separately excited DC motor is shown **Fig. 8**. Its voltage equation will be;

$$E_b = V - I_a \mathrm{R}_a - 2v_b \text{ (where } v_b \text{ is voltage drop per brush)}$$

2. **Self-excited DC motors:** These motors can be further classified as;

   I. **Shunt motors:** Their conventional diagram is shown in **Fig. 9**.

   Important relations:

Shunt field current, $I_{sh} = V/R_{sh}$

Armature current, $I_a = I_L - I_{sh}$

$$E_b = V - I_a\mathrm{R}_a - 2v_b$$

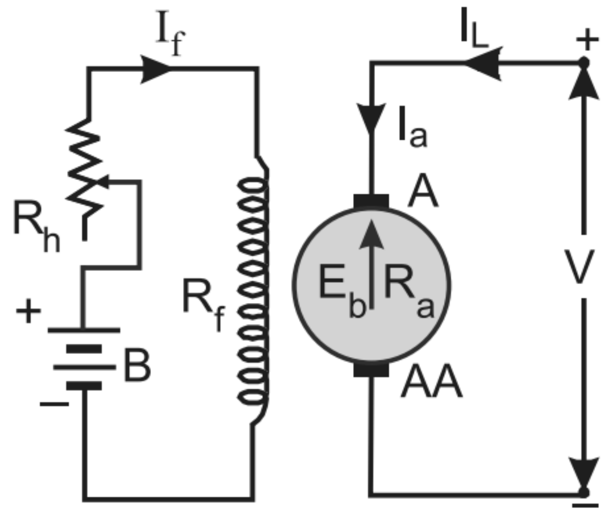


Figure 8. Circuit diagram of separately excited DC motor.

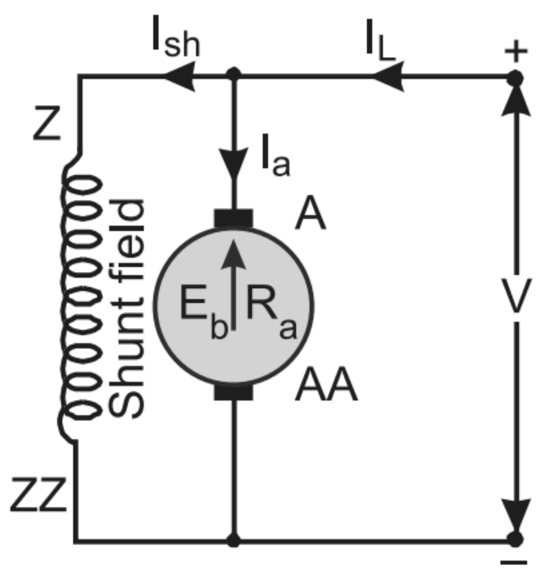


Figure 9. DC shunt motor.

II. **Series motor:** Its conventional diagram is shown in Fig. 10.

Important relations:

$I_{se} = I_L = I_a$

$E_b = V - I_a R_a - 2V_b$

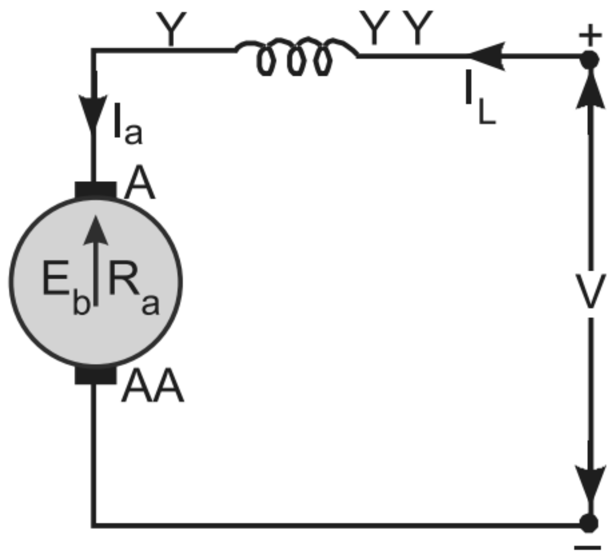


Figure 10. DC series motor.

III. Compound motor: Its conventional diagram (for long shunt) is shown in **Fig. 11(a)**.

$I_{sh} = V/R_{sh}$

$I_a = I_L - I_{sh}$

$E_b = V - I_a R_a - I_{se} R_{se} - 2V_b = \mathrm{V} - I_a(R_a + R_{se}) - 2V_b$

The compound motor can be further subdivided as;

(a) Cumulative compound motors: In these motors, the flux produced by both the windings is in the same direction, i.e.,

$$\phi_r = \phi_{sh} + \phi_{se}.$$

(b) Differential compound motors: In these motors, the flux produced by the series field winding is opposite to the flux produced by the shunt field winding, i.e.,

$$\phi_r = \phi_{sh} - \phi_{se}$$

Example 5.6

A 400 V DC motor takes an armature current of 100 A when its speed is 1000 rpm If the armature resistance is 0·25 ohm, calculate the torque produced in Nm.

Solution:

Here, $V = 400$ V; $I_a = 100$ A; $R_a = 0{\cdot}25\ \Omega$; $N = 1000$ rpm

$$\text{Induced emf, } E = V - I_a R_a \text{ (motor action)}$$

$$= 400 - 100 \times 0{\cdot}25 = 375 \text{ V}$$

Using the relation, $\omega T = EI_a$ or

$$\frac{2\pi NT}{60} = EI_a \qquad \left[\text{Because } \omega = \frac{2\pi N}{60}\right]$$

$$\therefore \quad \text{Torque produced, } T = \frac{60EI_a}{2\pi N} = \frac{60 \times 375 \times 100}{2\pi \times 1000} = \mathbf{358{\cdot}1\ Nm}\ (Ans.)$$

Example

The armature and series field winding resistance of a 220 V, four-pole DC series motor is 0.75 ohm. It has 782 wave wound armature conductors. If it draws 40 A from the supply mains and has a flux of 25 mWb, determine its speed and gross torque developed.

Solution:

Here, $V = 250$ V; $P = 4$; $A = 2$ (wave winding); $Z = 782$;

$$R_a + R_{se} = 0.75\ \Omega;\ I = 40 \text{ A};\ \phi = 25 \times 10^{-3} \text{ Wb}$$

$$E = V - I(R_a + R_{se}) = 250 - 40 \times 0{\cdot}75 = 220 \text{ V}$$

$$E = \frac{\phi ZNP}{60A}$$

or

$$N = \frac{60\,AE}{\phi\,ZP} = \frac{60 \times 2 \times 220}{25 \times 10^{-3} \times 782 \times 4} = \mathbf{337{\cdot}6\ rpm}\ (Ans.)$$

$$T_a = \frac{\phi ZPI_a}{2\pi A} = \frac{25 \times 10^{-3} \times 782 \times 4 \times 40}{2\pi \times 2} = \mathbf{248{\cdot}9\ Nm}\ (Ans.)$$

VII. Characteristics of DC Motors

The performance of a DC motor can be easily judged from its characteristic curves, known as motor characteristics. The characteristics of a motor are those curves which show relation between the two quantities. On the basis of these quantities, the following characteristics can be obtained:

1. Speed and Armature current i.e., $N - I_a$ Characteristics: It is the curve drawn between speed N and armature current I_a. It is also known as speed characteristics.
2. Torque and Armature current i.e., $T–I_a$ Characteristics: It is the curve drawn between torque developed in the armature T and armature current I_a. It is also known as electrical characteristic.
3. Speed and Torque i.e., $N–T$ characteristics: It is the curve drawn between speed N and torque developed in the armature T. It is also known as mechanical characteristics.

The following important relations must be kept in mind while discussing the motor characteristics:

$$E_b \propto N\phi \text{ or } N \propto \frac{E_b}{\phi} \text{ and } T \propto \phi I_a$$

A. Characteristics of Shunt Motors

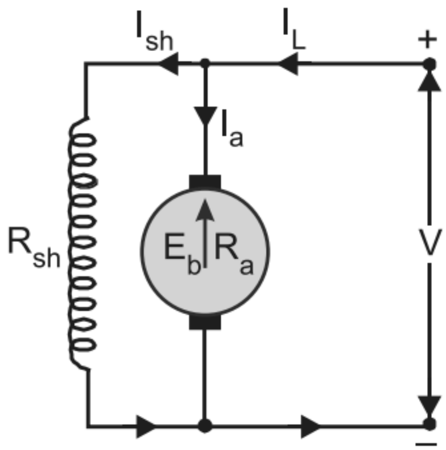
The conventional diagram of this motor is shown in **Fig. 11(a)**. In these motors, the shunt field current $I_{sh} = V/R_{sh}$ remains constant since the supply voltage V is constant. Hence, the flux in DC shunt motors is practically constant (although at heavy loads, somewhat flux decreases due to armature reaction).

i. $N - I_a$ characteristics

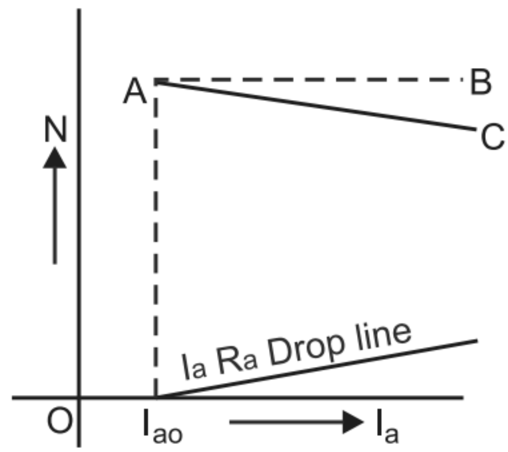
We know that, $N \propto \frac{E_b}{\phi}$

Since flux is constant; $E_b \propto N$

If the armature drop ($I_a R_a$) is negligible, the speed of the motor will remain constant for all values of load as shown by the dotted line AB in **Fig. 11(b)**. But strictly speaking, as the armature current increases due to the increase of load, armature drop $I_a R_a$ increases and speed of the motor decreases slightly as shown by the straight-line AC in **Fig. 11(b)** (neglecting armature reaction). Moreover, the characteristic curve does not start from a point of zero armature current because a small current, no-load armature current I_{a0}, is necessary to maintain rotation of the motor at no-load. Since there is no appreciable change in the speed of a DC shunt motor from no-load to full load that is why it is considered to be a constant speed motor. This motor is best suited where almost constant speed is required and the load may be thrown off totally and suddenly.



(a)



(b)

Figure 11. (a) Circuit for shunt motor (b) N-I_a characteristics of shunt motor.

ii. $T - I_a$ Characteristics

We know that, $T \propto \phi I_a$

Since flux is constant, $T \propto I_a$

Hence, the electrical characteristic (i.e., T – Ia) is a straight line passing through the origin as shown in **Fig. 12**. It is clear from the characteristic curve that a large armature current is required at the start if machine is on heavy load. Thus, shunt motor should never be started on load.

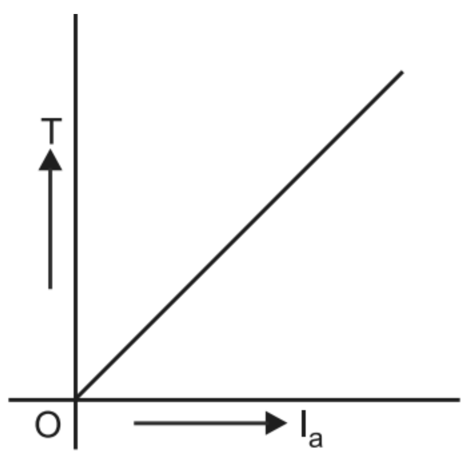


Figure 12. T–I_a characteristics of shunt motor.

LECTURE 4

iii. N – T Characteristics

The N – T characteristic is derived from the first two characteristics. When load torque increases, armature current I_a increases but speed decreases slightly. Thus, with the increase in load or torque, the speed decreases slightly as shown in **Fig. 13**.

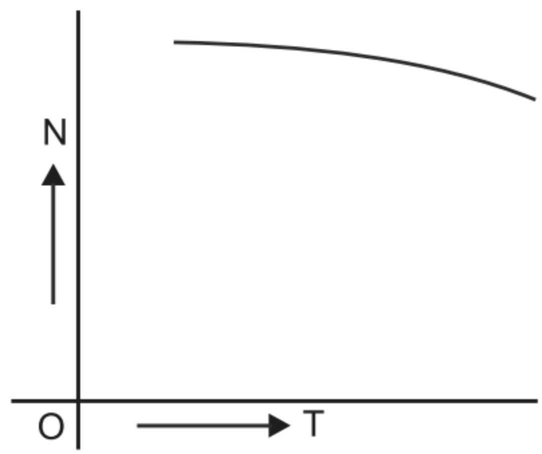


Figure 13. *N-T* characteristics of shunt motor.

B. Characteristics of Series Motors

The conventional diagram of a series motor is shown in **Fig. 14(a)**. In these motors, the series field winding carries the armature current. Therefore, the flux produced by the series field winding is proportional to the armature current before magnetic saturation, but after magnetic saturation flux becomes constant.

i. N – I_a Characteristics

We know that, $$N \propto \frac{E_b}{\phi}$$

where, $$E_b = \mathrm{V} - I_a(R_a + R_{se})$$

When armature current increases, the induced emf (back emf) Eb decreases, due to $I_a(R_a + R_{se})$ drop whereas flux ϕ increases $\phi \propto I_a$ as before magnetic saturation. However, under normal conditions $I_a(R_a + R_{se})$ drop is quite small and may be neglected. Considering E_b to be constant,

$$N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$$

Thus, before magnetic saturation, the $N - I_a$ curve follows the hyperbolic path as shown in **Fig. 14(b)**.

In this region, the speed decreases abruptly with the increase in load or armature current. After magnetic saturation, flux becomes constant, then

$$N \propto E_b \propto V - I_a(R_a + R_{se})$$

Thus, after magnetic saturation, the $N - I_a$ curve follows a straight-line path and speed decreases slightly as shown in **Fig. 14(b)**.

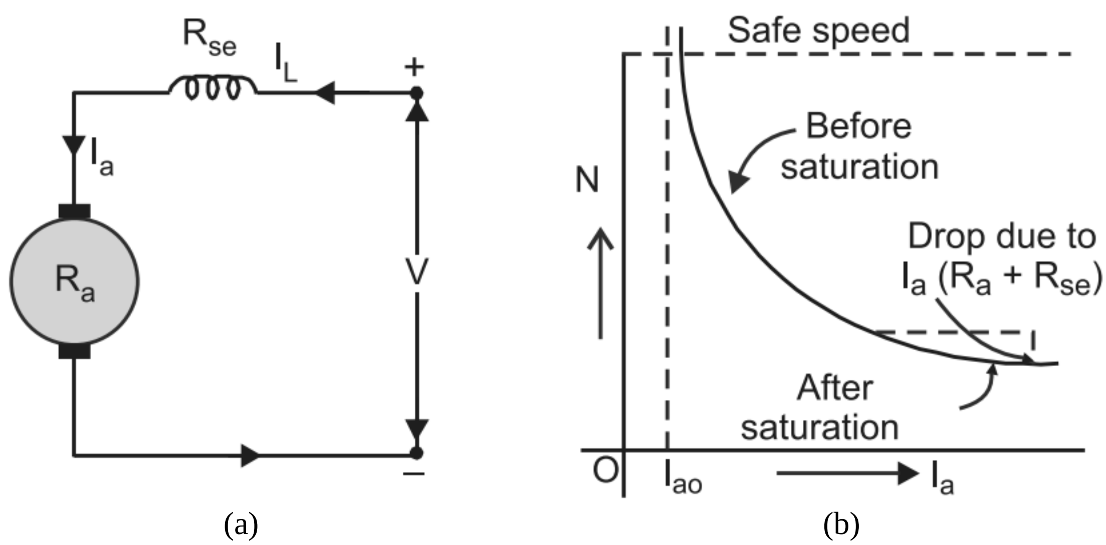


Figure 14. (a) Circuit diagram of series motor (b) N-I_a characteristics of DC series motor.

From this characteristic, it is concluded that the series motor is a variable speed motor, i.e., its speed changes when the armature current (or load) changes. As the load on this motor decreases, speed increases. If this motor is connected to the supply without load, armature current will be very small and hence speed will be dangerously high which may damage the motor due to heavy centrifugal forces.

Therefore, a series motor is never started on no-load. However, to start a series motor, mechanical load (not belt driven load because belt slips over the pulley) is put on it first then started.

ii. *$T - I_a$ Characteristics*

We know that, $T \propto \phi I_a$

In series motors, before magnetic saturation $\phi \propto I_a$

Hence, before magnetic saturation the electromagnetic torque produced in the armature is proportional to the square of the armature current. Therefore, this portion of the curve (OA) is a parabola passing through the origin as shown in **Fig. 15**.

However, after magnetic saturation, the flux ϕ becomes constant.

$\therefore\ T \propto I_a$

Hence, after magnetic saturation, the curve (AB) becomes a straight line.

It is seen that before magnetic saturation $T \propto I_a^2$. When load is applied to this motor at start, it takes large current and heavy torque is produced which is proportional to square of this current. Thus, this motor is capable to pick up heavy loads at the start and best suited for electric traction.

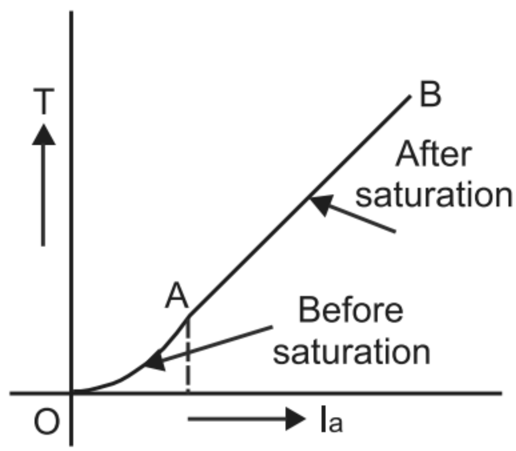


Figure 15. T-I_a characteristics of DC series motor.

iii. N – T Characteristics

This characteristic is derived from the first two characteristics. At low value of load, I_a is small, torque is small but the speed is very high. As load increases, I_a increases, torque increases but the speed decreases rapidly. Thus for increasing torque, speed decreases rapidly as shown in **Fig. 16**.

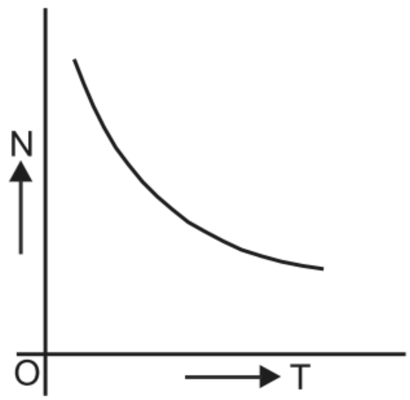


Figure 16. *N-T* characteristics of DC series motor.

VIII. Starting of DC Motors

To start a DC motor, when it is switched–ON to the supply with full rated voltage, it draws heavy current during starting period (more than its rated value). This excessive current overheats the armature winding and may even damage the winding insulation. Therefore, during the starting period a resistance called starter in connected in series with the armature circuit to limit the starting current.

- **Necessity of Starter for a DC Motor**

Under normal operating conditions, the voltage equation for a motor is given as

$$E_b = \mathrm{V} - I_a(R_a)$$

The armature current is given by the relation;

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

When the motor is at rest, the induced emf E_b in the armature is zero ($E_b \propto N$). Consequently, if full voltage is applied across the motor terminals, the armature will draw heavy current ($I_a = V/R_a$) because armature resistance is relatively small. This heavy starting current has the following effects :

i) It will blow out the fuses and prior to that it may damage the insulation of armature winding due to excessive heating effect if starting period is more.

ii) Excessive voltage drop will occur in the lines to which the motor is connected. Thus, the operation of the appliances connected to the same line may be impaired and in some cases they may refuse to work.

To avoid this heavy current at start, a variable resistance is connected in series with the armature, as shown in **Fig. 17**, called a starting resistance or starter, and thus the armature current is limited to safe value $\left(I_a = \frac{V}{R_a+R}\right)$. Once the motor picks up speed, emf is built up and current is reduced $\left(I_a = \frac{V-E_{b1}}{R_a+R}\right)$. After that the starting resistance is gradually reduced. Ultimately, the whole of the resistance is taken out of circuit when the motor attains normal speed.

Another important feature of a starter is that it contains protective devices such as overload protection coil (or relay) which provides necessary protection to the motor against over loading and no-volt release coil.

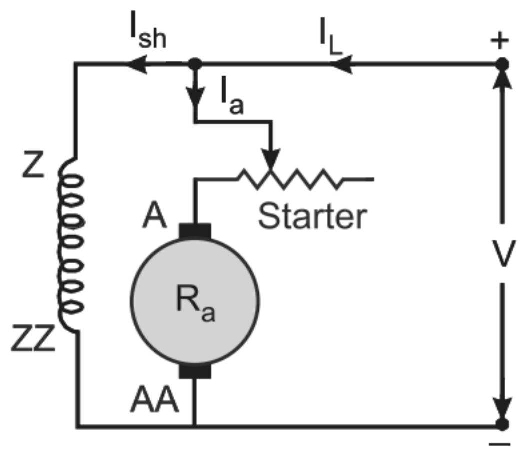
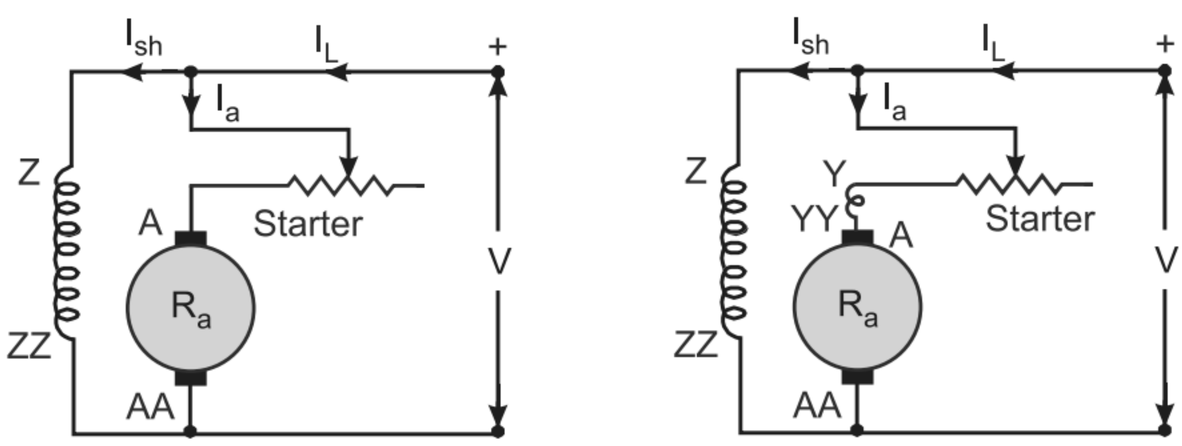


Figure 17. DC shunt motor starter.

A. Starters for DC Shunt and Compound Wound Motors

The basic function of a starter is to limit the current in the armature circuit during starting or accelerating period. Starters are always rated on the basis of output power and voltage of the motor with which they are to be employed, e.g., 10 HP, 250 V shunt motor starter). A simplest type of starter is just a variable resistance (a rheostat) connected in series with the armature alone (not with the motor as a whole) as shown in **Figs. 18(a) and (b)**.



(a) (b)

Figure 18. DC Shunt and Compound motor starter.

It may be noted that shunt field is kept independent of starting resistance. It is because when supply is connected, it receives normal rated voltage and sets up maximum (rated) flux. A higher value of flux results in a low operating speed and a higher motor torque for a particular value of starting current since speed is inversely proportion to flux per pole $(N \propto \frac{1}{\phi})$ whereas motor torque is proportional to product of flux per pole and armature current $(T \propto \phi\ I_a)$. Hence, for a given load torque, the motor will accelerate quickly and reduces the starting period. Thus, the heating effect to armature winding is reduced.

For all practical application, this starter is further modified which includes protective devices such as over-load release and no-volt release. The over-load release protects the motor against overloading i.e., when the motor is over-loaded (or short circuited) this relay brings the plunger to its OFF position. On the other hand, the no-volt release brings the plunger to its OFF position so that the motor may not start again without starter. For shunt and compound motors there are two standard types of starters named as (a) three-point starter and (b) four-point starter.

- Three-point Shunt Motor Starter

The schematic connection diagram of a shunt motor starter is shown in **Fig. 19**. It consists of starting resistance *R* divided into several sections. The tapping points of starting resistance are connected to number of studs. The last stud of the starting resistance is connected to terminal *A* to which one terminal of the armature is connected. The + ve supply line is connected to the line terminal *L* through main switch. From line terminal, supply is connected to the starting lever *SL* through overload release coil *OLRC*. A spring *S* is placed over the lever to bring it to the off position when supply goes off. A soft iron piece *SI* is attached with the starting lever which is pulled by the no volt release coil under normal running condition. The far end of the brass strip *BS* is connected to the terminal *Z* through a no volt release coil *NVRC*. One end of the shunt field winding in connected to *Z* terminal of the starter. An iron piece is lifted by *OLRC* under abnormal condition to short circuit the no-volt release coil. The negative supply line is connected directly to the other ends of shunt field winding and armature of the DC shunt motor.

- *Operation*

  First of all the main switch is closed with starting lever resting in off position. The handle is then turned clockwise to the first stud and brass strip. As soon as it comes in contact with first stud, whole of the starting resistance *R* is inserted in series with the armature and the field winding is directly connected across the supply through brass strip. As the handle is turned further the starting resistance is cut out of the armature circuit in steps and finally entire starting resistance is cut out of armature circuit.

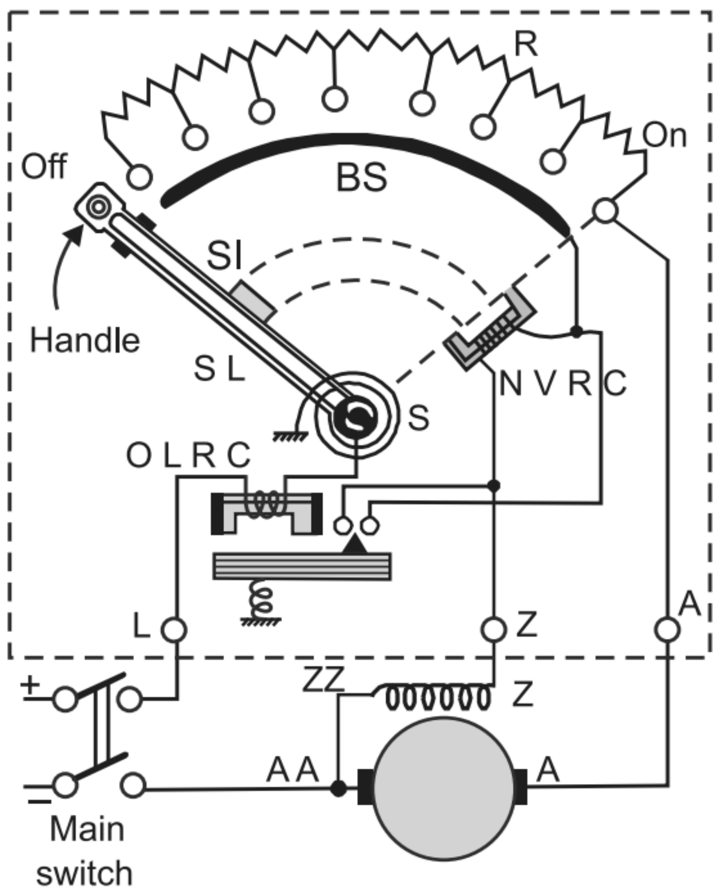


Figure 19. Three-point shunt motor starter.

❖ *No-volt Release Coil and its Function*

A no-volt release coil is a small electromagnet having many turns of fine wire. It is connected in series with shunt field winding and therefore, carries a small field current. When the handle is turned to on position, the no-volt release coil is magnetized by the field current and holds the starting lever at on position. In case of failure or disconnection of the supply, this coil is demagnetized, and the lever comes to the off position due to spring tension. Consequently. The motor is disconnected from the supply. If the spring with the no-volt release coil is not used the lever would remain in ON-position in case of supply failure. And again, when the supply comes, the motor would be connected directly to the lines without starter.

The other important advantage of connecting the no-volt release coil in series with the shunt field winding is that due to an accident if the circuit of field winding becomes open, the NVRC will be demagnetized, and the starting lever is immediately pulled back to off position by the spring. Otherwise, the motor would have attained dangerously high speed.

❖ *Over-load Release Coil and its Function*

An overload release coil is an electromagnet having small number of turns of thick wire. It is connected in series with the motor and carries the line current. When the motor is overloaded (or short circuited), a heavy current more than predetermined value will flow through it. Then, the iron piece (armature or plunger) is lifted and short circuits the no-volt release coil. Hence the starting lever is released and pulled back to the off position due to spring tension. Thus, the motor is disconnected from the supply and is protected against overloading.

Calculation of Step Resistances Used in Shunt Motor Starter

For starting a motor from stand still to its rated speed, it is normally desirable to increase the speed gradually to maintain the angular acceleration constant during the starting period. The angular acceleration is proportional to the net torque, which is in turn nearly proportional to the product of flux (ϕ) and armature current I_a i.e., T ∝ ϕ I_a. The flux ϕ will remain constant provided line voltage remains constant. Hence it follows that substantially constant angular acceleration calls for constant armature current during starting period.

We know, Speed, $N \propto \frac{E_b}{\phi} \propto \frac{V-I_aR}{\phi}$

where R = resistance of armature plus the resistance of starter.

Since I_a and ϕ are to be kept constant, therefore, for increasing the speed (N) gradually, R should be varied (reduced) in such a way that the above relation must be satisfied. For different values of armature current, the value of R is given by the expression,

$$R = \frac{V - KN}{I_a} \qquad \text{where } K \text{ is a constant}$$

Note the Steps: $N \propto \frac{V - I_aR}{\phi}$ or $\phi N \propto V - I_aR$

or $KN = V - I_aR$ or $R = \frac{V - KN}{I_a}$

In starters, usually the value of R is changed in steps and, therefore, armature current will change in two extreme values. Accordingly, the steps of the starter are designed in such a way that armature current varies in between these limits so that torque may not change to a greater degree.

The fuse or MCB placed in the motor circuit is usually not larger than 150% of the motor full load current.

LECTURE 4

Let I_1 and I_2 be the maximum and minimum value of the current drawn by the motor during starting. Let the starter has n-sections each having a resistance as r_1, r_2, r_3...r_n as shown in **Fig. 20**. Let the total resistance of armature circuit when the starting arm is kept at stud No. 1, 2, 3, … n and n + 1 be R_1, R_2, R_3, …R_n and R_{n+1} (where $R_{n+1} = R_a$), respectively.

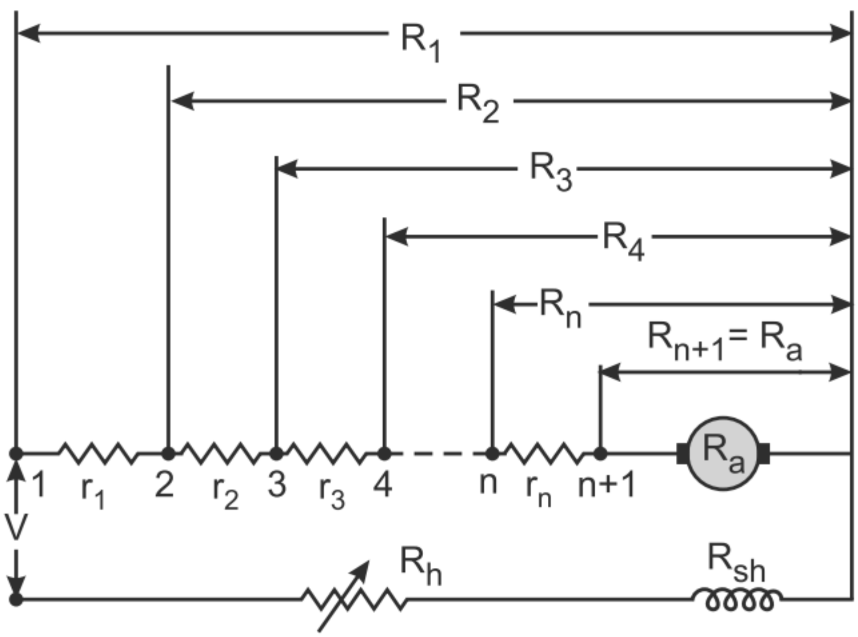


Figure 20. Design of shunt motor starter.

Just at the time of starting when the starting arm is brought in contact with stud-1, the motor is stationary and there is no back emf, the maximum value of current drawn by the motor,

$$I_1 = \frac{V}{R_1} \tag{1}$$

The motor starts rotating and picks up speed N_1 which develops a back emf E_{b1} (where $E_{b1} \propto N_1$) and the current drops to I_2 (the starting arm is still at stud-1), therefore,

$$I_2 = \frac{V - E_{b1}}{R_1} \tag{2}$$

Now the starting arm is shifted to stud-2, the speed of the motor is still N_1 and the back emf is also E_{b1} but the circuit resistance is reduced to R_2 due to this the current again attains its maximum value I_1, i.e.,

$$I_1 = \frac{V - E_{b1}}{R_2} \tag{3}$$

The motor picks-up speed further and its value reaches to N_2 which develops a back emf E_{b2} ($E_{b2} \propto N_2$) and the current drops to I_2 (the starting arm is still at stud-2), therefore,

$$I_2 = \frac{V - E_{b2}}{R_2} \tag{4}$$

Further, starting arm is shifted to stud-3, the speed is still N_2 and back emf is E_{b2} but the circuit resistance is reduced to R_3, thus the current again attains its maximum value I_1, i.e.,

$$I_1 = \frac{V - E_{b2}}{R_3} \tag{5}$$

Dividing eqn. (3) by (2) and eqn. (5) by (4), we get,

$$\frac{I_1}{I_2} = \frac{V - E_{b1}}{R_2} \times \frac{R_1}{V - E_{b1}} = \frac{V - E_{b2}}{R_3} \times \frac{R_2}{V - E_{b2}}$$

$$or \quad \frac{I_1}{I_2} = \frac{R_1}{R_2} = \frac{R_2}{R_3} = K \text{ (say)} \tag{6}$$

$$and \quad \frac{R_1}{R_2} \times \frac{R_2}{R_3} = K^2 \text{ or } \frac{R_1}{R_3} = K^2$$

Similarly, the starting arm is shifted to next studs in sequence and ultimately reaches to stud number (n + 1), then we get,

$$\frac{R_1}{R_2} = \frac{R_2}{R_3} = \frac{R_3}{R_4} = \cdots = \frac{R_{n-1}}{R_n} = \frac{R_n}{R_a} = K$$

$$\text{and } \frac{R_1}{R_2} \times \frac{R_2}{R_3} \times \frac{R_3}{R_4} \times \ldots \times \frac{R_{n-1}}{R_n} \times \frac{R_n}{R_a} = K^n \tag{7}$$

$$\text{or } \frac{R_1}{R_a} = K^n \text{ or } K = \left(\frac{R_1}{R_a}\right)^{\frac{1}{n}}$$

If the values of armature resistance R_a, limiting currents I_1 (max. value) and I_2 (min. value) are known, the value of R_1 and K can be determined from eqn. (1) and (6) respectively. At the same time, the number of section (n) can be determined by using eqn. (7).

By knowing the value of R_1 and K, one can determine the values of R_2, R_3, R_4, … R_n and then the value of resistance of each step can be determined. i.e., $r_1 = R_1 – R_2$; $r_2 = R_2 – R_3$; $r_3 = R_3 – R_2$; …; $r_n = R_n – R$

LECTURE 4

Example

A 152 V DC shunt motor has an armature resistance of 0.3 Ω, a brush voltage drop of 2 V, the rated full load current is 70 A. Calculate (i) the current at the instant of starting as a percentage of full load current (ii) the value of starting resistance to limit the motor current at the instant of starting to 150 percent of the rated load current.

Solution:

Here, $V = 152$ V; $R_a = 0.3\ \Omega$; $I_{fl} = 70$ A

(*i*) Starting current with no-additional resistance in the armature circuit,

$$I_S = \frac{V - \text{brush contact drop}}{R_a} = \frac{152 - 2}{0.3} = 500\ \text{A}$$

$$I_S \text{ as a \%age of full-load} = \frac{I_S}{I_{fl}} \times 100 = \frac{500}{70} \times 100 = 714.3$$

Let the total resistance required in the armature circuit to limit the starting current to 150 per cent of the rated load current be R_1, then

$$R_1 = \frac{V - \text{brush contact drop}}{1.5 \times I_{fl}} = \frac{152 - 2}{1.5 \times 70} = 1.43\ \text{ohm}$$

(*ii*) Additional resistance required for starting

$$R = R_1 - R_a = 1.43 - 0.3 = \mathbf{1.31}\ \Omega\ (Ans.)$$

Example

A 230 V shunt motor has an armature resistance of 0.4 Ω. The starting armature current must not exceed 45 A. If the number of sections are 5, calculate the values of resistance steps to be used in the starter.

Solution:

Number of sections of the starter, $n = 5$

Resistance of armature circuit at the starting instant

$$R_1 = \frac{V}{I_{max}} = \frac{230}{45} = 5.11\ \Omega$$

Ratio of maximum to minimum current during starting,

$$\frac{I_{max}}{I_{min}} = K = \left(\frac{R_1}{R_a}\right)^{1/n} = \left(\frac{5.11}{0.4}\right)^{1/5} = 1.6645$$

Resistance, $R_2 = \frac{R_1}{K} = \frac{5.11}{1.6645} = 3.07\ \Omega$; Resistance, $R_3 = \frac{R_2}{K} = \frac{3.07}{1.6645} = 1.844\ \Omega$

Resistance, $R_4 = \frac{R_3}{4} = \frac{1.84}{1.6645} = 1.108\ \Omega$; Resistance, $R_5 = \frac{R_4}{K} = \frac{1.108}{1.6645} = 0.666\ \Omega$

Resistance of 1st to 5th section

$$r_1 = R_1 - R_2 = 5.11 - 3.07 = \mathbf{2.04}\ \Omega\ (Ans.)$$

$$r_2 = R_2 - R_3 = 3.07 - 1.844 = \mathbf{1.226}\ \Omega\ (Ans.)$$

$$r_3 = R_3 - R_4 = 1.844 - 1.108 = \mathbf{0.736}\ \Omega\ (Ans.)$$

$$r_4 = R_4 - R_5 = 1.108 - 0.666 = \mathbf{0.442}\ \Omega\ (Ans.)$$

$$r_5 = R_5 - R_a = 0.666 - 0.4 = \mathbf{0.266}\ \Omega\ (Ans.)$$

LECTURE 4

Example

Find the value of the step resistance in a 6-stud starter for a 5 h.p. (3.73 kW), 200-V shunt motor. The maximum current in the line is limited to twice the full-load value. The total Cu loss is 50% of the total loss. The normal field current is 0.6 A and the full-load efficiency is found to be 88%.

Solution:

$$\text{Output} = 3730 \text{ W}$$

$$\text{Input} = \frac{\text{Output}}{\eta} = \frac{3730}{88} \times 100 = 4238 \text{ W}$$

$$\text{Total loss} = 4238 - 3730 = 508 \text{ W}$$

$$\text{Armature Cu loss} = \frac{508}{2} = 254 \text{ W}$$

$$\text{Input current} = \frac{\text{Input}}{V} = \frac{4238}{200} = 21.19 \text{ A}$$

$$\text{Armature current, } I_a = I_L - I_{sh} = 21.19 - 0.6 = 20.59 \text{ A}$$

Now $\quad (20.59)^2 R_a = 254$

$\therefore \quad R_a = \dfrac{254}{(20.59)^2} = 0.5989\ \Omega$

Permissible input current = $21.19 \times 2 = 42.38$ A

Permissible armature current = $42.38 - 0.6 = 41.78$ A

$\therefore \quad R_1 = \dfrac{200}{41.78} = 4.787\ \Omega;\ n = 5;\ \dfrac{R_1}{R_a} = K^5$

$\therefore \quad 4.787 = K^5 \times 0.5989$

$\therefore \quad K^5 = 4.787/0.5989 = 7.993$

or $\quad 5 \log K = \log 7.993 = 0.9027$

$\therefore \quad \log K = 0.1805;\ K = 1.516$

Now $\quad R_2 = \dfrac{R_1}{K} = \dfrac{4.789}{1.516} = 3.159\ \Omega$; $\quad R_3 = \dfrac{R_2}{K} = \dfrac{3.159}{1.516} = 2.084\ \Omega$

$R_4 = \dfrac{R_3}{K} = \dfrac{2.084}{1.516} = 1.376\ \Omega$; $\quad R_5 = \dfrac{R_4}{K} = \dfrac{1.376}{1.516} = 0.908\ \Omega$

Resistance in 1st step – $R_1 - R_2 = 4.787 - 3.159 =$ **1.628 Ω.** *(Ans.)*

Resistance in 2nd step – $R_2 - R_3 = 3.159 - 2.084 =$ **0.075 Ω.** *(Ans.)*

Resistance in 3rd step – $R_3 - R_4 = 2.084 - 1.376 =$ **0.708 Ω.** *(Ans.)*

Resistance in 4th step – $R_4 - R_5 = 1.376 - 0.908 =$ **0.468 Ω.** *(Ans.)*

Resistance in 5th step – $R_5 - R_a = 0.908 - 0.5989 =$ **0.309 Ω.** *(Ans.)*

B. Series Motor Starter

A series motor starter is also called a two-point starter. Its internal and external connections are shown in Fig. 21.

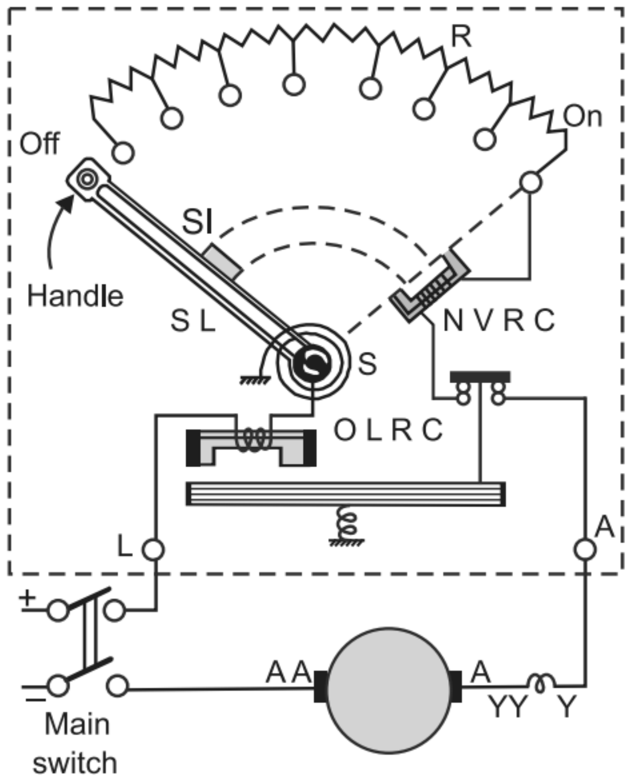


Figure 21. Two-point series motor starter.

Here, for starting the motor, the control arm or plunger is moved in clockwise direction from its OFF position to ON position against the spring tension. In the beginning, all the sections of the starting resistance are connected in series with the armature to limit the current to predetermined value. As the starting arm moves, various steps of the starting resistance are cut out of circuit and ultimately whole of the starting resistance is cut-out and the control arm is held in the ON position by an electromagnet. The hold-on (no-volt release) coil is connected in series with the armature circuit. If the motor loses its load, current drawn by the motor decreases which decreases the strength of the hold-on coil. Immediately the arm goes back to the OFF position due to strong spring tension; thus preventing the motor from over-speed. The control arm or plunger also goes back to the OFF position when supply goes OFF or when the supply voltage decreases appreciably. L and Y are the two points of the starter through which supply line terminal and the motor (series field) terminal is connected.

For stopping the motor, the line switch should always be opened rather than bringing the control arm back to its OFF position. If it is done a heavy sparking occurs at the last stud placed near the OFF position. This sparking occurs due to dissipation of energy stored in the magnetic field of series field winding.

Example

A 240 V series motor takes 40 A when giving its rated output at 1500 rpm. Its armature and series field resistance is 0.18 Ω and 0.12 Ω respectively. Find the external resistance which must be added to obtain rated torque (i) at starting and (ii) at 1000 rpm.

Solution:

Since torque remains the same in both the cases, the current drawn by the motor remains constant at 40 A, because $T \propto \Phi I$.

We know, current drawn by the motor, $I = \dfrac{V - E_b}{R_a + R_{se} + R}$

where R is external resistance connected in series with motor at start

$$\therefore \quad 40 = \frac{240 - 0}{0.18 + 0.12 + R} \qquad \text{(since at start } E_b = 0\text{)}$$

$$\text{or} \quad R = \frac{240}{40} - 0.3 = \mathbf{5.7}\ \Omega\ (Ans.)$$

$$\text{Back emf, } E_{b_1} = V - I\,(R_a + R_{se}) = 240 - 40 \times (0.18 + 0.12) = 228 \text{ V}$$

$$\text{Back emf, } E_{b_2} = E_{b_1} \times \frac{N_2}{N_1} = 228 \times \frac{1000}{1500} = 152 \text{ V}$$

$$\because \quad I = \frac{V - E_b}{R_a + R_{se} + R},\ 40 = \frac{240 - 152}{0.18 + 0.12 + R}$$

$$\text{or} \quad R = \frac{88}{40} - 0.3 = \mathbf{1.9}\ \Omega\ (Ans.)$$

LECTURE 4

IX. Applications of DC Motors

As per the characteristics of DC motors, different types of DC motors are applied for different jobs as explained below:

1. **Separately excited motors**: Very accurate speeds can be obtained by these motors. Moreover, these motors are best suited where speed variation is required from very low value to high value. These motors are used in steel rolling mills, paper mills, diesel – electric propulsion of ships, etc.

2. **Shunt motors:** From the characteristics of a shunt motor we have seen that it is almost constant speed motor. It is, therefore, used;

(i) Where the speed between no-load to full load has to be maintained almost constant.

(ii) Where it is required to drive the load at various speeds (various speeds are obtained by speed control methods) and any one of the speed is required to be maintained almost constant for a relatively long period.

As such the shunt motors are most suitable for industrial drives such as lathes, drills, grinders, shapers, spinning and weaving machines, line shafts in the group drive, etc.

3. **Series motors:** The characteristics of a series motor reveal that it is variable speed motor i.e., the speed is low at higher torques and vice-versa. Moreover, at light loads or at no-load, the motor attains dangerously high speed. It is, therefore, employed:

(i) Where high torque is required at the time of starting to accelerate heavy loads quickly.

(ii) Where the load is subjected to heavy fluctuations and speed is required to be adjusted automatically.

As such the series motors are most suitable for electric traction, cranes, elevators, vacuum cleaners, hair driers, sewing machines, fans and air compressors, etc.

4. **Compound motors:** The important characteristic of this motor is that the speed falls appreciably on heavy loads as in a series motor, but at light loads, the maximum speed is limited to safe value. It is, therefore, used;

(i) Where high torque is required at the time of starting and where the load may be thrown off suddenly.

(ii) Where the load is subjected to heavy fluctuations.

As such the cumulative compound, motors are best suited for punching and shearing machines, rolling mills, lifts and mine - hoists, etc.