UNIVERSITY OF DIYALA

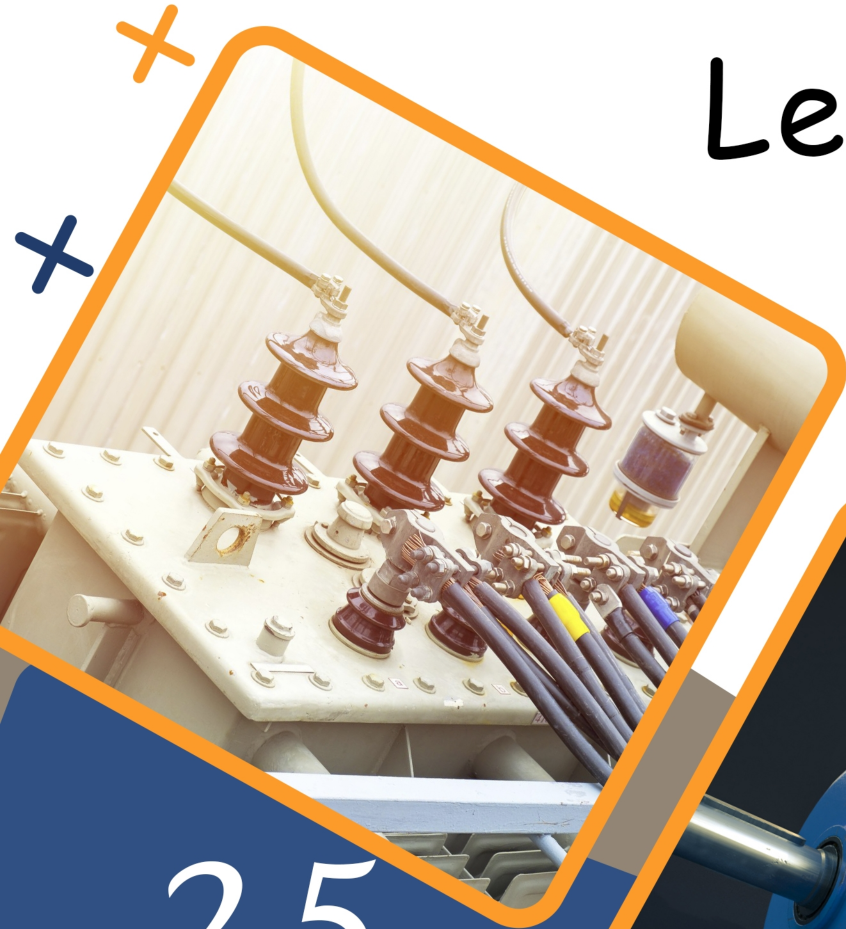
COLLEGE OF ENGINEERING

DEPARTMENT OF THE ELECTRICAL POWER AND MACHINES ENGINEERING

Second Stage

ELECTRICAL MACHINES

Lecture: 4



Lecturer
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D.C. MOTOR

Introduction:

A motor is a device which converts an electrical energy into the mechanical energy. The energy conversion process is exactly opposite to that involved in a D.C. generator. In a generator the input mechanical energy is supplied by a prime mover while in a D.C. motor, input electrical energy is supplied by a D.C. supply. The construction of a D.C. machine is same whether it is a motor or a generator.

Principle of Operation of a D.C. Motor:

The principle of operation of a D.C. motor can be stated in a single statement as *"when a current carrying conductor is placed in a magnetic field; it experiences a mechanical force"*. In a practical D.C. motor, field winding produces a required magnetic field while armature conductors play a role of a current carrying conductors and hence armature conductors experience a force. As conductors are placed in the slots which are on the periphery, the individual force experienced by the conductors acts as a twisting or turning force on the armature which is called a *torque*. The torque is the product of force and the radius at which this force acts. So overall armature experiences a torque and starts rotating.

Consider a single conductor placed in a magnetic field, it is clear that on one side of the conductor, both the fluxes are in the same direction. In this case, on the left of the conductor there is gathering of the flux lines as two fluxes help each other. As against this, on the right of the conductor, the two fluxes are in opposite direction and hence try to cancel each other. Due to this, the density of the flux lines in this area gets weakened. So on the left, there exists high flux density area while on the right of the conductor there exists low flux density area as shown in the Figure (1).

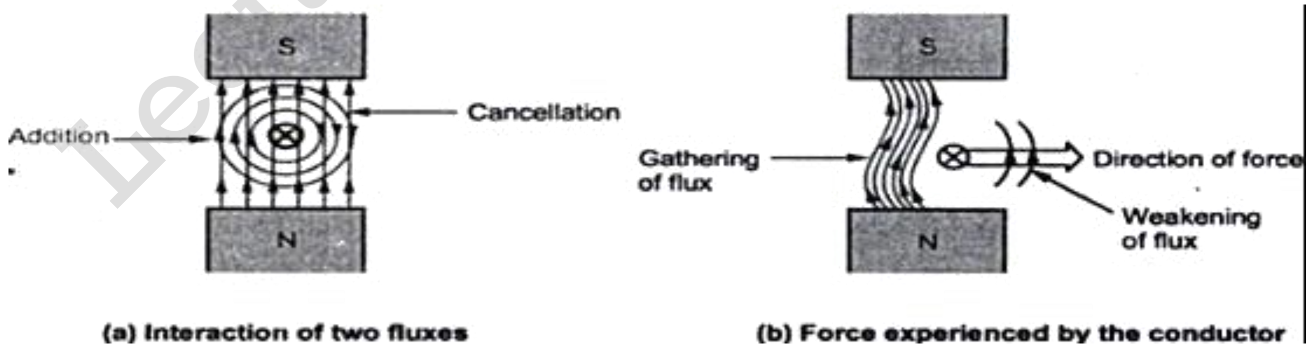


Figure (1)

This flux distribution around the conductor acts like a stretched rubber band under tension. This exerts a mechanical force on the conductor which acts from high flux.

density area towards low flux density area, $i.e.$ from left to right for the case considered as shown in the Figure (1-b).

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

Direction of Rotation of Motor:

The magnitude of the force experienced by the conductor in a motor is given by,

$F = B\, l\, I$ Newton (N)

Where:

B = Flux density due to the flux produced by the field winding.
l = Active length of the conductor.
I = Magnitude of the current passing through the conductor.

The direction of such force $i.e.$ the direction of rotation of a motor can be determined by *Fleming's left hand rule*. So *Fleming's right hand rule* is to determine direction of induced e.m.f. $i.e.$ for generating action while *Fleming's left hand rule* is to determine direction of force experienced $i.e.$ for motoring action.

Fleming's Left Hand Rule:

States that, 'Outstretch the three fingers of the left hand namely the first finger, middle finger and thumb such that they are mutually perpendicular to each other. Now point the first finger in the direction of magnetic field and the middle finger in the direction of the current then the thumb gives the direction of the force experienced by the conductor.

The Fleming's left hand rule can be diagrammatically shown as in the Figure (2).

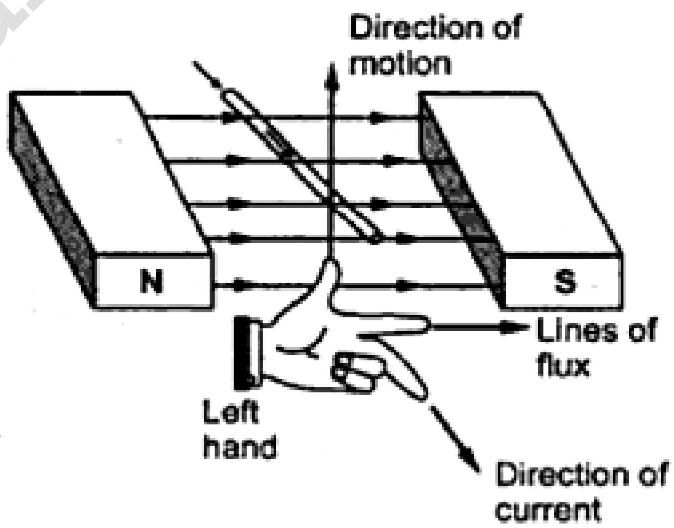


Figure (2): Fleming's left hand rule

It can be seen from the Figure (3) that if the direction of the main field in which current carrying conductor is placed, is reversed, force experienced by the conductor reverses it's direction. Similarly keeping main flux direction unchanged, the direction of current passing through the conductor is reversed, the force experienced by the conductor reverses it's direction. However if both the directions are reversed, the direction of the force experienced remains the same.

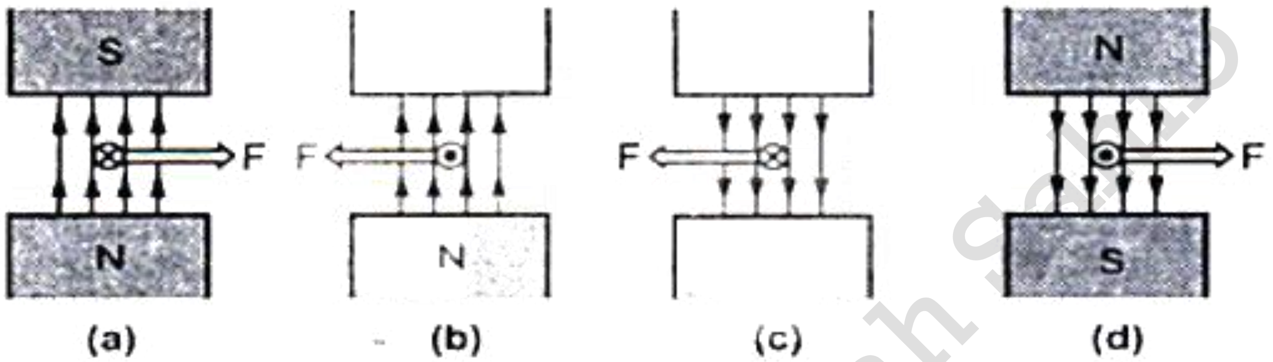


Figure (3): Direction of force experienced by conductor

Note: So in a practical motor, to reverse its direction of rotation, either direction of main field produced by the field winding is reversed or direction of the current passing through the armature is reversed.
Note: The direction of the main field can be reversed by changing the direction of current passing through the field winding, which is possible by interchanging the polarities of supply which is given to the field winding.

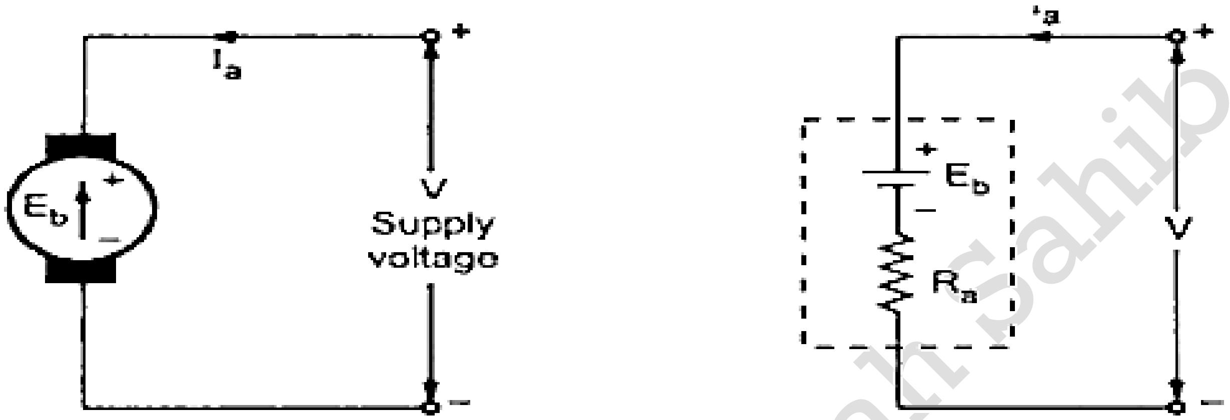
Significance of Back E.M.F.:

It is seen in the generating action, that when a conductor cuts the lines of flux, e.m.f. gets induced in the conductor.

- The question is obvious that in a D.C. motor, after a motoring action, armature starts rotating and armature conductors cut the main flux. So is there a generating action existing in a motor?
- The answer to this question is Yes.

After a motoring action, there exists a generating action. There is an induced e.m.f. in the rotating armature conductors according to *Faraday's law of electromagnetic induction*. This induced e.m.f. in the armature always acts in the opposite direction of the supply voltage. This is according to the *Lenz's law* which states that the direction of the induced e.m.f. is always so as to oppose the cause producing it. In a D.C. motor, electrical input *i.e.* the supply voltage is the cause and hence this induced e.m.f. opposes the supply voltage. This e.m.f. tries to set up a current through the armature which is in the opposite direction to that, which supply voltage is forcing through the conductor. So as this e.m.f. always opposes the supply voltage, it is called *back e.m.f.* and denoted as E_b, its magnitude can be determined by the e.m.f. equation. So,

$$E_b = \frac{\Phi Z N}{60}\frac{P}{A} \quad \text{volt}$$



(a) Back e.m.f. in a D.C. motor (b) Equivalent circuit

Figure (4)

This e.m.f. is shown schematically in the Figure (4-a). So if V is supply voltage in volts and R_a is the value of the armature resistance, the equivalent electric circuit can be shown as in the Figure (4-b).

Note: the back e.m.f. is always less than supply voltage ($E_b < V$).

Types of D.C. Motors:

Similar to the D.C. generators, the D.C. motors are classified depending upon the way of connecting the field winding with the armature winding. The different types of D.C. motors are:

(a) Permanent magnet D.C. motor

(b) Electromagnet D.C. motor

 (1) Separately-excited D.C. motor

 (2) Self-excited D.C. motor (shunt, series and compound motors)

(a) Permanent-Magnet D.C. Motor:

The permanent-magnet D.C. motor shown in Figure (5), is construct in the same manner as D.C. generator.

When this type of motor is used, the D.C. power supply is connected directly to the armature conductors through the brush to commutator assembly. The magnetic field is produced by permanent magnets mounted on the stator (yoke).

The permanent-magnet motor has several advantages over conventional types of D.C. motors. The advantage is a reduced operational *cost*, and The *direction* of *rotation* of a permanent magnet motor can be *reversed* by reversing the source polarities. The speed of the permanent-magnet motor are similar to those of the shunt wound D.C. motor.

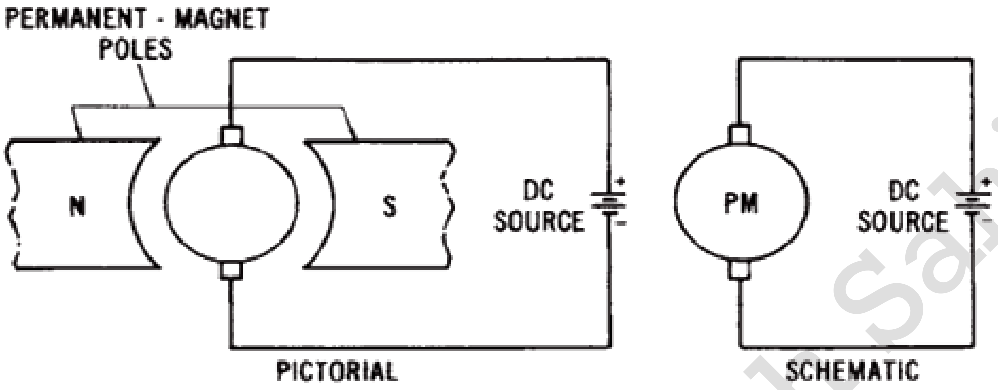


Figure (5)

(b) Self Excited D.C. Motor-Magnet D.C. Motor:

(*i*) D.C. Shunt Motor:

The field winding is connected across the armature winding and the combination is connected across the supply, as shown in the Figure (6). The shunt field winding has more number of turns with less cross-sectional area.

$$I_L = I_a + I_{sh}$$

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

$$V = E_b + I_a R_a + V_{brush}$$

Note: As long as supply voltage is constant, the flux produced is constant. Hence D.C. shunt motor is called constant flux motor. So flux produced by the field winding is proportional to the current passing through it $i.e.\ I_{sh}$.

$$\Phi \propto I_{sh}$$

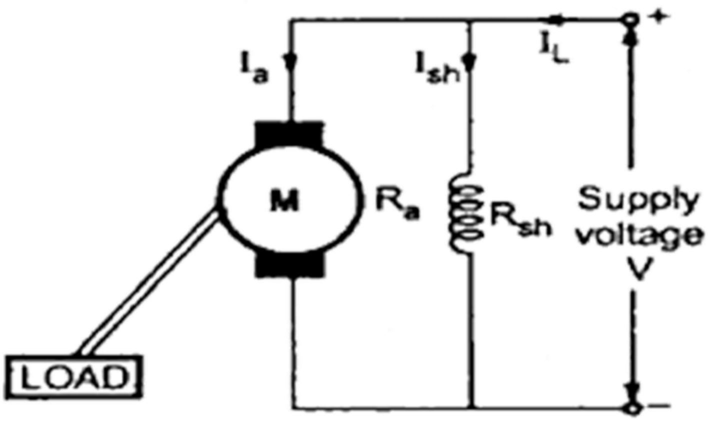


Figure (6): Shunt motor

(*ii*) D.C. Series Motor:

In this type of motor, the series field winding is connected in series with the armature and the supply, as shown in the Figure (7). The value of series field winding resistance is very small and it is made of small number of turns having; laree cross-sectional area.

$$I_L = I_a = I_{se}$$
$$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$$
$$V = E_b + I_a (R_a + R_{se}) + V_{brush}$$

Note: In series motor, entire armature current is passing through the series field winding. So flux produced is proportional to the armature current.

$$\Phi \propto I_{se} \propto I_a \quad \text{(for series motor)}$$

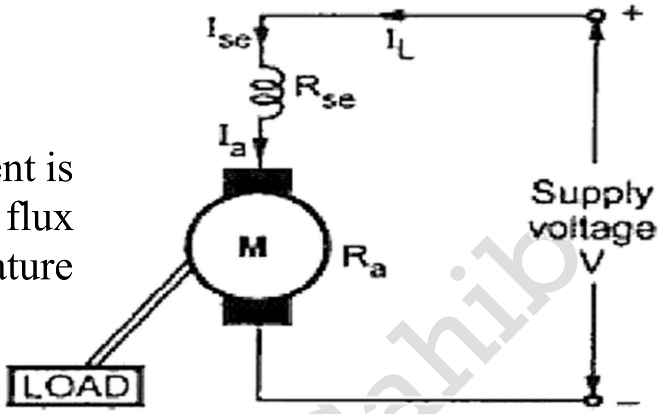


Figure (7): Series motor

(*iii*) D.C. Compound Motor:

The compound motor consists of series and shunt field windings. It is classified as long and short shunt compound motor. And its types are

A. Long Shunt Compound Motor
B. Short Shunt Compound Motor

(a) Long Shunt Compound Motor:

In this type, the shunt field winding is connected across the combination of armature and the series field winding as shown in Figure (8).

$$I_L = I_{sh} + I_{se}$$
$$I_a = I_{se}$$
$$I_{sh} = \frac{V}{R_{sh}}$$
$$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$$
$$V = E_b + I_a (R_a + R_{se}) + V_{brush}$$

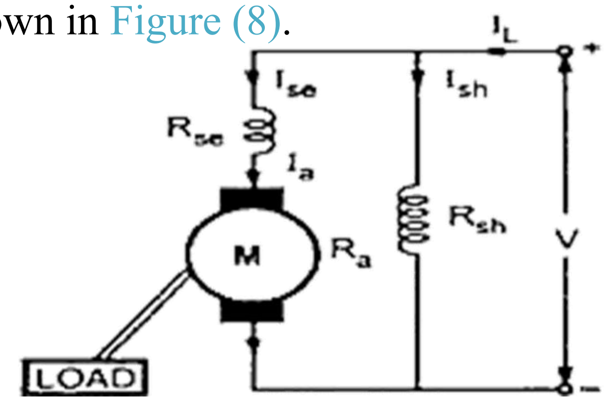


Figure (8): Long shunt compound motor

(b) Short Shunt Compound Motor:

In this type, shunt field winding is connected in parallel with armature winding & series field is connected in series with this combination, as shown in Figure (9).

$I_L = I_{se}$
$I_L = I_a + I_{sh}$
$I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}$
$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$

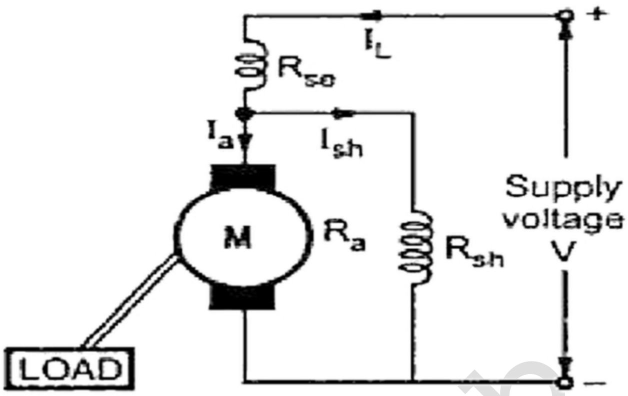


Figure (9): Short shunt compound motor

Note: If the two field windings are wound in such a manner that the fluxes produced by the two always help each other, the motor is called *cumulatively compound*. If the fluxes produced by the two field windings are trying to cancel each other (they are in opposite direction), the motor is called *differential compound*.

Note: A long shunt compound motor can be of cumulative or differential type. Similarly short shunt compound motor can be cumulative or differential type.

Power Equation of a D.C. Shunt Motor:

The voltage equation of a D.C. motor is given by, $V = E_b + I_a R_a$
Multiplying both sides of the above equation by I_a we get $VI_a = E_b I_a + I_a^2 R_a$
This equation is called power equation of a D.C. motor.
VI_a = Net electrical power input to the armature measured in watts (W).
$I_a^2 R_a$ = Power loss due to the resistance of the armature called armature copper loss.
$E_b I_a$ = is called electrical equivalent of gross mechanical power (P_m) developed by the armature.

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

Condition for Maximum Power for Shunt Motor:

For a motor from power equation it is known that,
P_m = Gross mechanical power developed $= E_b I_a = VI - I_a^2 R_a$
For maximum P_m, $\frac{dP_m}{dI_a} = 0$

$\therefore \quad 0 = V - 2I_a R_a$

$$I_a = \frac{V}{2R_a} \quad i.e \quad I_a R_a = \frac{V}{2}$$

Substituting in voltage equation,

$V = E_b + I_a R_a \quad \Rightarrow\Rightarrow \quad V = E_b + (V/2)$

$E_b = V/2$ … Condition for maximum power

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

Example 1: A 220V D.C. machine has an armature resistance of 0.5Ω. If the full-load armature current is 20A, find the induced e.m.f. when the machine acts as (*i*) generator (*ii*) motor.

Solution:

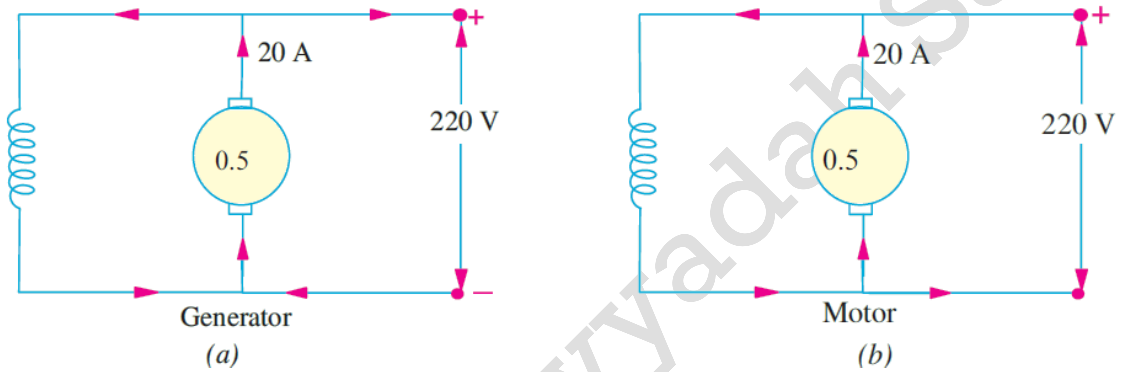


Figure (10)

As shown in Figure (10), the D.C. machine is assumed to be shunt-connected. In each case, shunt current is considered negligible because its value is not given.

(*i*) As Generator Figure (10-a) $E_g = V + I_a R_a = 220 + (0.5 \times 20) = 230\text{V}$

(*ii*) As Motor Figure (10-b) $E_b = V - I_a R_a = 220 - (0.5 \times 20) = 210\text{V}$

Example 2: A 440V, shunt motor has armature resistance of 0.8Ω and field resistance of 200Ω. Determine the back e.m.f. when giving an output of 7.46kW at 85 percent efficiency.

Solution: $\eta = \dfrac{P_{\text{output}}}{P_{\text{input}}}$

∴ Motor input power $P_{\text{input}} = \dfrac{7.46 \times 10^3}{0.85} \cong 8{,}776.5\text{W}$

$P_{\text{input}} = I_L V$

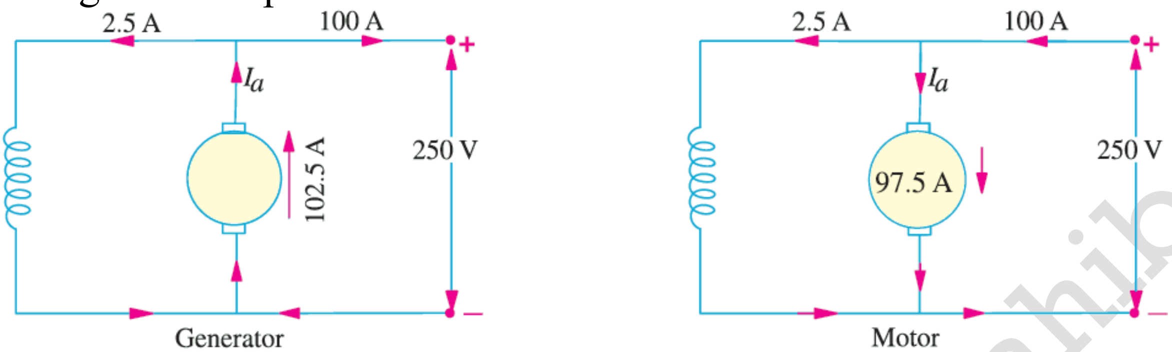
∴ Motor input current $I_L = \dfrac{8{,}776.5}{440} \cong 19.95\text{A}$

$I_{sh} = \dfrac{440}{200} = 2.2\text{A}$

$I_a = I_L - I_{sh} = 19.95 - 2.2 = 17.75\text{A}$

Now, $E_b = V - I_a R_a = 440 - (17.75 \times 0.8) = 425.8\text{V}$

Example 3: A 25kW, 250V, D.C. shunt generator has armature and field resistances of 0.06Ω and 100Ω respectively. Determine the total armature power developed when working (*i*) as a generator delivering 25kW output and (*ii*) as a motor taking 25kW input.



(a) Figure (11) (b)

Solution:

As Generator Figure (11-a): $P_{out} = 25\text{kW}$; $P_{out} = I_L V$

Output current, $I_L = \frac{25{,}000}{250} = 100\text{A}$; $I_{sh} = \frac{250}{100} = 2.5\text{A}$; $I_a = I_L + I_{sh} = 102.5\text{A}$

Generated e.m.f., $E_g = V + I_a R_a = 250 + (102.5 \times 0.06) = 256.15\text{V}$

Power developed in armature $= E_b I_a = \frac{256.15 \times 102.5}{1{,}000} \cong 26.26\text{kW}$

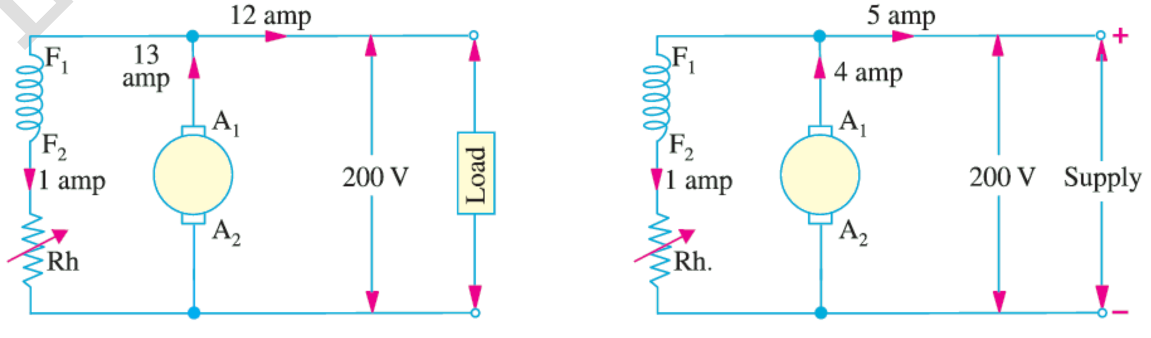
As Motor Figure (11-b): $P_{input} = 25\text{kW}$; $P_{input} = I_L V$

Motor input current, $I_L = 100\text{A}$; $I_{sh} = 2.5\text{A}$; $I_a = I_L - I_{sh} = 97.5\text{A}$

$$E_b = V - I_a R_a = 250 - (97.5 \times 0.06) = 250 - 5.85 = 244.15\text{V}$$

Power developed in armature $= E_b I_a = \frac{244.15 \times 97.5}{1{,}000} = 23.8\text{kW}$

Example 4: A 4 pole, 32 conductor, lap-wound D.C. shunt generator with terminal voltage of 200V delivering 12A to the load has $R_a = 2$ and field circuit resistance of 200Ω. It is driven at 1,000 $r.p.m.$ Calculate the flux per pole in the machine. If the machine has to be run as a motor with the same terminal voltage and drawing 5A from the mains, maintaining the same magnetic field, find the speed of the machine.



(*a*) Generator-action (*b*) Motor-action

Figure (12)

Solution:

As Generator Figure (12-a): $I_{sh} = V/R_{sh} = \frac{200}{200} = 1\text{A}$; $I_L = 12\text{A}$

$$I_a = I_L + I_{sh} = 12 + 1 = 13\text{A}$$

$$E_g = V + I_a R_a = 200 + (13 \times 2) = 226\text{V}$$

$$E_g = \frac{\Phi Z N}{60}\frac{P}{A} \Rightarrow\Rightarrow 226 = \frac{\Phi \times 32 \times 1{,}000}{60}\frac{4}{4} \Rightarrow \Phi = 0.42375\text{Wb}$$

As Motor Figure (12-b): $I_{sh} = V/R_{sh} = \frac{200}{200} = 1\text{A}$; $I_L = 5\text{A}$

$$I_a = I_L - I_{sh} = 5 - 1 = 4\text{A}$$

$$E_b = V - I_a R_a = 200 - (4 \times 2) = 192\text{V}$$

$$E_b = \frac{\Phi Z N}{60}\frac{P}{A} \Rightarrow\Rightarrow 192 = \frac{0.42375 \times 32 \times N}{60}\frac{4}{4} \Rightarrow\Rightarrow N \cong 850\, r.p.m.$$