Md. Tariqul Islam, Lecturer, Dept. of EEE, Green University of Bangladesh
Contact Number: 01782463503, Emailing Address: tariqul@eee.green.edu.bd

Chapter Four
DC Motor

Learning Outcomes:

After the ending of the lesson, students will be able to know about

- The operating principle of a dc motor.
- Back emf and its significance.
- Needs of a starter circuit
- Speed control procedure of a dc motor

WORKING PRINCIPLE OF A DC MOTOR

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

Fleming Left Hand Rule

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

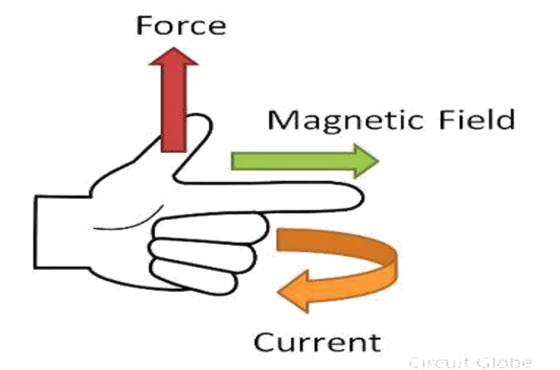

Fig: Flemings left hand rule

The formula calculates the magnitude of the force,

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

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

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

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

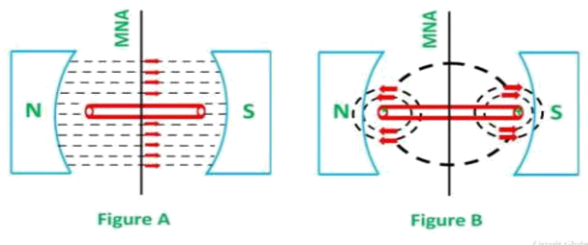

Fig: magnetic field induces around the coil.

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

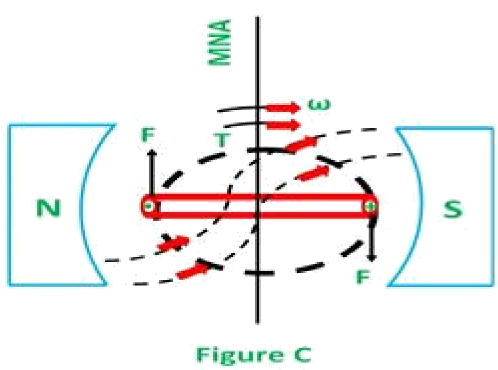

Fig: Field produced due to poles alone

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

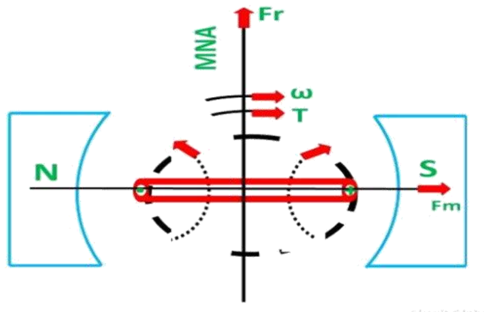

Fig: Field produced due to conductors alone

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

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

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

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

Back Emf and its Significance in DC Motor

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

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

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

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

where, P=number of poles of dc motor

Φ= flux per pole

Z=total number of armature conductors

N=armature speed

A=number of parallel paths in armature winding

As all other parameters are constant, therefore,

$E_b \propto N$

Significance of back emf in dc motor

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

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

Mechanical power developed in the armature = EbIa

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

From the motor figure,

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

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

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

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

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

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

Power Equation of a D.C. Motor

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

$$V = E_b + I_a R_a$$

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

$$V I_a = E_b I_a + I_a^2 R_a$$

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

Need of Starters for DC Motors

The dc motor has no back EMF. At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor. Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine is cut out of the circuit when the machine gains it speeds. The armature current of a motor is given by

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

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

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

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

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

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

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

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

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

Speed Control of a DC motor

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

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

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

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

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

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

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

Md. Tariqul Islam, Lecturer, Dept. of EEE, Green University of Bangladesh
Contact Number: 01782463503, Emailing Address: tariqul@eee.green.edu.bd

Armature Resistance Control of DC Motor

Shunt Motor

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

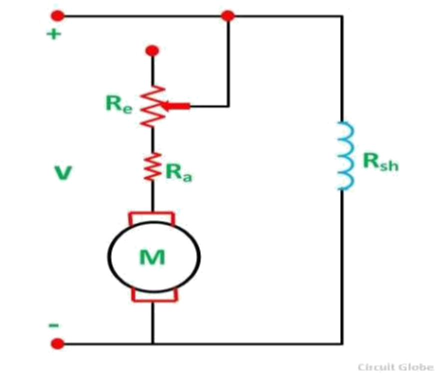

Fig: Connection diagram of a shunt motor of the armature resistance control method

The **speed current characteristic** of the shunt motor is shown below.

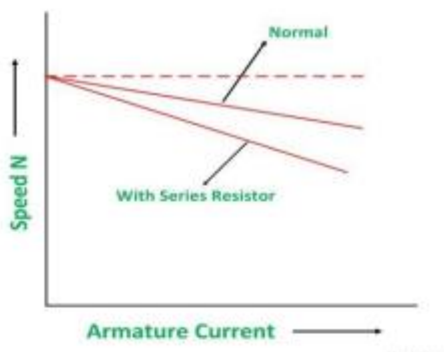

Fig: Speed current characteristic of the shunt motor

Series Motor:

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

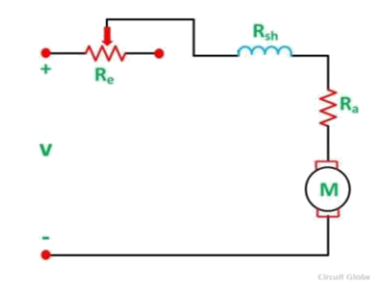

Fig: Diagram of speed control of the DC Series motor

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

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

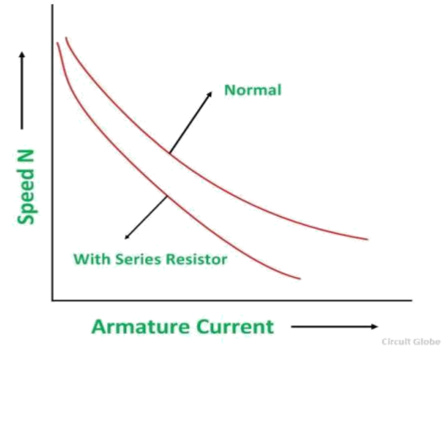

Fig: Speed–current characteristic of a series motor

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

Disadvantages of Armature Resistance Control Method

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

Field Flux Control Method of DC Motor

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

Shunt Motor

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

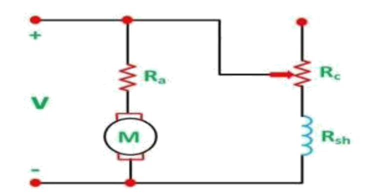

Fig: Shunt Field Regulator

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

Md. Tariqul Islam, Lecturer, Dept. of EEE, Green University of Bangladesh
Contact Number: 01782463503, Emailing Address: tariqul@eee.green.edu.bd

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

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

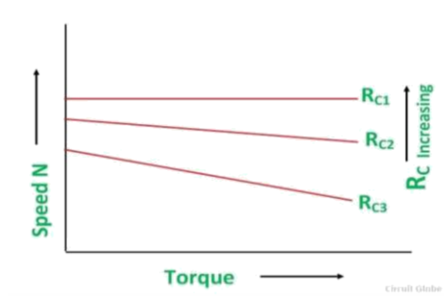

Fig: speed-torque curve for shunt motor

30.14. Thyristor Speed Control of Separately-excited D.C. Motor

In Fig. 30.32, the bridge rectifier converts a voltage into d.c. voltage which is then applied to the armature of the separately-excited d.c. motor *M*.

As we know, speed of a motor is given by

$$N = \frac{V - I_a R_a}{\Phi}\left(\frac{A}{ZP}\right)$$

If Φ is kept constant and also if $I_a R_a$ is neglected, then, $N \propto V \propto$ voltage across the armature. The value of this voltage furnished by the rectifier can be changed by varying the firing angle α of the thyristor *T* with the help of its contol circuit. As α is increased *i.e.*, thyristor firing is delayed

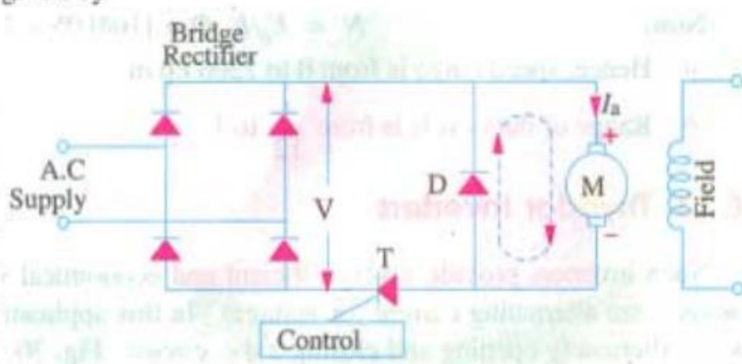

Fig. 30.32

more, its conduction period is reduced and, hence, armature voltage is decreased which, in turn, decreases the motor speed. When α is decreased *i.e.*, thyristor is fired earlier, conduction period is increased which increases the mean value of the voltage applied across the motor armature. Consequently, motor speed is increased. In short, as α increases, *V* decreases and hence *N* decreases. Conversely, as α decreases, *V* increases and so, *N* increases. The free-wheeling diode *D* connected across the motor provides a circulating current path (shown dotted) for the energy stored in the inductance of the armature winding at the time *T* turns OFF. Without *D*, current will flow through *T* and bridge rectifier, prohibiting *T* from turning OFF.

Math Problems

Example 29.1. *A 220-V d.c. machine has an armature resistance of 0.5 Ω. If the full-load armature current is 20 A, find the induced e.m.f. when the machine acts as (i) generator (ii) motor.*

(Electrical Technology-I, Bombay Univ. 1987)

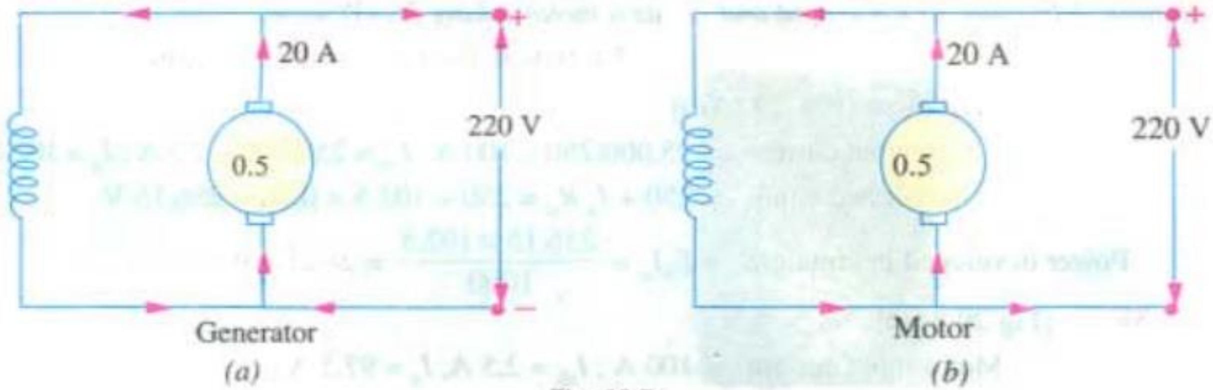

Fig. 29.7

Solution. As shown in Fig. 29.7, the d.c. machine is assumed to be shunt-connected. In each case, shunt current is considered negligible because its value is not given.

(*a*) As Generator [Fig. 29.7(*a*)] $E_g = V + I_a R_a = 220 + 0.5 \times 20 =$ **230 V**

(*b*) As Motor [Fig 29.7 (*b*)] $E_b = V - I_a R_a = 220 - 0.5 \times 20 =$ **210 V**

Example 29.2. *A separately excited D.C. generator has armature circuit resistance of 0.1 ohm and the total brush-drop is 2 V. When running at 1000 r.p.m., it delivers a current of 100 A at 250 V to a load of constant resistance. If the generator speed drop to 700 r.p.m., with field-current unaltered, find the current delivered to load.* **(AMIE, Electrical Machines, 2001)**

Solution. $R_L = 250/100 = 2.5$ ohms.

$E_{g1} = 250 + (100 \times 0.1) + 2 = 262$ V.

At 700 r.p.m., $E_{g2} = 262 \times 700/1000 = 183.4$ V

If I_a is the new current, $E_{g2} - 2 - (I_a \times 0.1) = 2.5\, I_a$

This gives $I_a = 96.77$ amp.

Extension to the Question : *With what load resistance will the current be 100 amp, at 700 r.p.m.?*

Solution. $E_{g2} - 2 - (I_a \times 0.1) = R_L \times I_a$

For $I_a = 100$ amp, and $E_{g2} = 183.4$ V, $R_L = 1.714$ ohms.

OBE Based Questions (for practice)

Q.1. Suppose Mr. Zahid is working on a DC motor in his laboratory. He is supposed to use the starter circuit while starting the motor. But he skipped it and found out that the motor got damaged. What might be the reason behind it?

Answer to the Question No. 01

- The current passing through the armature circuit is Ia=(V-E)/Ra. Where, V=supply voltage, E= Back emf, and Ra = armature resistance.
- At starting, there is no Back emf (E) in the circuit.
- Since, the armature resistance is very small, the armature current will be very high due to this zero back emf in the circuit.
- Because of this high current, the motor will be overheated and burn.

Q. 2. Suppose you are working on a dc motor in your laboratory. At the start of the motor, you are using a starter circuit, and when the motor is geared up to the full speed, then the starter is removed from the circuit. After a while, you observe that the field circuit of a motor is open-circuited. What may happen under this condition? How can you solve this problem?

Answer to the Question No. 02

- We know that the speed of motor control

$$Ea = k\emptyset S$$

$$\text{Hence, } S = (Ea)/K\emptyset \qquad (1)$$

Here, Ø=magnitude flux, Ea=back emf and S=speed

- If the field circuit is open under the running condition, the flux will be zero.
- As a result, the motor will rotate at infinite speed that may damage the motor.
- Practically, it will damage the windings of the motor and also probably crush the shaft if the fuse doesn't blow out soon enough.

Q.3. In a laboratory, Bubli was observing the speed of a dc motor. At that time, this dc motor was rotating at 750 rpm. But she wanted to increase the motor speed up to 1000 rpm. What do you think, which method (armature control or field control) would be appropriate in this situation and why? Show proper logic in support of your answer.

Try It Yourself