Theory

Introduction of DC Motor:

The principle of conversion of electrical energy into mechanical energy by electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821 and consisted of a free-hanging wire dipping into a pool of mercury. A permanent magnet was placed in the middle of the pool of mercury. When a current was passed through the wire, the wire rotated around the magnet, showing that the current gave rise to a circular magnetic field around the wire. This motor is often demonstrated in school physics classes, but brine (salt water) is sometimes used in place of the toxic mercury. A later refinement is the Barlow's Wheel. These were demonstration devices, unsuited to practical applications due to limited power.

Figure 1

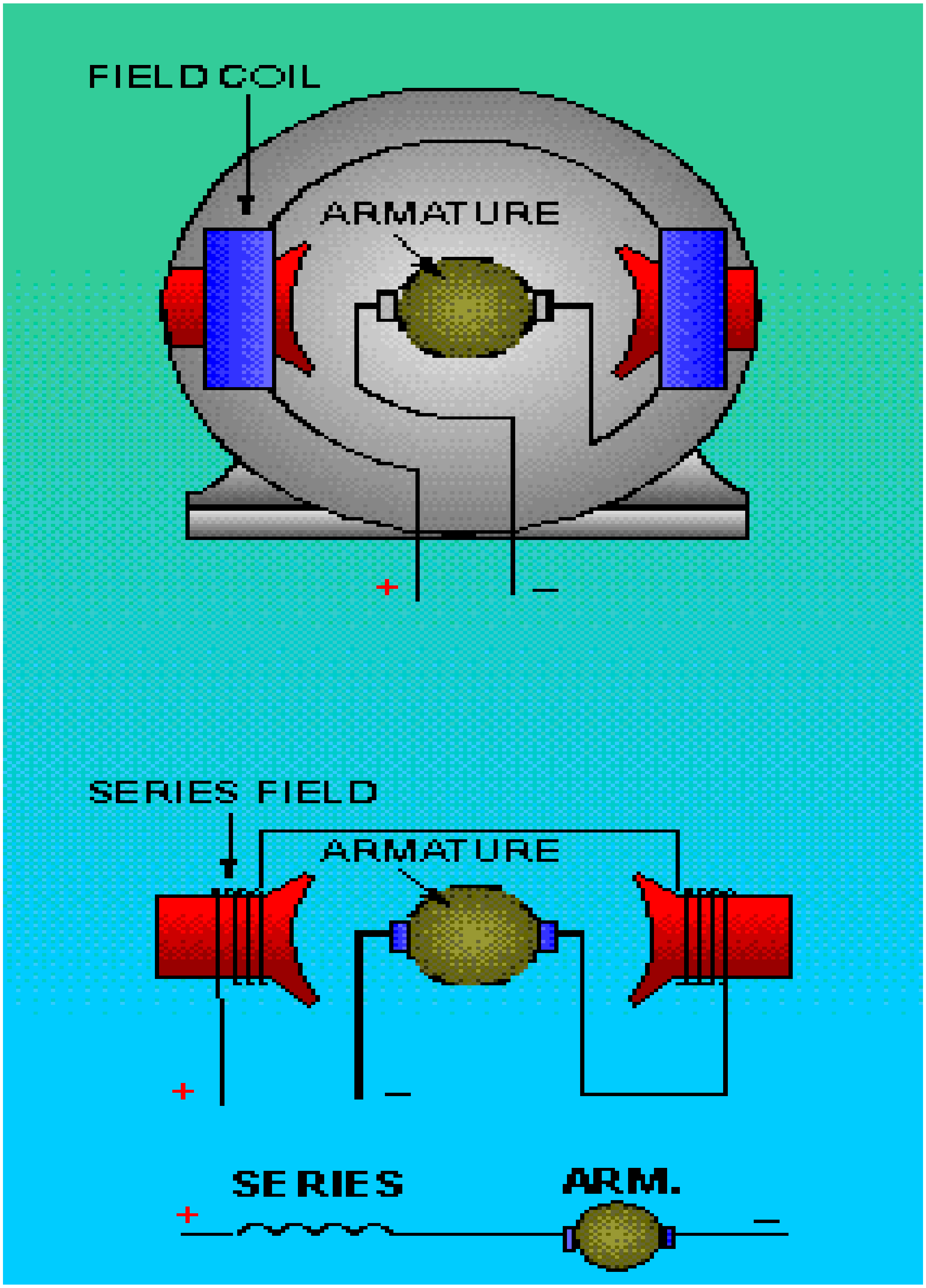


Figure 2

The first real electric motor, which using electromagnets for both stationary and rotating parts was demonstrated by Ányos Jedlik in 1828 Hungary, who later developed a motor powerful enough to propel a vehicle. The principle of conversion of electrical energy into mechanical energy by electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821 and consisted of a free-hanging wire dipping into a pool of mercury. A permanent magnet was placed in the middle of the pool of mercury. When a current was passed through the wire, the wire rotated around the magnet, showing that the current gave rise to a circular magnetic field around the wire. The DC motor is very useful where wide range of speed and good speed regulation is required such as electric traction.

DC Machine:

The direct current (DC) motor is one of the first machines to convert electrical power into mechanical power. Permanent magnet (PM) direct current convert electrical energy into mechanical energy through the interaction of two magnetic fields. One field is produced by a permanent magnet assembly; the other field is produced by an electrical current flowing in the motor windings. These two fields result in a torque which tends to rotate the rotor. As the rotor turns, the current in the windings is commutated to produce a continuous torque output.

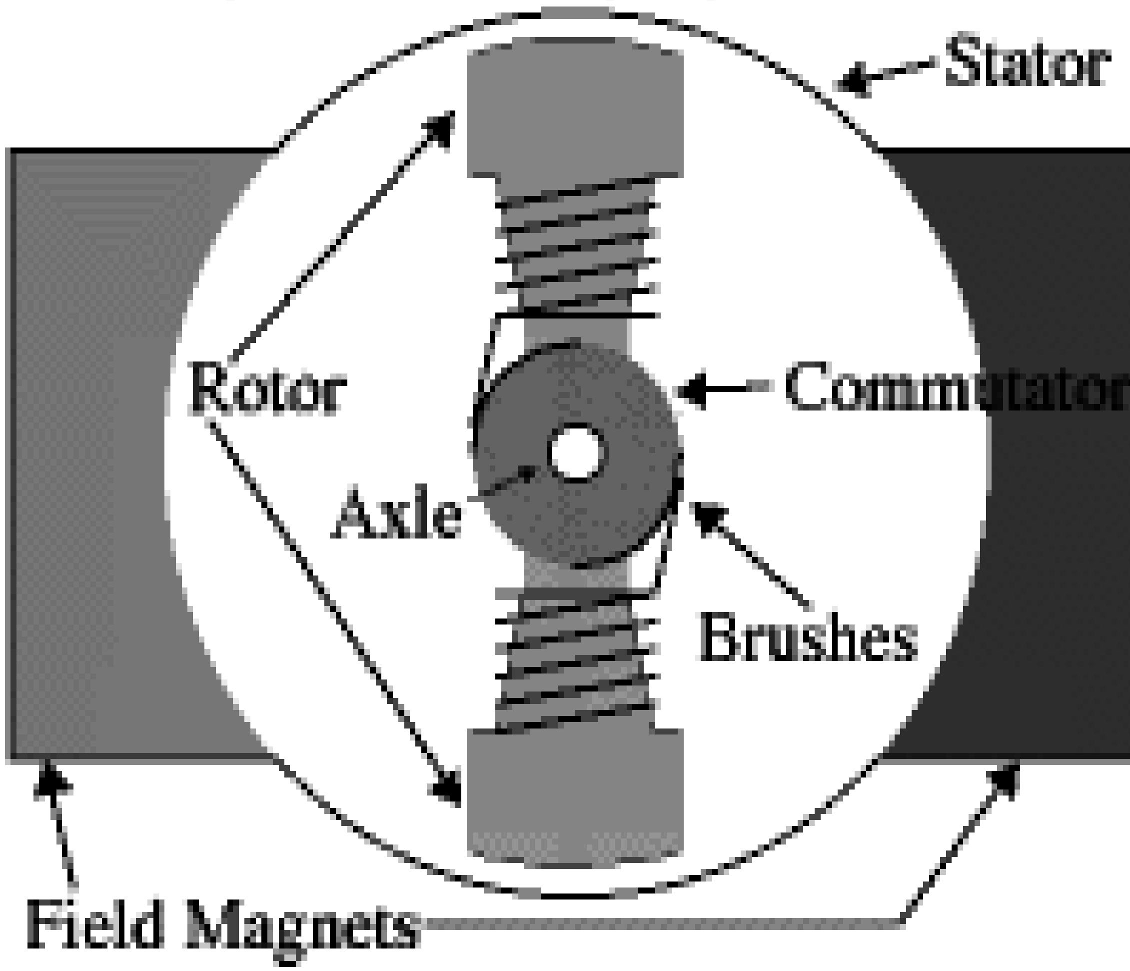
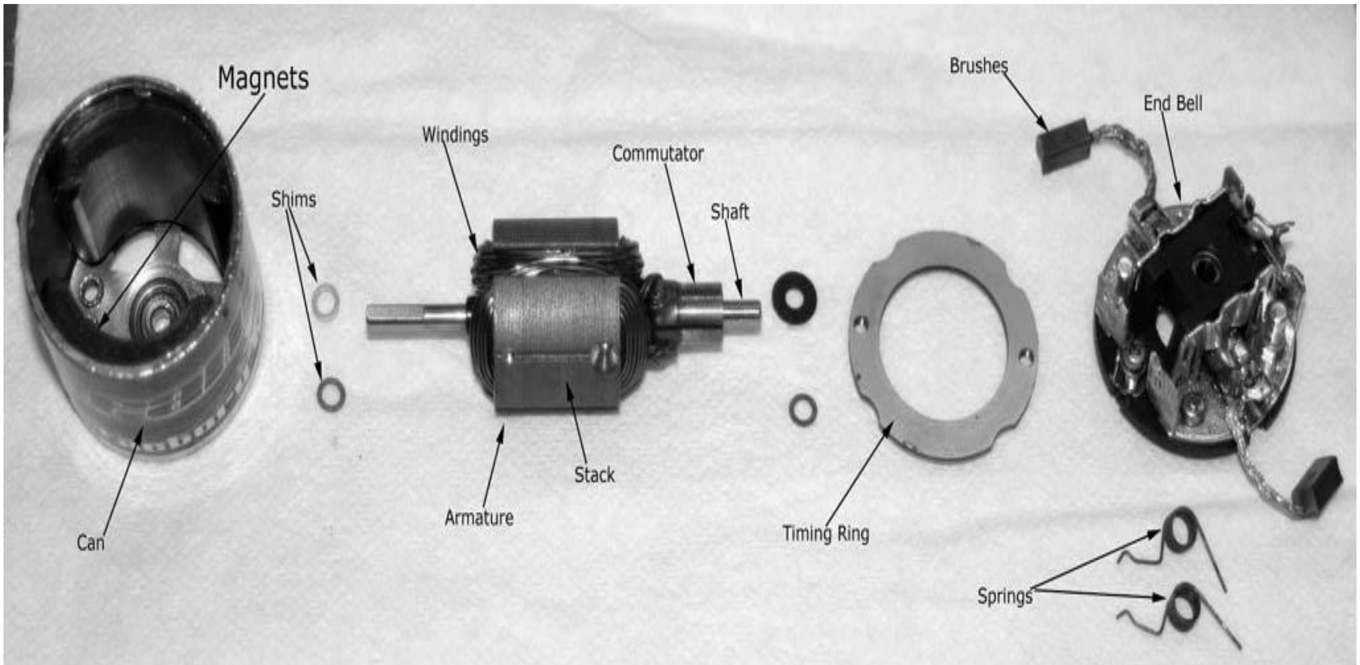


Figure 3



Constructional Description of DC Machine **Figure 4**

Selection of DC Motor:

Choosing DC motor and associated equipment for a given application requires consideration of several factors.

- **Speed Range:**

If field control is to be used, and a large speed range is required, the base speed must be proportionately lower and the motor size must be larger. If speed range is much over 3:1, armature voltage control should be considered for at least part of the range. Very wide dynamic speed range can be obtained with armature voltage control. However, below about 60% of base speed, the motor should be DC rated or used for only short periods.

- **Speed Variation with Torque :**

Applications requiring constant speed at all torque demands should use a shunt-wound DC motor. If speed change with load must be minimized, a DC motor regulator, such as one employing feedback from a tachometer, must be used. When the DC motor speed decrease as the load increases, compound or series-wound DC motors may be used or a DC motor power supply with a drooping volt-ampere curve could be used with a shunt-wound DC motor.

- **Duty cycle :**

Direct current motors are seldom used on drives that run continuously at one speed and load. Motor size needed may be determined by either the peak torque requirement or heating.

- **Peak torque :**

The peak torque that a DC motor delivers is limited by that load at which damaging commutation begins. DC motor brush and commutator damage depends on sparking severity and duration. Therefore, the DC motor's peak torque depends on the duration and frequency of occurrence of the overload. DC motor peak torque is often limited by the maximum current that the power supply can deliver.

DC motors can commutate greater loads at low speed without damage. NEMA standards specify that machines powered by DC motors must deliver at least 150% rated current for 1 minute at any speed within rated range, but most DC motors do much better.

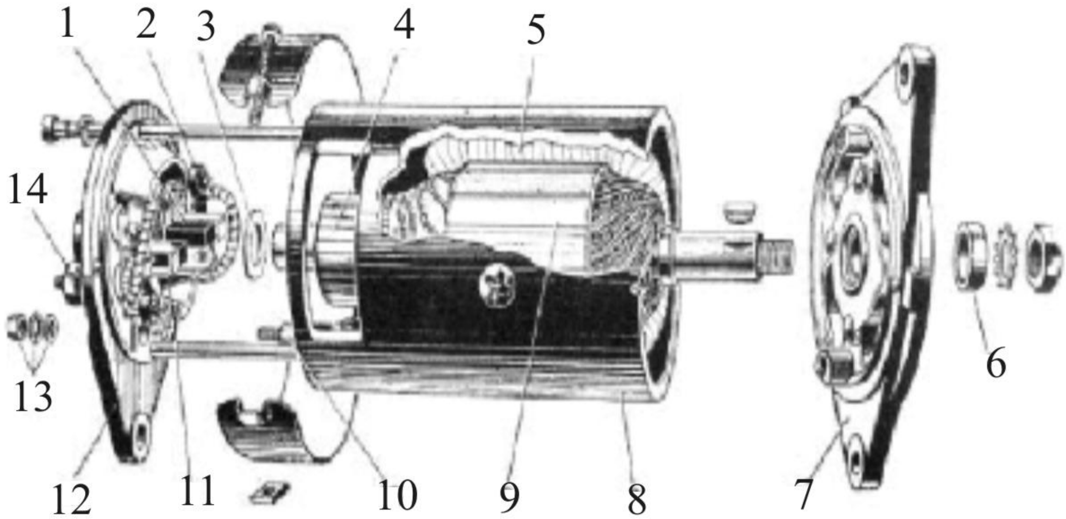
- **Heating :**

DC motor temperature is a function of ventilation and electrical/mechanical losses in the machine. Some DC motors feature losses, such as core, shunt-field, and brush-friction losses, which are independent of load, but vary with speed and excitation.

The best method to predict a given DC motor's operating temperature is to use thermal capability curves available from the DC motor manufacturer. If curves are not available, DC motor temperature can be estimated by the power - loss method. This method requires total losses versus load curve or an efficiency curve.

For each portion of the duty cycle, power loss is obtained and multiplied by the duration of that portion of the cycle. The summation of these products divided by the total cycle time gives the DC motor's average power loss. The ratio of this value to the power loss at the motor rating is multiplied by the DC motor's rated temperature rise to give the approximate temperature rise of the DC motor when operated on that duty cycle.

Construction of dc machine:



1. Brush
2. Brush springs
3. Thrust washer
4. Commutator
5. Field coil
6. Spacer
7. Driving end bracket
8. Field frame
9. Armature
10. Field terminal
11. Brush holder
12. Commutator end bracket
13. Field terminal nuts and washer
14. Main output terminal

Figure 5

Cut Section View of DC Motor:

The construction of a DC motor is almost identical to that of a DC generator, both physically and electrically. In fact, most DC generators can be made to act as DC motors, and vice versa. To better understand the operation and construction of DC machines, a few basic terms and purpose of each of the following components of a DC machine.

1. Armature
2. Rotor
3. Stator
4. Field
5. Commutator

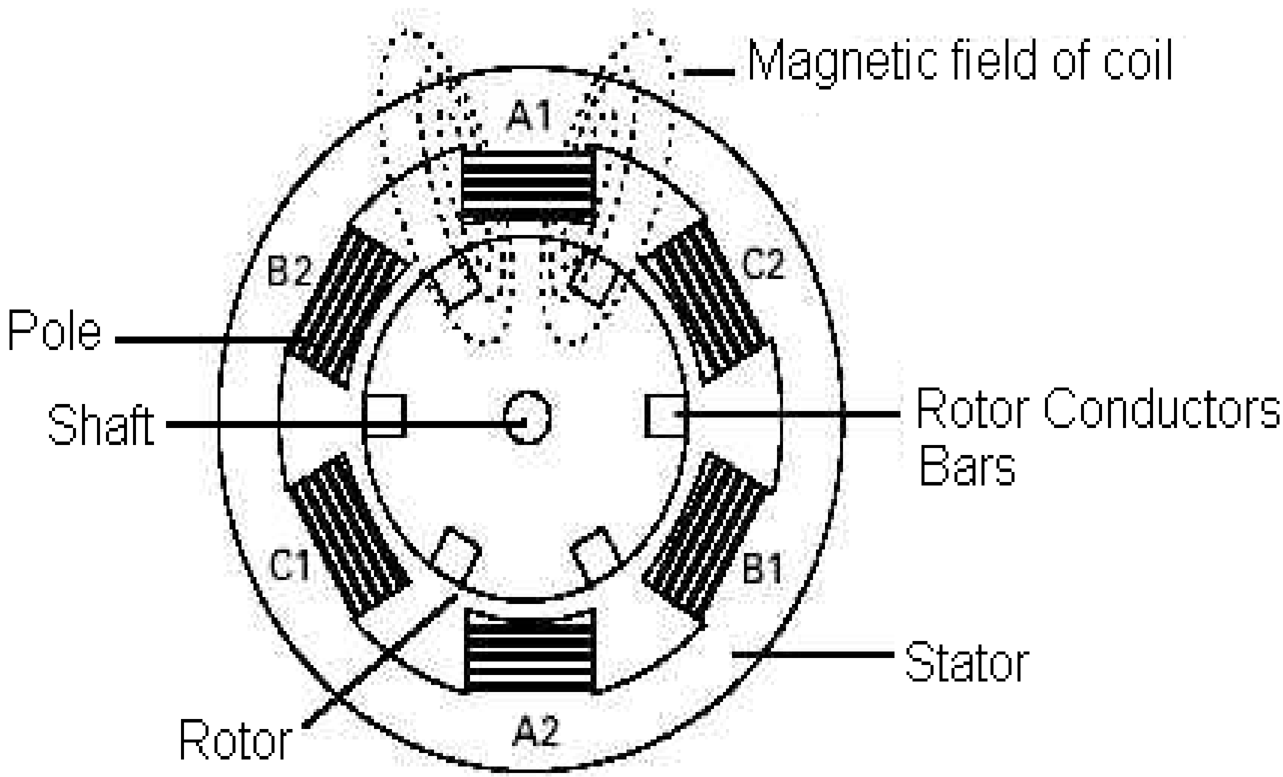


__Figure 6

1. Armature:

The purpose of the armature is to provide the energy conversion in a DC machine. In a DC generator, the armature is rotated by an external mechanical force, such as a steam turbine. This rotation induces a voltage and current flow in the armature. Thus, the armature converts mechanical energy to electrical energy. In a DC motor, the armature receives voltage from an outside electrical source and converts electrical energy into mechanical energy in the form of torque.

2. Rotor:

The purpose of the rotor is to provide the rotating element in a DC machine. In a DC generator, the rotor is the component that is rotated by an external force. In a DC motor, the rotor is the component that turns a piece of equipment. In both types of DC machines, the rotor is the armature.

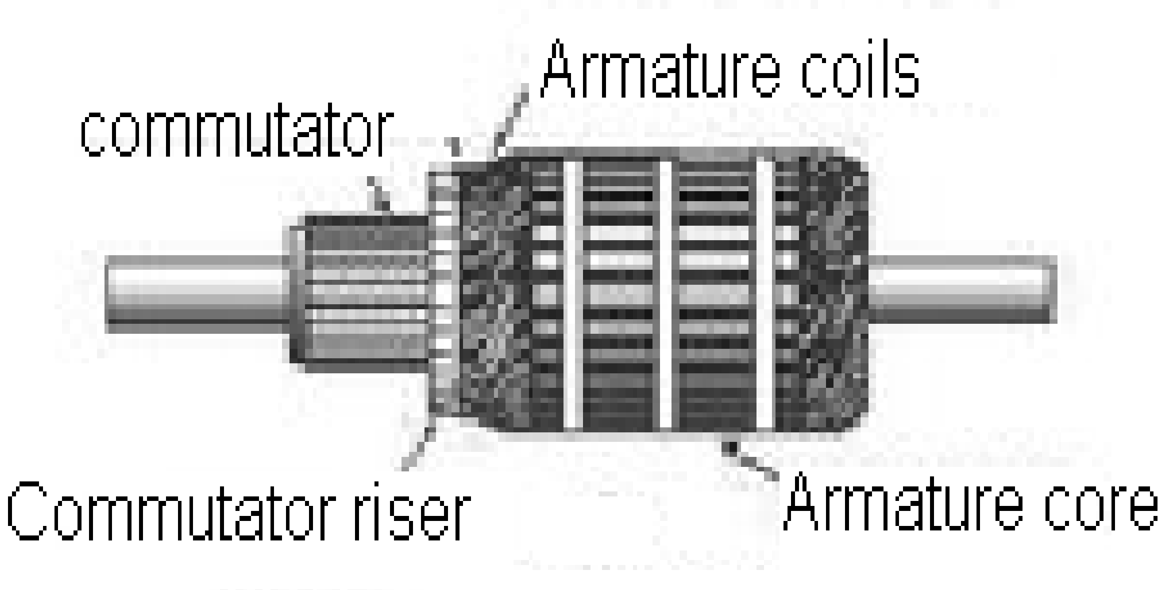
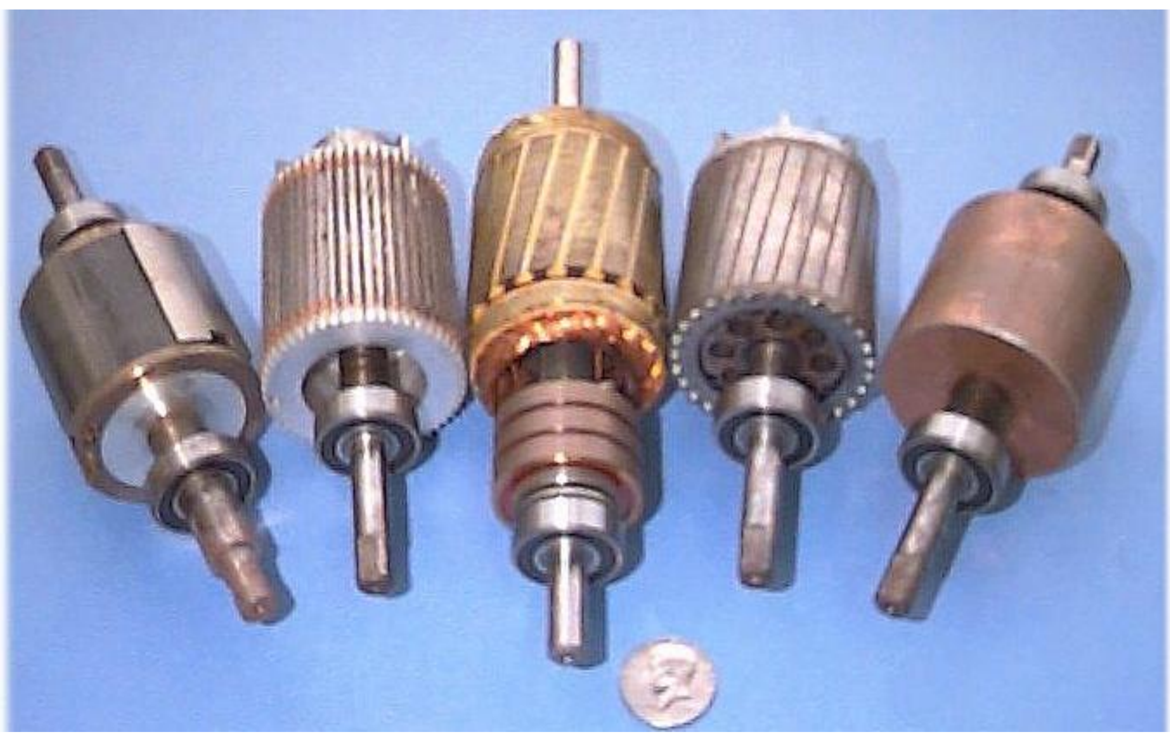


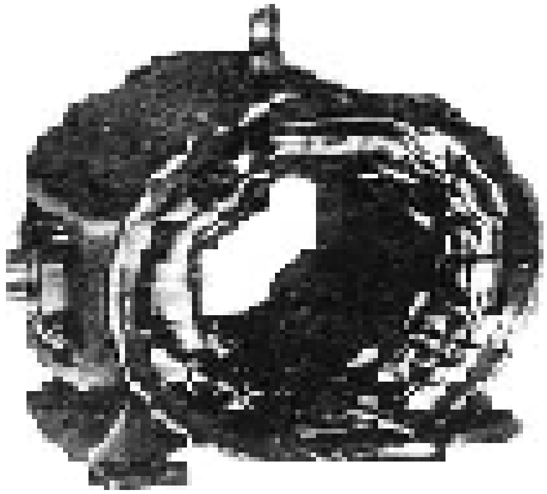
Figure 7

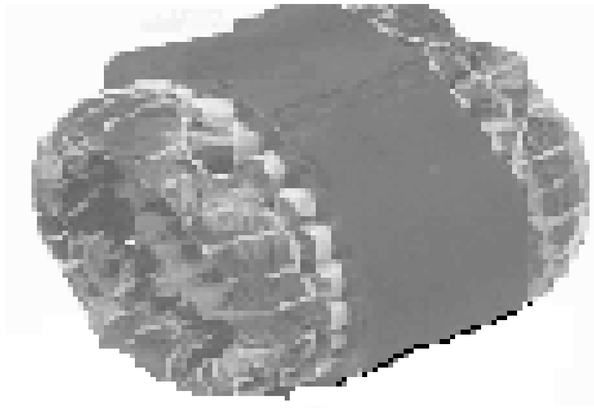


Rotor of DC motor **Figure 8**

3. Stator :

The stator is the part of a motor or generator that is stationary. In DC machines, the purpose of the stator is to provide the magnetic field. The stator is provided by a permanent magnet.





Stator with Yoke **Stator with Winding** **Figure 9**

4. Field:

The purpose of the field in a DC machine is to provide a magnetic field for producing either a voltage (generator) or a torque (motor). The field in a DC machine is produced by either a permanent magnet or an electromagnet. Normally, electromagnets are used because they have an increased magnetic strength, and the magnetic strength is more easily varied using external devices. In Figure 4 and 5 the field is provided by the stator.

5. Commutator:

Commutation in a DC motor is the process of reversing armature current at the moment when unlike poles of the armature and field are facing each other, thereby reversing the polarity of the armature field. Like poles of the armature and field then repel each other, causing armature rotation to continue. Armature reaction takes place when armature current causes the armature to become an electromagnet. The armature field disturbs the field from the pole pieces. This results in a shift of the neutral plane in the direction of rotation. Compensating winding and inter poles are used to counteract the effects of armature reaction. They are supplied by armature current and shift the neutral plane back to its original position.

It typically consists of a set of copper contacts, fixed around the circumference of the rotating part of the machine (the rotor), and a set of spring-loaded carbon brushes fixed to the stationary part of the machine (the stator) that complete the electrical circuit from the rotor's windings to the outside of the machine. Friction between the copper contacts and the brushes eventually causes wear to both surfaces. The carbon brushes, being made of a softer material, wear faster and are designed to be replaced easily without dismantling the machine. The copper contacts are usually inaccessible and, on small motors, are not designed to be repaired. On large motors the commutator may be re-surfaced with abrasives. Each segment of the commutator is insulated from the adjacent segments; a large motor may contain hundreds of segments.

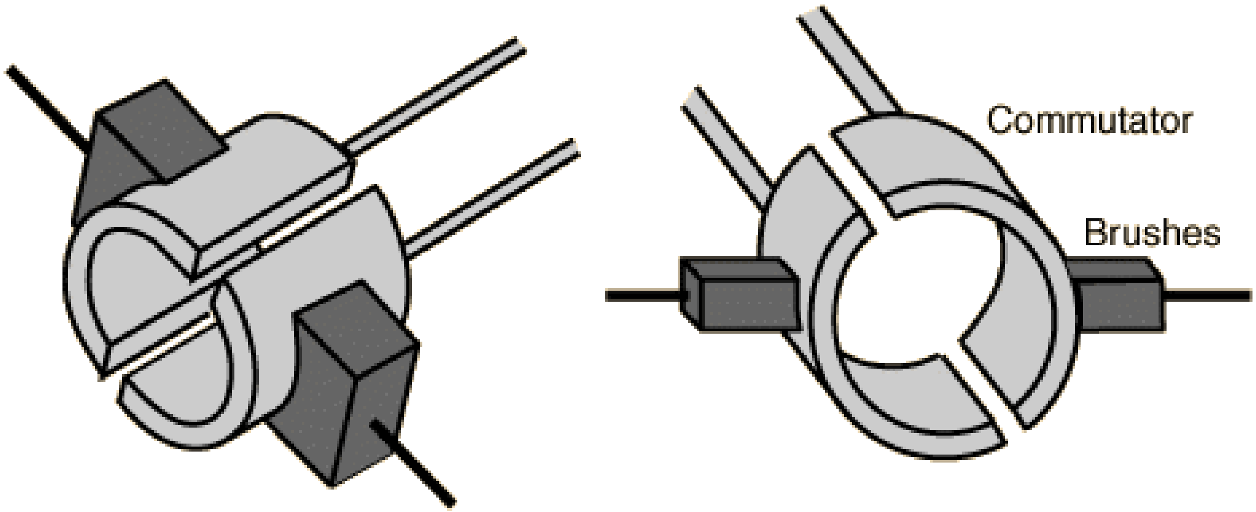


Figure 10

Other parts of DC motor are as follow:

Yoke:

Yoke is an outer frame. It serves two purposes.

(i) It provides mechanical support for the poles and acts as a protecting cover for the whole machine and

(ii) It carries the magnetic flux produced by the poles.

In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is employed. The modern process of forming the yoke consists of rolling a steel slab round a cylindrical mandrel and then welding it at the bottom. The feet and the terminal box etc, are welded to the frame afterwards. Such yokes possess sufficient mechanical strength and have high permeability.

Pole Cores and Pole Shoes:

The field magnet consists of pole ores and pole shoes. The pole shoes have two purposes

(i) They spread out the flux in the air gap and also, being larger cross section, reduce the reluctance of the magnetic path

(ii) They support the exciting coils (field coils)

Field Poles:

The pole cores can be made from solid steel castings or from laminations. At the air gap, the pole usually fans out into what is known as a pole head or pole shoe. This is done to reduce the reluctance of the air gap. Normally the field coils are formed and placed on the pole cores and then the whole assembly is mounted to the yoke.

Field Coils:

The field coils are those windings, which are located on the poles and set up the magnetic fields in the machine. They also usually consist of copper wire are insulated from the poles. The field coils may be either shunt windings (in parallel with the armature winding) or series windings (in series with the armature winding) or a combination of both.

Armature Core or Stack:

The armature stack is made up thin magnetic steel laminations stamped from sheet steel with a blanking die. Slots are punched in the lamination with a slot die. Sometimes these two operations are done as one. The laminations are welded, riveted, bolted or bonded together.

It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of the field magnets. In addition to this its most important function is to provide a path of low reluctance to the flux through the armature from a N-pole to a S-pole. It is cylindrical or drum shaped and is built up of usually circular sheet steel discs or laminations approximately 5mm thick. It is keyed to the shaft.

Armature Windings:

The armature windings are usually former-wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coil are insulated from each other. The conductors are placed in the armature slots which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in the slot and is secured in place by special hard wood or fiber wedges.

Brushes and Bearings:

The brushes, whose function is to collect current from commutator, are usually made of carbon or graphite and are in the shape of a rectangular block. These brushes are housed in brush-holders usually of the box type variety. Because of their reliability, ball-bearings are frequently employed, though for heavy duties, roller bearings are preferable. The ball and rollers are generally packed in hard oil for quieter operation and for reduced bearing wear, sleeve bearings are used which are lubricated by ring oilers fed from oil reservoir in the bearing bracket.

Fleming Right Hand Rule of DC Generator:

Also known as the Generator Rule this is a way of determining the direction of the induced emf of a conductor moving in a magnetic field.

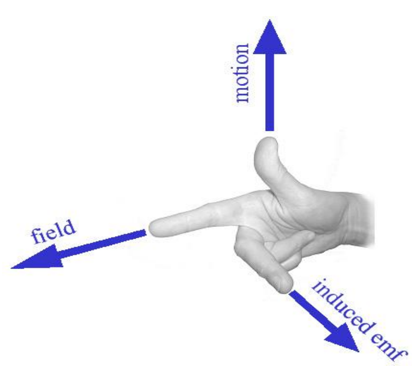
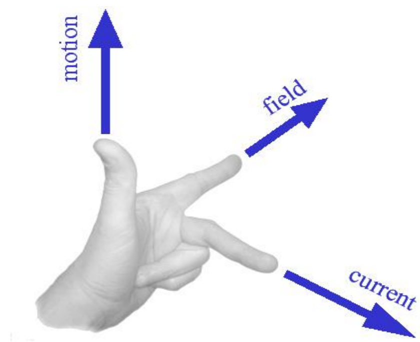


Figure 11

The thumb, the first and the second fingers on the right hand are held so that they are at right angles to each other. So, when a wire carrying current sits perpendicular to a magnetic field, a force is created on the wire causing it to move perpendicular to the field and direction of current. If the first finger points in the direction of the magnetic field and the thumb in the direction of the motion of the conductor then the second finger will point in the direction of the induced emf in the conductor.

Fleming Left Hand Rule of DC Motor:

Also known as the Motor Rule this is a way of determining the direction of a force on a current carrying conductor in a magnetic field.



Picture's Representation of Fleming Left Hand Rule

Figure 12

The thumb, the first and the second fingers on the left hand are held so that they are at right angles to each other. So, when a wire carrying current sits perpendicular to a magnetic field, a force is created on the wire causing it to move perpendicular to the field and direction of current. If the first finger points in the direction of the magnetic field and the second finger the direction of the current in the wire, then the thumb will point in the direction of the force on the conductor.

Principle of DC Machine:

The main principle of DC motor is that current flow through the armature coil causes the armature to act as a magnet. The armature poles are attracted to field poles of opposite polarity, causing the armature to rotate. It is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand rule and whose magnitude is given by

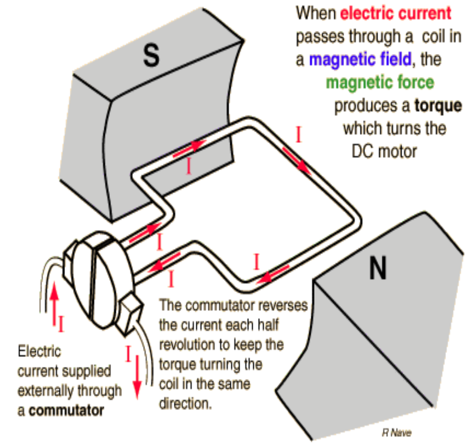
Force, $F = B\ I\ L$ Newton

Where,

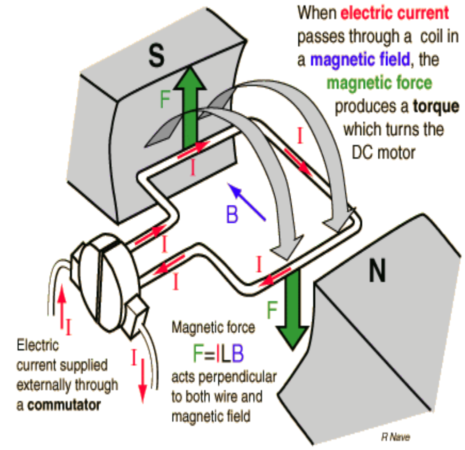
B is the magnetic field in weber/m^2,

I is the current in amperes and

L is the length of the coil in meter.



(a)



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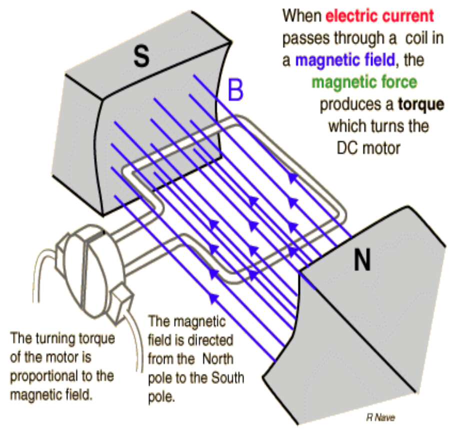

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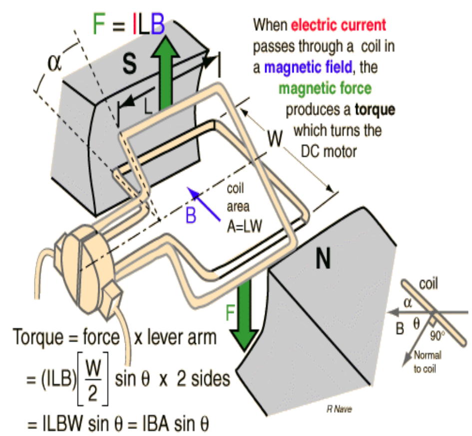


(d)

Operating Behavior of DC Motor **Figure 13**

The force, current and the magnetic field are all in different directions. Poles of a magnet, an upward force will move one wire up and a downward force will move the other wire down. So the wire does not get twisted. This arrangement also makes sure that at the current always passes down on the right and back on the left so that the rotation continues.

Torque of DC motor:

When a current carrying conductor is placed in the magnetic field, a force is exerted or it exerts turning movement or torque $F \times r$. This torque is produced due to electromagnetic effect hence is called electromagnetic torque.

Since,

$V = E_b + I_a Ra$

Multiplying both sides by I_a, we get

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

i.e., Total electrical power = Mechanical power developed.

Supplied to the armature by the armature = Losses due to armature resistance.

So, we can say that

Pm = Mechanical power developed by the armature = $F_b I_a$

Also the mechanical power rotating armature can be given in terms of torque T and speed n.

i.e., Pm = ωT

Where, n in rps, T in Newton meter.

Hence, $\omega T = E_b I_a$

Or $T = E_b I_a / \omega$

But E_b = øZNP/60A

Where N, speed in rpm.

Or N/60 = n speed in rps.

E_b = Z n ø P/A

So torque, T = (Z ø n P/ω A) Ia

But ω = 2¶n

Therefore, T = (0.159 P ø Z /A) Ia

For a particular DC motor, the no of poles (P); no of conductor per parallel path (Z/A) are constant.

T = K I_a, where K= (0.159 P ø Z /A)

Thus we conclude that torque produced in the armature is directly proportional to flux per pole and armature current, moreover, the direction of electromagnetic torque developed in the armature depends upon the current in 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, direction of torque does not change.

DC motor classification:

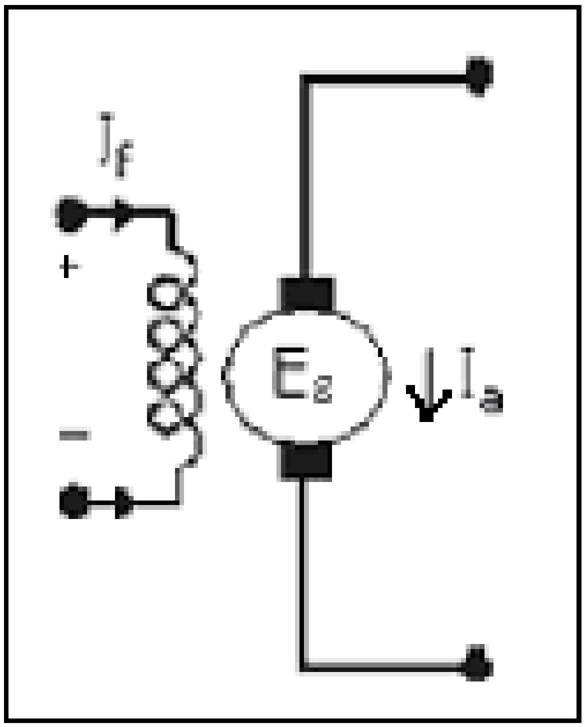
DC motor can be classified into two ways on the basis of their field execution as:

Separately exited DC motor:

A DC motor whose field winding is supplied current from an external DC source.

The conventional diagram of separately excited DC motor is shown in figure 7; its voltage equation will be;

$E_b = V - I_a R_a - 2Vb$



Separately Excited DC Motors

Figure 14

DC Series Motor Lab

Self Excited DC Motor:

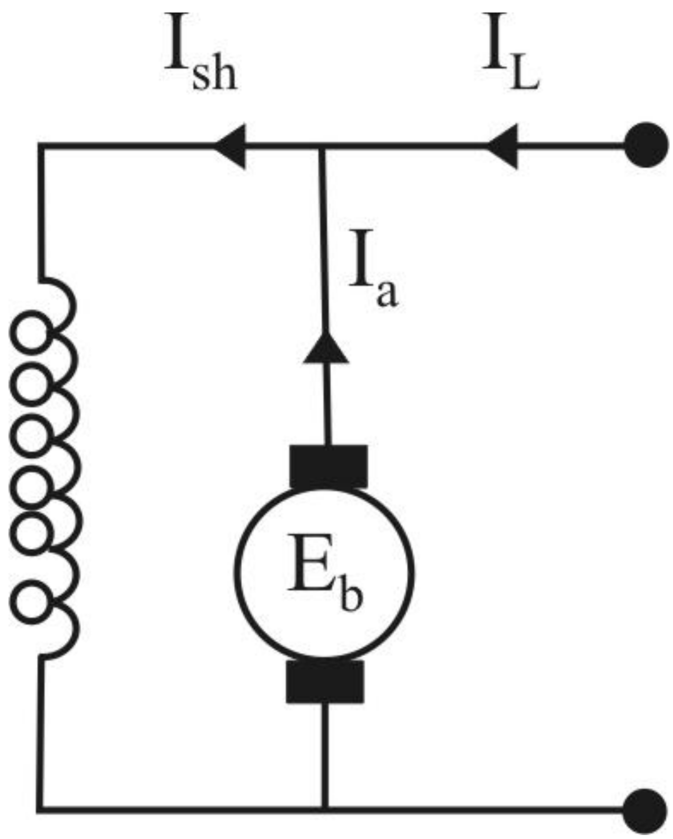
A DC motor whose field winding is supplied current by the motor itself.

DC motors can be divided into three classes, designated according to the method of connecting the armature and the field windings as:

Shunt-Wound Motors:

In shunt wound DC motors, the field windings are connected in parallel (shunt) across the armature coil. The field strength is independent of the armature current. Shunt-motor speed varies only slightly with changes in load, and the starting torque is less than that of other types of DC motors. The shunt motor is probably the most common DC motor used in industry today. Components of the shunt motor are the armature, labeled A1 and A2, and the field, labeled F1 and F2. The coils in the shunt field are composed of many turns of small wire, resulting in low shunt field current and moderate armature current. This motor provides starting torque that varies with the load applied and good speed regulation by controlling the shunt field voltage. If the shunt motor loses it's field it will accelerate slightly until CEMF rises to a value sufficient to shut off the torque producing current. In other words, the shunt motor will not destroy itself if it loses its field, but it won't have the torque required to do the job it was designed for.

This type of motor runs practically a constant speed, regardless of the load. It is the type generally used in commercial practice and is usually recommended where starting conditions are not usually severs. Speed of the shunt-wound motors may be regulated in two ways: first, by inserting resistance in series with the armature, thus decreasing speed: and second, by inserting resistance in the field circuit, the speed will vary with each change in load: in the latter, the speed is practically constant for any setting of the controller. This latter is the most generally used for adjustable-speed service, as in the case of machine tools. The shunt motor is probably the most common DC motor used in industry today. Components of the shunt motor are the armature, labeled A1 and A2, and the field, labeled F1 and F2. The coils in the shunt field are composed of many turns of small wire, resulting in low shunt field current and moderate armature current. This motor provides starting torque that varies with the load applied and good speed regulation by controlling the shunt field voltage. If the shunt motor loses it's field it will accelerate slightly until EMF rises to a value sufficient to shut off the torque producing current. In other words, the shunt motor will not destroy itself if it loses its field, but it won't have the torque required to do the job it was designed for.



Shunt Wound DC Motor

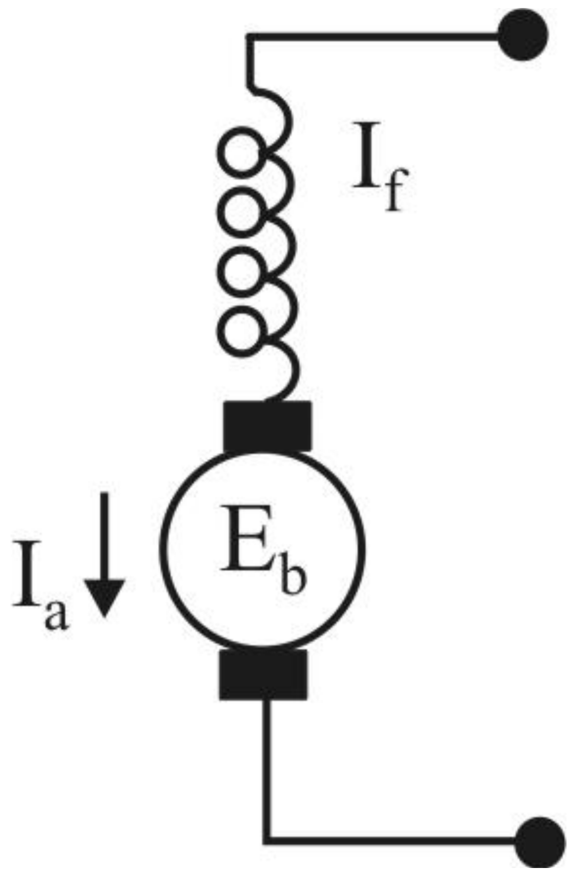
Figure 15

Some of the common uses of the shunt motor are machine shop lathes, and industry process lines where speed and tension control are critical.

Series -Wound Motors:

In series motor, the field windings are connected in series with the armature coil. The field strength varies with changes in armature current. When its speed is reduced by a load, the series motor develops greater torque. Its starting torque is greater than other types of DC motors. Its speed varies widely between full-load and no-load. Unloaded operation of large machines is dangerous. Components of a series motor include the armature, labeled A1 and A2, and the field, S1 and S2. The same current is impressed upon the armature and the series field. The coils in the series field are made of a few turns of large gauge wire, to facilitate large current flow. This provides high starting torque, approximately 2 ¼ times the rated load torque. Series motor armatures are usually lap wound. Lap windings are good for high current, low voltage applications because they have additional parallel paths for current flow. Series motors have very poor speed control, running slowly with heavy loads and quickly with light loads. A series motor should never drive machines with a belt. If the belt breaks, the load would be removed and cause the motor to over speed and destroy itself in a matter of seconds. Common uses of the series motor include crane hoists, where large heavy loads will be raised and lowered and bridge and trolley drives on large overhead cranes. The series motor provides the starting torque required for moving large loads. Traction motors used to drive trains are series motors that provide the required torque and horsepower to get massive amounts of weight moving.

This type of motor speed varies automatically with the load, increasing as the load decreases. Use of series motor is generally limited to case where a heavy power demand is necessary to bring the machine up to speed, as in the case of certain elevator and hoist installations, for steel cars, etc. Series-wound motors should never be used where the motor can be started without load, since they will race to a dangerous degree. Components of a series motor include the armature, labeled A1 and A2, and the field, S1 and S2. The same current is impressed upon the armature and the series field. The coils in the series field are made of a few turns of large gauge wire, to facilitate large current flow. This provides high starting torque, approximately 2¼ times the rated load torque. Series motor armatures are usually lap wound. Lap windings are good for high current, low voltage applications because they have additional parallel paths for current flow. Series motors have very poor speed control, running slowly with heavy loads and quickly with light loads. A series motor should never drive machines with a belt. If the belt breaks, the load would be removed and cause the motor to over speed and destroy itself in a matter of seconds.



Series- Wound Motors

Figure 16

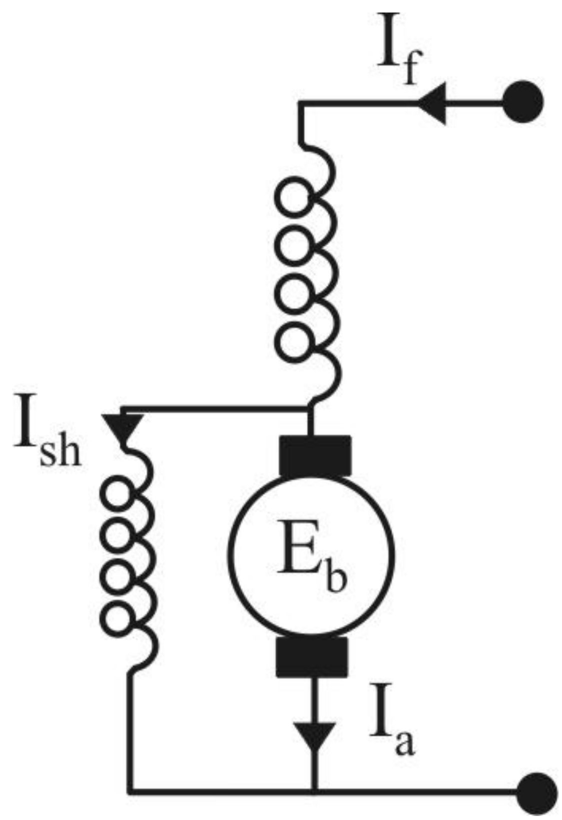
DC Series Motor Lab

This type of motor develops a very large amount of turning force, called torque, from a standstill. Because of this characteristic, the series dc motor can be used to operate small electric appliances, portable electric tools, cranes, winches, hoists, and the like. Another characteristic is that the speed varies widely between no-load and full-load. Series motors cannot be used where a relatively constant speed is required under conditions of varying load. A major disadvantage of the series motor is related to the speed characteristic mentioned in the last paragraph. The speed of a series motor with no load connected to it increases to the point where the motor may become damaged. Usually, either the bearings are damaged or the windings fly out of the slots in the armature. There is a danger to both equipment and personnel. Some load must ALWAYS be connected to a series motor before you turn it on. This precaution is primarily for large motors. Small motors, such as those used in electric hand drills, have enough internal friction to load themselves. Common uses of the series motor include crane hoists, where large heavy loads will be raised and lowered and bridge and trolley drives on large overhead cranes. The series motor provides the starting torque required for moving large loads.

Compound-Wound DC Motors:

In compound motor, one set of field windings is connected in series with the armature, and one set is connected in parallel. The speed and torque characteristics are a combination of the desirable characteristics of both series and shunt motors. When comparing the advantages of the series and shunt motors, the series motor has greater torque capabilities while the shunt motor has more constant and controllable speed over various loads. These two desirable characteristics can be found in the same motor by placing both a series field and shunt field winding on the same pole. Thus, we have the compound motor. The compound motor responds better to heavy load changes than a shunt motor because of the increased current through the series field coils. This boosts the field strength, providing added torque and speed.

If a shunt coil is added to a series motor at light loads (when a series motor tends to over speed) the added shunt field flux limits the top speed, eliminating self-destruction. A combination of the shunt wound and series wound types combines the characteristics of both. Characteristics may be varied by varying the combination of the two windings. These motors are generally used where severe starting conditions are met and constant speed is required at the same time. When comparing the advantages of the series and shunt motors, the series motor has greater torque capabilities while the shunt motor has more constant and controllable speed over various loads. These two desirable characteristics can be found in the same motor by placing both a series field and shunt field winding on the same pole. Thus, we have the compound motor. Common uses of the compound motor include elevators, air compressors, conveyors, presses and shears. Compound motors can be operated as shunt motors by disconnecting the series field. Many manufacturing process lines are designed this way.



Compound Wound DC Motor

Figure 17

Compound motors can be connected two ways, cumulatively and differentially. When connected cumulatively, the series field is connected to aid the shunt field, providing faster response than a straight shunt motor. When connected differentially, the series field opposes the shunt field. Differentially connected compound motors are sometimes referred to as “suicide motors,” because of their penchant for self destruction. If perhaps, the shunt field circuit were to suddenly open during loading, the series field would then assume control and the polarity of all fields would reverse. This results in the motor stopping, and then restarting in the opposite direction. It then operates as an unloaded series motor and will destroy itself. Differentially connected motors can also start in the opposite direction if the load is too heavy. Therefore, it is seldom used in industry.

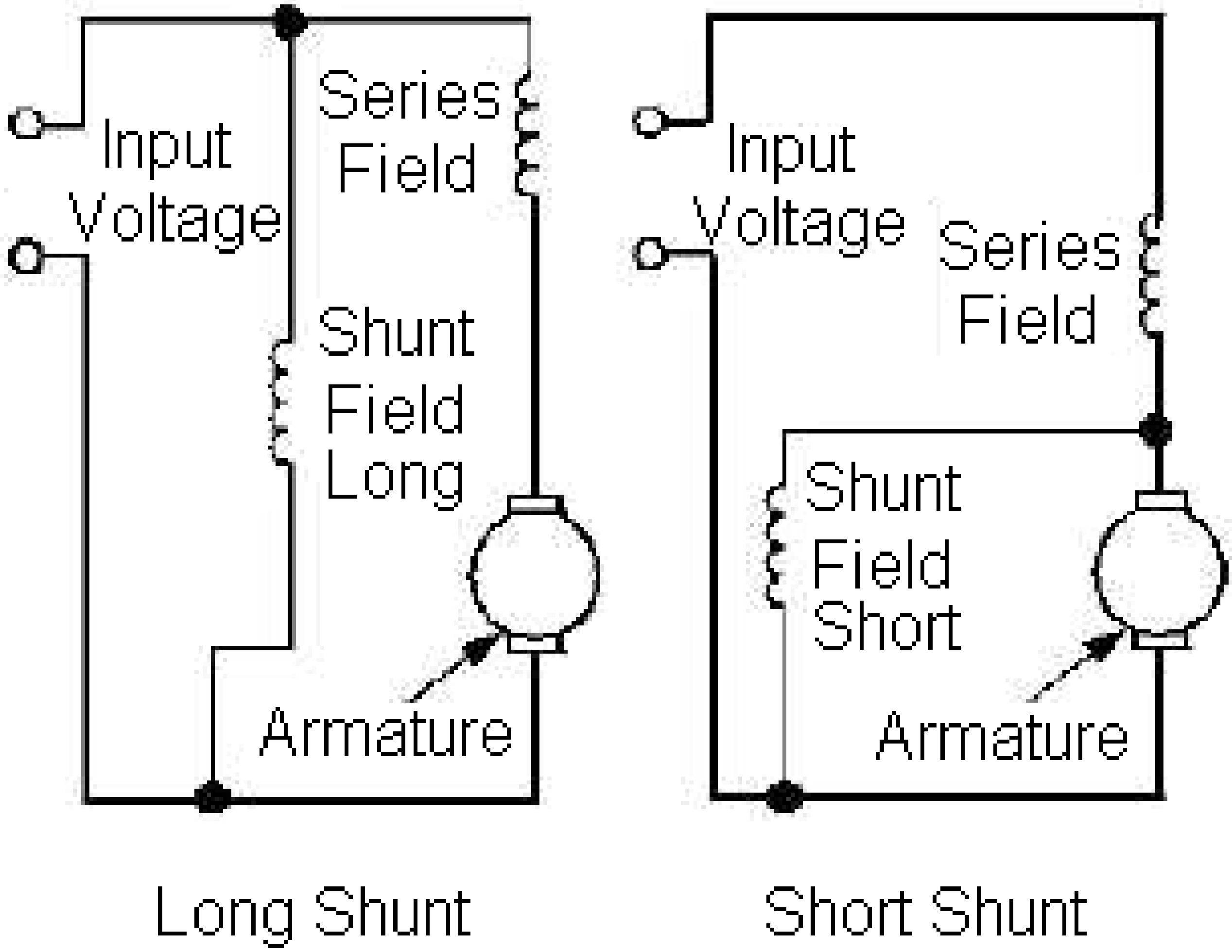

Input
Voltage
Series
Field
Shunt
Field
Long
Armature
Long Shunt
Input
Voltage
Series
Field
Shunt
Field
Short
Armature
Short Shunt

Figure 18

Speed Control of DC Motor:

Speed of the DC motor is given by the relation:

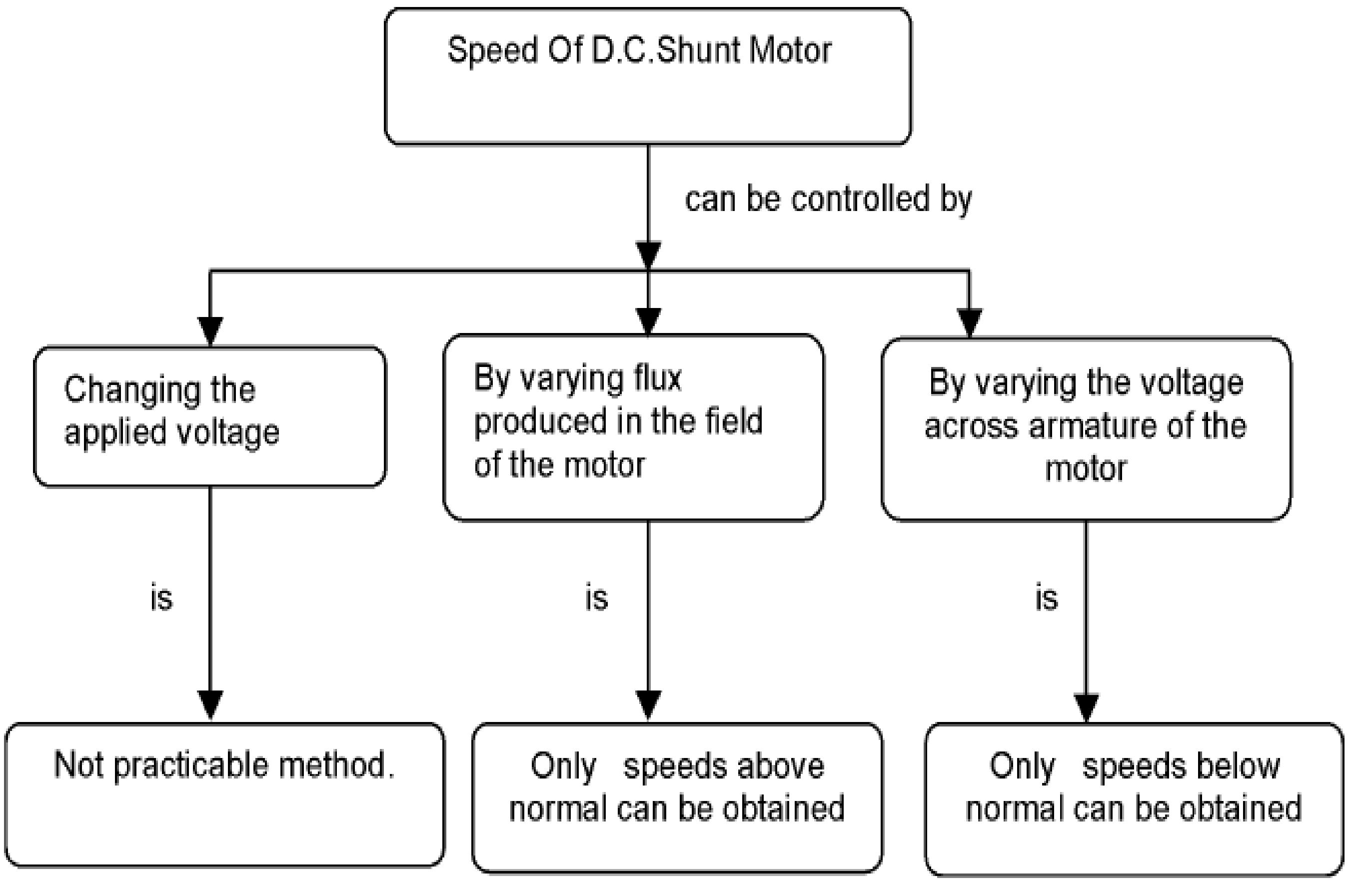


Figure 19

$N = V – I_A R_A / \Phi$

where,

N = Speed of the DC motor.

V = Applied voltage in DC motor.

Φ = Flux per pole of DC motor.

I_A = Armature current in DC motor.

R_A = Armature resistance of DC motor.

From the above equation it is clear that the speed of DC motor can be controlled

- By varying flux per pole this is known as flux or field control method.
- By varying the armature drop that is by varying the resistance of the armature circuit this is known as armature controlled method.
- By varying the applied voltage this is known as voltage controlled method.

DC Series Motor Lab

Speed control of DC Series Motor:

1. Field Control Method:

In this method a variable resistance R is connected in parallel with the armature. Its effect is that it diverts the path of the line current. Some of the current flows through the diverter and reduces the armature current. For a given constant load torque, if a armature current is reduced then flux must increase ($T \propto \Phi I_A$). This results in increase in current drawn by the motor and a fall in speed ($N \propto 1/\Phi$). By adjusting the value of diverter resistance any speed below normal speed can be obtained by this method. This method is more economical as very little power is wasted in the shunt field variable resistance due to relatively small current.

2. Armature Control Method:

In this method, a variable resistance R is connected in series with the armature. If the current taken by the motor is constant then speed depends upon the induced e.m.f {that is $N \propto Eb$, where $Eb = [V – Ia (Ra + Rse)]$. With the addition of variable resistance induced emf reduces $Eb = [V – Ia (Ra + Rse + R)]$ and hence the speed. By changing the value of variable resistance any speed below normal speed can be obtained. This method is neither efficient economical as large power is wasted in the control resistance since it carries full armature current.

3. Voltage Controlled Method:

In this method the voltage across the series motors is changed by connecting them in series or in parallel or the combination of both. this is widely used in electric traction when the motor are connecting in series low speed are obtained and when they are connected in parallel high speeds nearly 4 times to that of first case are obtained.

Characteristic of Series Motors :

In this motor 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 is constant.

Speed and Armature Current Characteristic:

It is the curve drawn between the speed and armature current. It is known as speed characteristic.

We know that

$N \propto E_b / \Phi$

Where

$E_b = V – I_A (R_A + R_{SE})$

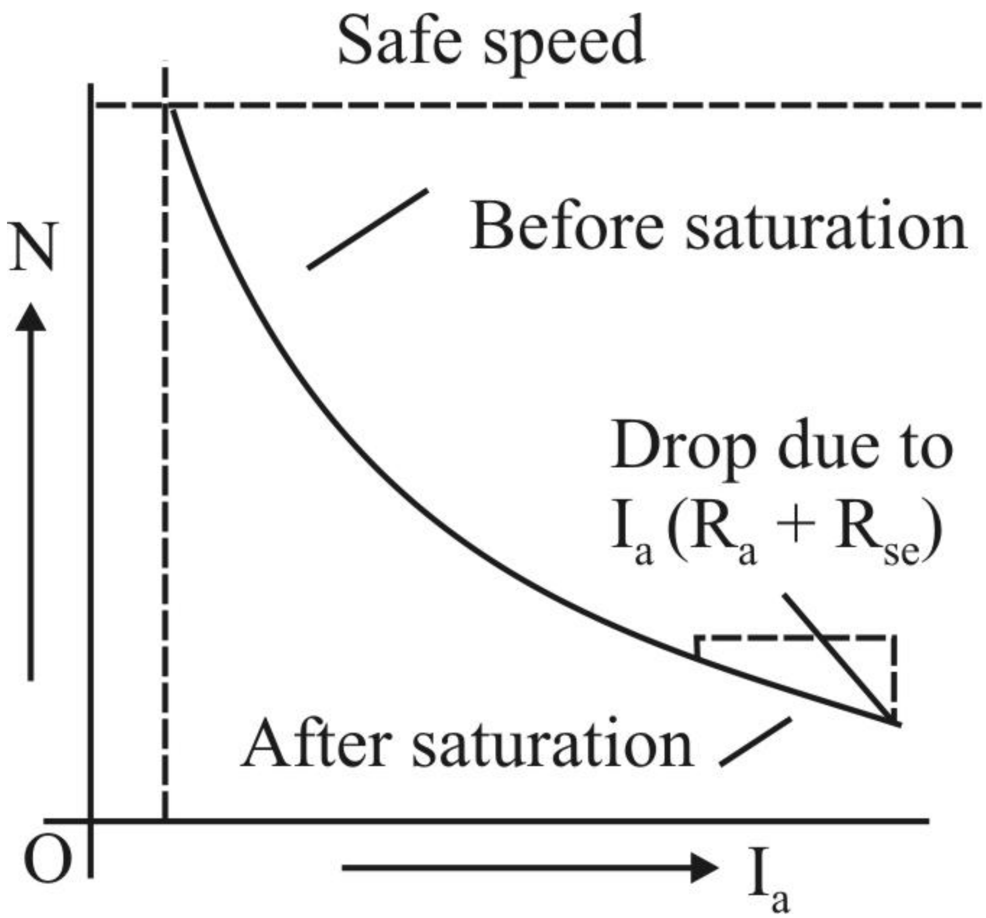


Figure 20

When armature currant increases the induced emf decrease due to I_A (R_A + R_{SE}) drop, whereas flux increase as $\Phi \propto I_A$ before magnetic saturation. However under normal condition I_A (R_A + R_{SE}) drop is quite small and may be neglected.

Considering E_b to be constant, $N \propto 1 / \Phi \propto 1 / I_A$.

Before magnetic saturation curve follow the hyperbolic path. In this region the speed decreases abruptly with the increase in load or armature current.

After magnetic saturation flux become constant, then

$N \propto E_b \propto V - I_A (R_A + R_{SE})$

Thus curve follow a straight line as shown in Figure 15, from this characteristic it is concluded that the series motor is a variable speed motor that is its speed change when the load varies. As the load on this motor decrease the speed increases. If this motor is connected to the supply with load, the armature current will be very small and hence the speed will be dangerously increase which may damage the motor due to heavy centrifugal force, therefore the series motor is never started with no load.

- **Torque and Armature Current Characteristic:**

It is the curve drawn between the torque develop and armature current, known as electrical characteristic.

We know that $T \propto \Phi I_A$

In series motor before magnetic saturation,

$\Phi \propto I_A$ and $T \propto I_A^2$

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 figure 16.

However after magnetic saturation the flux Φ become constant

Therefore, $T \propto \Phi$

Hence the curve becomes a straight line.

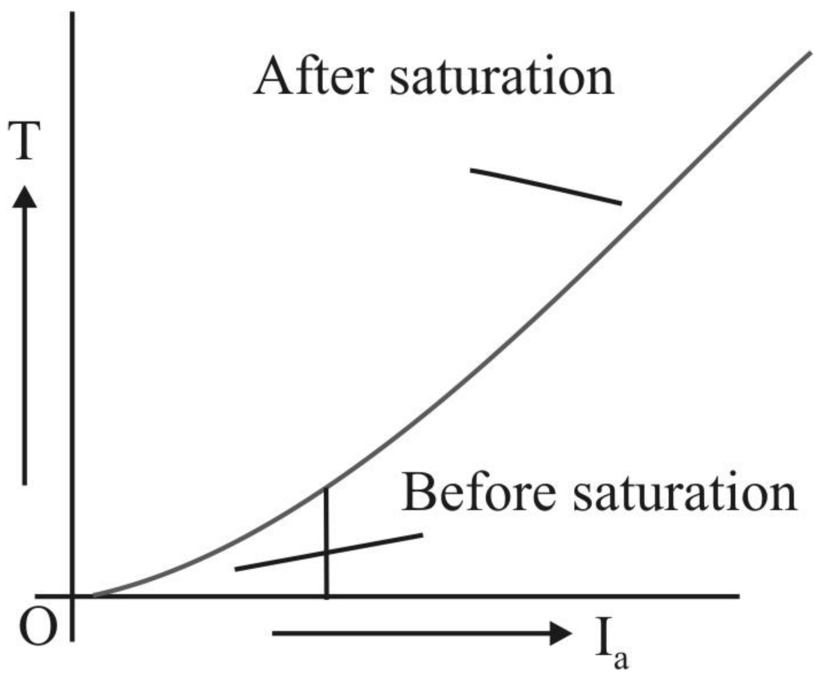


Figure 21

It is concluded that, before magnetic saturation when load is applied to this motor at start it takes large current and heavy load is produced which is proportional to the square of the current, thus this motor is capable to pick heavy load at the start and best suited for electric traction.

- **Speed and Torque Characteristic :**

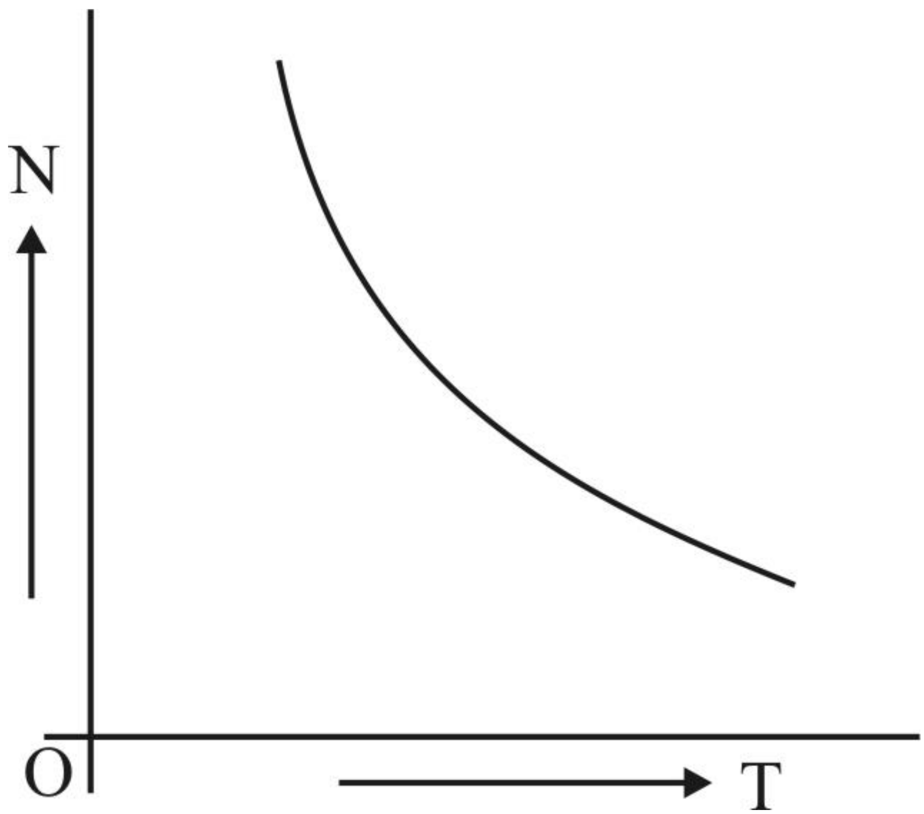


Figure 22

It is the curves drawn between the torques develop and speed, known as mechanical characteristic. It is derived from the first two characteristic.

At low value of load, I is small, torque is small but the speed is very high as load increases, I increases, torque increases but the speed decrease rapidly. Thus for increasing torque speed decreases rapidly.

Speed Regulation of motor :

Speed regulation is the change in speed with the change in load torque, other conditions being constant. A motor has good regulation if the change between the no load speed and full load speed is small.

Percent Speed Regulation = (SNL - SFL) / SFL x 100

A shunt motor has good speed regulation while a series motor has poor speed regulation. For some applications such as cranes or hoists, the series motor has an advantage since it results in the more deliberate movement of heavier loads. Also, the slowing down of the series motor is better for heavy starting loads. However, for many applications the shunt motor is preferred.

DC Series Motor Lab

Voltage Regulation of motor:

Voltage Regulation is the change in terminal voltage with the change in load current at constant speed. A generator has good regulation if the change in voltage between no load and full load is small. If the change is large, the regulation is poor. Expressed in equation form:

Percent Voltage Regulation = $(E_{NL} - E_{FL}) / E_{FL} \times 100$

The regulation of a separately excited machine is better than that of a shunt machine. However, the best regulation is obtained with a compound machine. The series machine has practically no regulation at all and, therefore, has little practical application.

Losses and efficiency of motor:

Friction and Windage losses:

These losses include bearing friction, brush friction, and windage. They are also known as mechanical losses. They are constant at a given speed but vary with changes in speed. Power losses due to friction increase as the square of the speed and those due to windage increase as the cube of the speed.

Armature Copper Losses:

These are the I^2R losses of the armature circuit, which includes the armature winding, commutator, and brushes. They vary directly with the resistance and as the square of the currents.

Field Copper Losses:

These are the I^2R losses of the field circuit which can include the shunt field winding, series field winding, Interpole windings and any shunts used in connection with these windings. They vary directly with the resistance and as the square of the currents.

Core Losses:

These are the hysteresis and eddy current losses in the armature. With the continual change of direction of flux in the armature iron, an expenditure of energy is required to carry the iron through a complete hysteresis loop. This is the hysteresis loss. Also since the iron is a conductor and revolving in a magnetic field, a voltage will be generated. This, in turn, will result in small circulating currents known as eddy currents. If a solid core were used for the armature, the eddy current losses would be high. They are reduced by using thin laminations, which are insulated from each other. Hysteresis and eddy current losses vary with flux density and speed.

Efficiency of motor:

For generations or motors, the efficiency is equal to the output divided by the input. However, in a generator, the input is mechanical while the output is electrical. In a motor the opposite is true, therefore:

Motor Efficiency = (Input - Losses)/Input

Generator Efficiency = Output / (Output + Losses)

Advantages:

The greatest advantage of DC motors may be speed control. Since speed is directly proportional to armature voltage and inversely proportional to the magnetic flux produced by the poles, adjusting the armature voltage and/or the field current will change the rotor speed. Today, adjustable frequency drives can provide precise speed control for AC motors, but they do so at the expense of power quality, as the solid-state switching devices in the drives produce a rich harmonic spectrum. The DC motor has no adverse effects on power quality.

Drawbacks:

1. Power supply, initial cost, and maintenance requirements are the negatives associated with DC motors.
2. Rectification must be provided for any DC motors supplied from the grid. It can also cause power quality problems.
3. The construction of a DC motor is considerably more complicated and expensive than that of an AC motor, primarily due to the commutator, brushes, and armature windings. An induction motor requires no commutator or brushes, and most use cast squirrel-cage rotor bars instead of true windings, two huge simplifications.
4. Maintenance of the brush / commutator assembly is significant compared to that of induction motor designs.
5. In spite of the drawbacks, DC motors are in wide use, particularly in niche applications like cars and small appliances.

Applications:

1. Industrial applications use DC motors because the speed-torque relationship can be varied to almost any useful form, for both DC motor and regeneration applications in either direction of rotation. Continuous operation of DC motors is commonly available over a speed range of 8:1. Infinite range (smooth control down to zero speed) for short durations or reduced load is also common.
2. DC motors are often applied where they momentarily deliver three or more times their rated torque. In emergency situations, DC motors can supply over five times rated torque without stalling (power supply permitting).
3. Dynamic braking (DC motor-generated energy is fed to a resistor grid) or regenerative braking (DC motor-generated energy is fed back into the DC motor supply) can be obtained with DC motors on applications requiring quick stops, thus eliminating the need for, or reducing the size of a mechanical brake.
4. DC motors feature a speed, which can be controlled smoothly down to zero, immediately followed by acceleration in the opposite direction--without power circuit switching and DC motors respond quickly to changes in control signals due to the DC motor's high ratio of torque

to inertia.

5. The DC machine is used as a motor when there is a demand for a continue regulation of rotational speed. Although there is a disadvantage due to the fact that brushes are not without friction, it requires considerably less cost for the supply equipment, which makes the DC machines sometimes more economical than three-phase drives. The Application areas of a DC machine are electric rolling mill drives, conveyor drives or machine tools. In the last application, the machine is excited with permanent magnets instead of using electrical excitation in order to reduce the size of construction and losses in the excitation circuit. The DC generator is used as a Leonard generator, as an excitation machine for synchronous generators or as permanent excited tachometer generator.