DC Motor

- The direct current (DC) machine can be used as a motor or as a generator, i.e. construction of DC motor and generator is same.
- DC Machine is most often used as a motor.
- The major advantages of dc machines are the easy speed and torque regulation.
- However, their application is limited to mills, mines and trains. As examples, trolleys and underground subway cars may use dc motors.

DC Motor

- The recent development of power electronics has reduced the use of dc motors and generators.
- The electronically controlled ac drives are gradually replacing the dc motor drives in factories.
- Nevertheless, a large number of dc motors are still used by industries.

Construction

DC Machine Construction



Figure 2.1 Cross sectional view of a DC machine

- The stator of the dc motor has poles, which are excited by dc current to produce magnetic fields.
- In the neutral zone, in the middle between the poles, commutating poles are placed to reduce sparking of the commutator. The commutating poles are supplied by dc current.
- Compensating windings are mounted on the main poles. These short-circuited windings damp rotor oscillations.



- The poles are mounted on an iron core that provides a closed magnetic circuit.
- The motor housing supports the iron core, the brushes and the bearings.
- The rotor has a ring-shaped laminated iron core with slots.
- Coils with several turns are placed in the slots. The distance between the two legs of the coil is about 180 electric degrees.



- The coils are connected in series through the commutator segments.
- The ends of each coil are connected to a commutator segment.
- The commutator consists of insulated copper segments mounted on an insulated tube.



- The rotor has a ring-shaped laminated iron core with slots.
- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.



Mica Insulation between segments

Copper segment

Copper conductors

- The *commutator* switches the • current from one rotor coil to the adjacent coil,
- The switching requires the ٠ interruption of the coil current.
- The sudden interruption of an ٠ inductive current generates high voltages.
- The high voltage produces flashover and arcing between the commutator segment and the brush.



Mica Insulation between segments

Copper segment

Copper conductors

DC Machine Construction



Figure 2.2 Connections of rotor coils with commutator.

DC Motor Operation

DC Motor Operation

- In a dc motor, the stator poles are supplied by dc excitation current, which produces a dc magnetic field.
- The rotor is supplied by dc current through the brushes, commutator and coils.
- The interaction of the magnetic field and rotor current generates a force that drives the motor



DC Motor Operation

- Before reaching the neutral zone, the current enters in segment 2 and exits from segment 1,
- Therefore, current enters the coil end at slot **b** and exits from slot a during this stage.
- After passing the neutral zone, the current enters segment 1 and exits from segment 2,
- This reverses the current direction through the rotor coil, when the coil passes the neutral zone.



(a) Rotor current flow from segment 2 to 1 (slot **b** to **a**)



(b) Rotor current flow from segment 1 to 2 (slot **a** to **b**)

Back emf

- When rotor rotates, armature conductors cut the field flux and an emf is generated.
- In a DC motor, this emf is called back emf.
- The induced emf in the rotating armature conductors always acts in the opposite direction of the supply voltage .
- According to the Lenz's law, the direction of the induced emf is always so as to oppose the cause producing it .
- In a DC motor, the supply voltage is the cause and hence this induced emf opposes the supply voltage.

EMF equation

Let,

- ► Ø= useful flux per pole in weber (Wb)
- \triangleright Z = total number of armature conductors
- \blacktriangleright P = number of poles
- \blacktriangleright A = Number of parallel paths in armature
- \triangleright N = armature speed in rpm
- E_b = back emf generated in any one of the parallel path

EMF equation

- Flux cut by 1 conductor in 1 revolution = $P * \phi$
- Time for one revolution = (1/N) minutes
- Average emf generated in one conductor

= (Flux cut by one conductor in one revolution)/(Time in second for one revolution)

 $= P \ \phi \ N \ / 60$

- Number of conductors in each parallel path = Z / A
- $E_b = P\phi NZ/60A$

Voltage and Power equation of DC Motor

Voltage and Power equation of DC Motor:

 $V = E_b + I_a R_a$

If we multiply the above equation by *Ia*, we will get

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

 VI_a =electrical power supplied to the motor

 $E_b I_a$ =electrical equivalent of the mechanical power produced by the motor. $I_a{}^2 R_a$ = power loss taking place in armature winding Thus,

 $E_b I_a = V I_a - I_a^2 R_a =$ input power – power loss thus, $E_b I_a =$ Gross mechanical power produce by the motor = P_m

Torque equation of DC Motor

mechanical power required to rotate the shaft on mechanical side $=T\omega$(1)

T =Torque in Newton-meter

 ω = angular velocity in radian/second

gross mechanical power produce by the motor on electrical side

 E_b =back emf in volts

 I_a =armature current in ampere

equating equations (1) and (2), we get,

 $E_b I_a = T\omega....(3)$

Torque equation of DC Motor

 $\omega = (2\pi N)/60$ where, N = Speed in rpm, and $E_b = (N \emptyset Z P)/(60 \text{ A})$

Thus, equation (3) becomes,

 $(N \emptyset Z P)^* I_a / (60 \text{ A}) = T(2\pi N) / 60$

 $T = P \emptyset Z I_a / (2\pi A) = 0.159 P \emptyset Z I_a / A = (0.159 P Z / A) \emptyset I_a$

P,Z and A are constants, hence we can write,

 $T \propto \emptyset I_a$

Thus torque produce by the DC Motor is proportional to the main field flux \emptyset and armature current I_a .

Types of DC Motor

Classification of the DC motor depends on the way of connecting the armature and field windings. DC motors are classified as:

- 1. DC Shunt Motor
- 2. DC Series Motor
- 3. DC Compound Motor

DC Shunt Motor



DC Shunt Motor

- In dc shunt motor the armature and field winding are connected in parallel across the supply voltage .
- The resistance of the shunt winding R_{sh} is always higher than the resistance of armature winding R_a .
- Since V and R_{sh} both remains constant the field current I_{sh} remains essentially constant, as the I_{sh} is responsible for generation of flux.

Thus, $\emptyset \propto I_{sh}$

• Therefore, shunt motor is also called as constant flux motor.

Torque and Speed equation of DC Shunt Motor

As we have seen for dc motor,

$$T \propto \emptyset I_a$$

but for dc shunt motor, $\emptyset \propto I_{sh}$

and I_{sh} is constant, thus \emptyset is also constant. So torque in dc shunt motor can be written as,

For dc motor, $T \propto I_a$ $E_b = (N \emptyset Z P)/(60 \text{ A})$

Z, P, A, Ø and 60 are constants.

Thus, $N \propto E_b = (V - I_a R_a)$ i.e. $N \propto (V - I_a R_a)$

Characteristics of DC Shunt Motor

To study the performance of the DC shunt Motor various types of characteristics are to be studied. These are:

- 1. Torque Vs Armature current characteristics.
- 2. Speed Vs Armature current characteristics.
- 3. Speed Vs Torque characteristics.

Characteristics of DC Shunt Motor



Characteristics of DC shunt motor

• The shaft torque T_{sh} is less than armature torque due to stray losses.

Applications of DC Shunt Motor

These motors are constant speed motors, hence used in applications requiring constant speed, such as:

- 1) Lathe machine
- 2) Drilling machine
- 3) Grinders
- 4) Blowers
- 5) Compressors

DC Series Motor



DC Series Motor

- The field winding is connected in series with the armature.
- The current passing through the series winding is same as the armature current .
- Therefore, the series field winding has fewer turns of thick wire than the shunt field winding.
- Also, the field winding will posses a low resistance then the armature winding.

Characteristics of DC Series Motor

To study the performance of the DC series Motor, the various types of characteristics are:

- 1. Torque Vs Armature current characteristics.
- 2. Speed Vs Armature current characteristics.
- 3. Speed Vs Torque characteristics

Characteristics of DC Series Motor

We know that, $T \propto \emptyset I_a$ Further, for DC series motor, $I_a = I_f = I$ Therefore, $T \propto I_a^2$ (A) Also, $E_b = (N\emptyset ZP)/(60 \text{ A})$ i.e. $N \propto E_b/\emptyset$ So, $N \propto 1/\emptyset$ or $N \propto 1/I_a$ (B)

Characteristics of DC Series Motor



Characteristics of DC series motor

Applications of DC Series Motor

These motors are useful in applications where high starting torque and quick acceleration is required, such as:

- 1) Traction
- 2) Hoists and Lifts
- 3) Cranes
- 4) Rolling mills
- 5) Conveyors



DC Compound Motor

- The DC compound motor is a combination of the series motor and the shunt motor.
- It has a series field winding that is connected in series with the armature and a shunt field that is in parallel with the armature.
- The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor . It can further be classified as:
- 1. Short shunt compound motor
- 2. Long shunt compound motor

Short Shunt Compound Motor

• When shunt field winding is connected in parallel with armature like dc shunt motor and this assembly is connected in series with the series field winding then this type of motor is called as short shunt compound motor.



Short-shunt connection

- Depending on the polarity of the connection short shunt motor is classified as:
- 1. Cumulative compound motor.
- 2. Differential compound motor.

Cumulative compound motor (short shunt)

- The two field windings i.e. series and shunt are wounded in such a way that the fluxes produced by them add or assist each other.
- The top of the shunt field is having positive polarity and is connected to the positive terminal of the armature.



 (a) Cummulative compound de motor (short shunt)

Cumulative compound motor (short shunt)

- The cumulative compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds. Since the shunt field is wired with similar polarity in parallel with the magnetic field aiding the series field and armature field, it is called cumulative. When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly.
- Recall that the shunt motor can provide smooth operation at full speed, but it cannot start with a large load attached, and the series motor can start with a heavy load, but its speed cannot be controlled. The cumulative compound motor takes the best characteristics of both the series motor and shunt motor, which makes it acceptable for most applications.

Differential compound motor (short shunt)

- Differential compound motors use the same motor and windings as the cumulative compound motor, but they are connected in a slightly different manner to provide slightly different operating speed and torque characteristics.
- The shunt field winding is connected in such a way that its polarity is reversed to the polarity of the armature. Since the shunt field is still connected in parallel with the armature only, it is considered a short shunt.

Differential compound motor (short shunt)

In the differential compound motor the shunt field is connected so that its magnetic field opposes the magnetic fields in the armature and series field. When the shunt field's polarity is reversed like this, its field will oppose the other fields and the characteristics of the shunt motor are not as pronounced in this motor. This means that the motor will tend to over speed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm. These two characteristics make the differential motor less desirable than the cumulative motor for most applications.

Long Shunt Compound Motor

- When the shunt field is connected in parallel with both the series field and the armature then this type of motor is called as long shunt compound motor.
- Depending on the polarity of connection of shunt field winding, series field winding and armature, long shunt motor is also classified as:
- 1. Cumulative Compound Motor.
- 2. Differential Compound Motor.



Characteristics of DC Compound Motor

To study the performance of the DC compound motor, the various types of characteristics are:

- 1. Torque Vs Armature current characteristics.
- 2. Speed Vs Armature current characteristics.
- 3. Speed Vs Torque characteristics

Characteristics of DC Compound Motor

- In dc compound motors, both shunt and series field acting simultaneously.
- In cumulative compound motor series field assist the shunt field.
- In such motors when armature current increases the field flux increases.
- So for given armature current the torque developed will be greater and speed lower when compared to a dc shun motor.
- In differential compound motor series field opposes the shunt field, therefore when armature current decreases the field flux decreases, so for given armature current, the torque developed will be lower and speed greater when compare to the dc shunt motor.

Characteristics of DC Compound Motor





Applications of Cumulative Compound Motor

These motors have high starting torque. They can be operated even at no loads as they run at a moderately high speed at no load. Hence cumulative compound motors are used for the following applications.

- 1. Elevators
- 2. Rolling mills
- 3. Punches
- 4. Shears
- 5. Planers

Applications of Differential Compound Motor

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

STARTER

Need of Starter

We know that,

 $V = E_b + I_a R_a....$ for a dc shunt motor and $V = E_b + I_a (R_a + R_s)...$ for a dc series motor Hence, the expression for I_a are as follows: $I_a = (V - E_b) / R_a...$ for dc shunt motor $I_a = (V - E_b) / (R_a + R_s)...$ for dc series motor At the time of starting of the motor, speed N=0 and hence the back emf $E_b = 0$. Hence the armature current at the time of starting is given by, $I_a(starting) = V / R_a...$ for dc shunt motor $I_a(starting) = V / (R_a + R_s)...$ for dc series motor

Need of Starter

- Since the values of R_a and R_s are small, the starting currents will be tremendously large if the rated voltage is applied at the time of starting.
- The starting current of the motor can be 15 to 20 times higher than the full load current.
- Due to high starting current the supply voltage will fluctuate.
- Due to excessive current, the insulation of the armature winding may burn.
- The fuses will blow and circuit breakers will trip.
- For dc series motors the torque $T \propto I_a^2$. So an excessive large starting torque is produced. This can put a heavy mechanical stress on the windings and shaft of the motor resulting in the mechanical damage to the motor.
- To avoid all these effects we have to keep the starting current of motor under safe limit. This is achieved by using starter.

Principle of starter

- Starter is basically a resistance which is connected in series with the armature winding only at the time of starting the motor to limit the starting current.
- The starter will remain in the circuit at the time of starting and will go out of the circuit gradually as the motor speeds up to a desire speed.



Principle of starter

- At the time of starting, the starter is in the start position so that the full starter resistance appears in series with the armature. This will reduce the starting current.
- The starter resistance is then gradually cut off. The motor will speed up, back emf will be developed and it will regulate the armature current. Now, the starter is no longer required.
- Thus starter is pushed to the Run position under the normal operating condition. The value of starter resistance is zero in this position and it does not affect the normal operation.

Types of starter:

- 1. Three point starter
- 2. Four point starter

SPEED CONTROL

Speed Control of DC Motor

We know the Back Emf, $\mathbf{E}_{\mathbf{b}} = \frac{P\emptyset NZ}{_{60A}}$

where, P = no. of poles, Ø = flux/pole, N = speed in rpm,

Z = no. of armature conductors, A = number of parallel paths.

 $\mathbf{E}_{\mathbf{b}}$ can also be written as, $\mathbf{E}_{\mathbf{b}} = \mathbf{V} \cdot \mathbf{I}_{\mathbf{a}} \mathbf{R}_{\mathbf{a}}$

Thus, from the above equations, we can write, $N = E_b 60A/P\emptyset Z$

For a DC motor, A, P and Z are constants.

Therefore, $\mathbf{N} \propto \mathbf{K} \mathbf{E}_{\mathbf{h}} / \mathbf{\emptyset}$ (where, K=constant)

This shows the speed of a dc motor is directly proportional to the back emf and inversely proportional to the flux per pole.

Speed Control of DC Shunt Motor

Field flux Control Method:

- To control the field flux, a rheostat is added in series with the field winding as shown in the circuit diagram.
- Adding more resistance in series with the field winding will decrease the field current and hence the field flux decreases and speed of the motor increases.
- Using this method, we always get speed above rated speed.



Speed Control of DC Shunt Motor

Armature Resistance Control Method:

 When the supply voltage V and the armature resistance R_a are kept constant, speed is directly proportional to the armature current I_a.



• Thus, if we add a resistance in series with the armature,

 I_a decreases and, hence, the speed also decreases.

- Construction of Permanent Magnet DC Motor (PMDC) is similar to conventional DC Motor except the stator poles are replaced by suitable permanent magnets.
- No need to have field windings.
- Although dc motors up to 75 hp have been designed with permanent magnets, the major application of permanent magnets is confined to fractional-horsepower motors for economic reasons.



- In a conventional dc motor with a wound-field circuit, flux per pole depends on the current through the field winding and can be controlled.
- However, flux in a PM motor is essentially constant and depends on the point of operation.
- For the same power output, a PM motor has higher efficiency and requires less material than a wound dc motor of the same ratings.
- However, the design of a PM motor should be such that the effect of demagnetization due to armature reaction, which is maximum at standstill, is as small as economically possible.
- Since the flux in a PM motor is fixed, the speed- and current-torque characteristics are basically straight lines as shown in the next slide.



where K_a , V_s , Φ_p , R_a , and T_d are the machine constant, supply voltage, flux per pole, resistance of the armature winding, and developed torque.



Speed- and current-torque characteristics of a PM motor.

- The speed-torque characteristic of a PM motor can be controlled by changing either the supply voltage or the effective resistance of the armature circuit.
- The change in the supply voltage varies the no-load speed of the motor without affecting the slope of the characteristic.
- Thus for different supply voltages, a set of parallel speed-torque characteristics can be obtained, as shown in the following Figure.



Operating characteristics for different supply voltages.