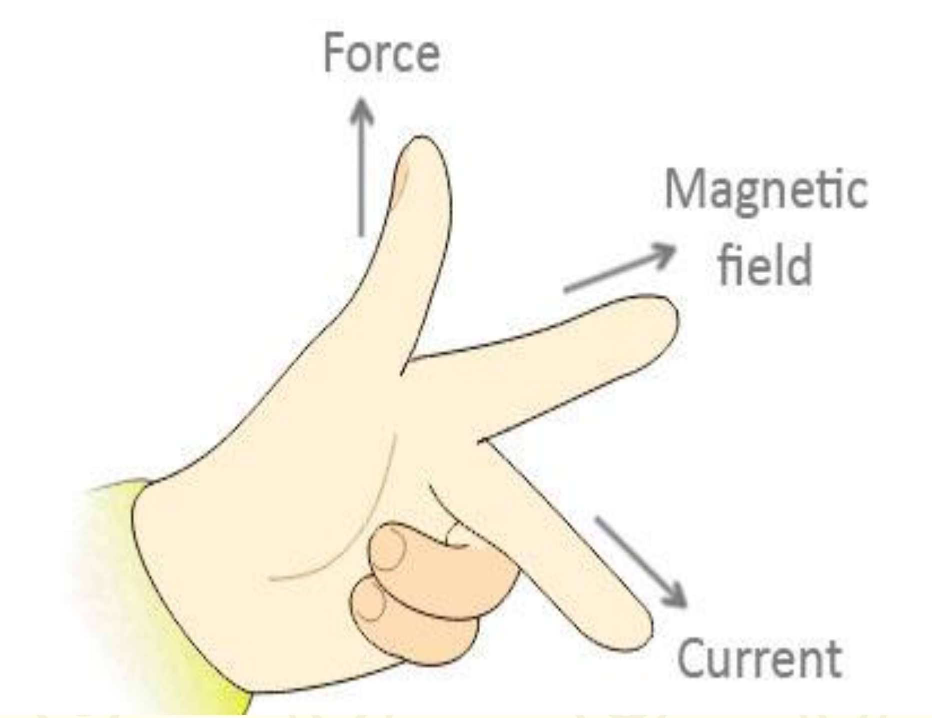
4.2 DC Motors

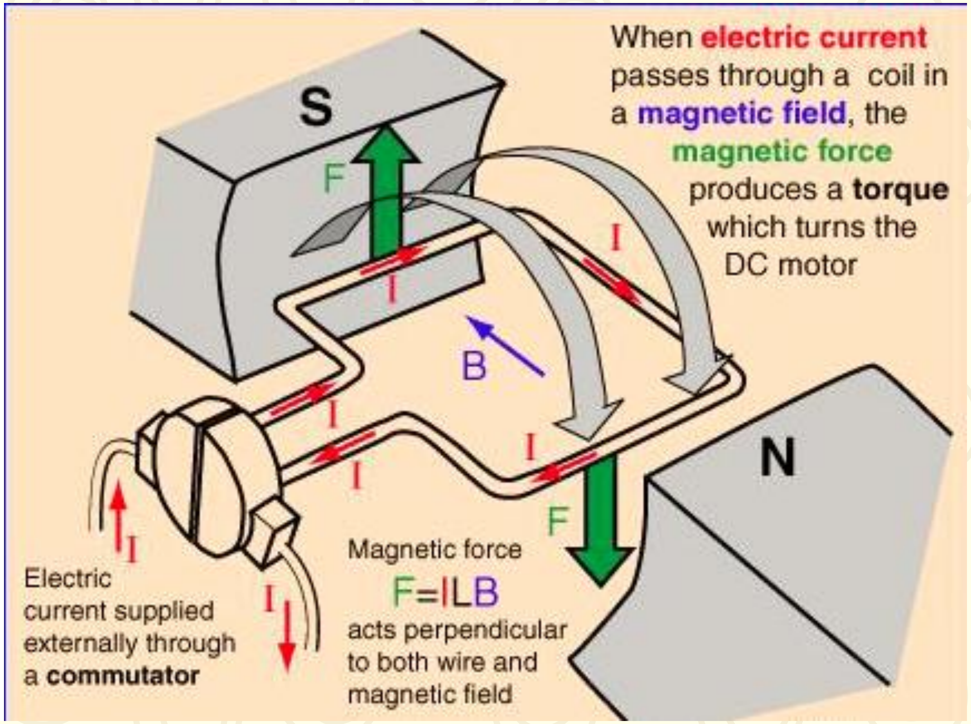
Syllabus

Construction and working principle of DC motors such as series, shunt and compound, torque-speed characteristics, selection criteria and applications (no derivations and numerical expected)

Working Principle of DC motors

- An electric motor is a machine which converts electric energy into mechanical energy.
- Its action is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force. The direction of force is given by Fleming's left hand rule and magnitude is $F=BIL$ Newton, where B is flux density wb/m^2, I is current through conductor, L is length of conductor.



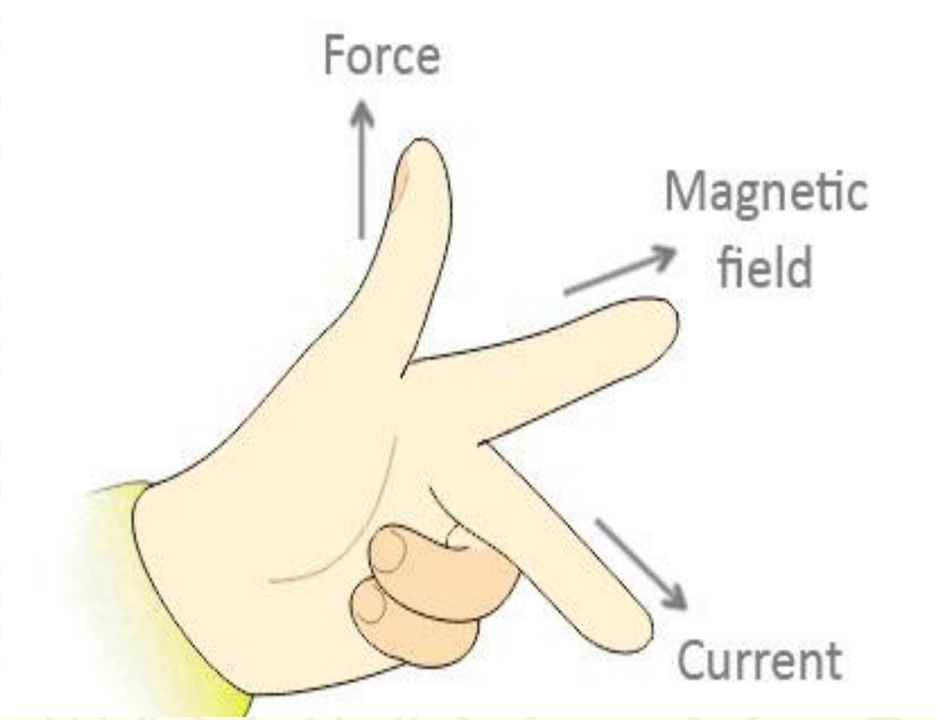


Working Principle of DC motors

WATCH BELOW UTUBE VIDEO

y2mate.com - DC Motors_ How Do They Work_ Construction & Working Principle_fWyzPdyCAzU_360p.mp4

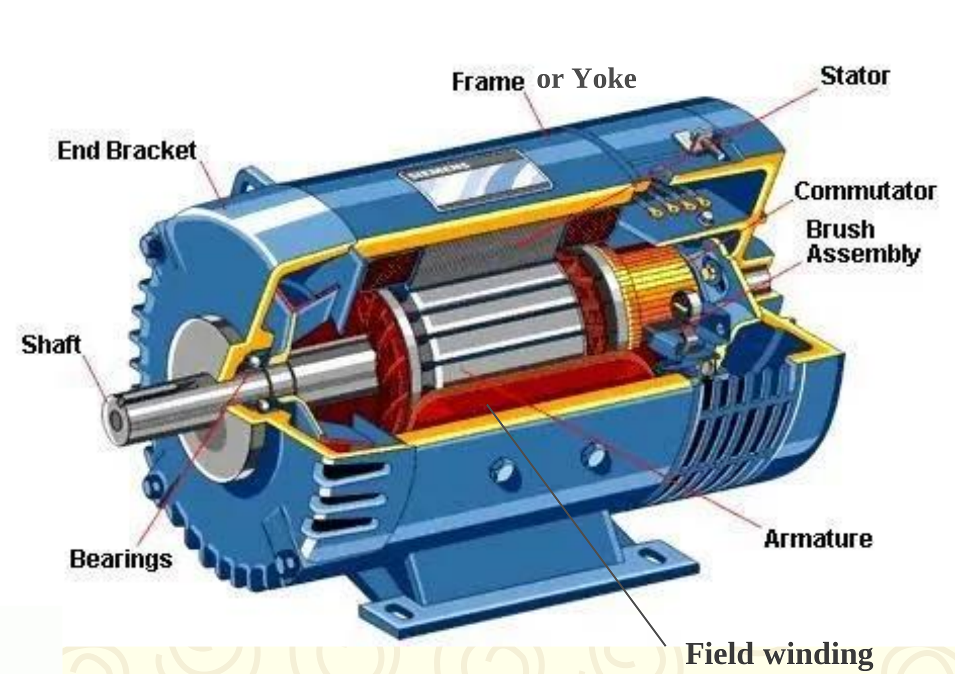
Fleming's left hand rule

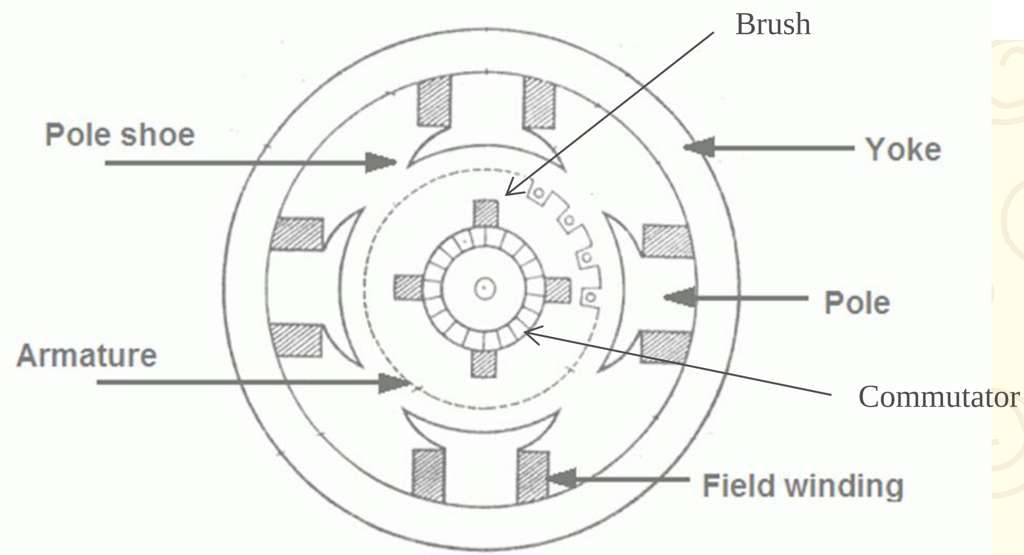


According to **Fleming's left hand rule**, if the thumb, fore-finger and middle finger of the left hand are stretched to be perpendicular to each other as shown in the illustration at left, and if the fore finger represents the direction of magnetic field, the middle finger represents the direction of current, then the thumb represents the direction of force. Fleming's left hand rule is applicable for motors.

Construction of DC motors

The main parts used in the construction of a DC motor are the yoke, poles, field winding, Armature, commutator, carbon brushes, bearings





Construction of a DC Motor

Construction of DC motors…

- **Yoke/Frame:**

The yoke acts as the outer cover of a DC motor and it is also known as the frame. The yoke is an iron body, made up of low reluctance magnetic material such as cast iron, silicon steel, rolled steel etc. Yoke serve two purposes, firstly it provides mechanical protection to the outer parts of the machine secondly it provides low reluctance path for the magnetic flux.

- **Poles and Pole Shoe**

The pole and pole shoe are fixed on the yoke by bolts. These are made of thin cast steel or wrought iron laminations which are riveted together. Poles produce the magnetic flux when the field winding is excited. Pole shoe is an extended part of a pole. Due to its shape, the pole area is enlarged and more flux can pass through the air gap to the armature.

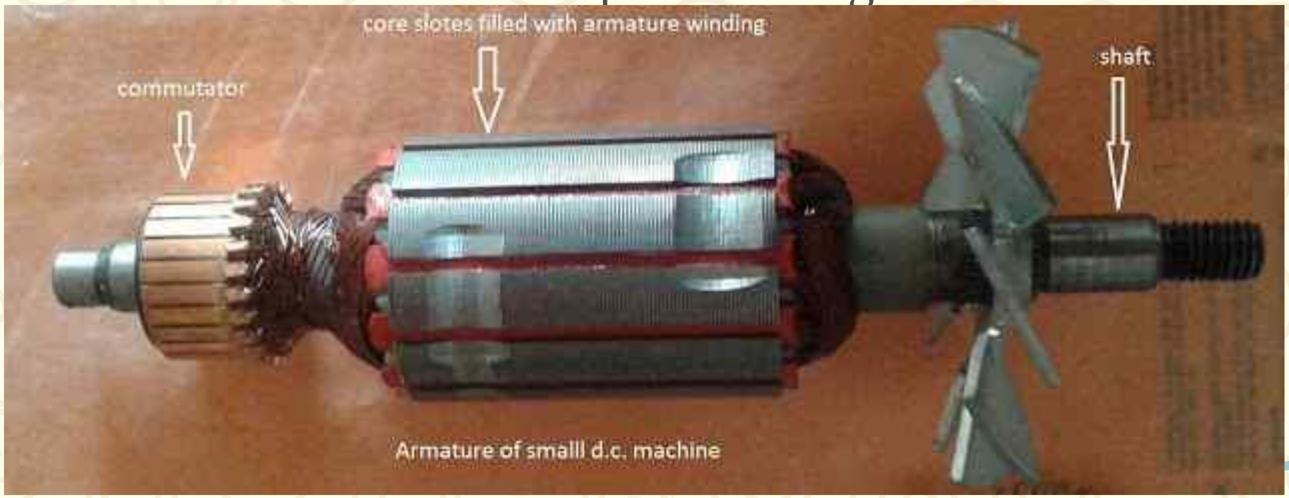
Construction of DC motors…

- **Field Winding**

The coils around the poles are known as field (or exciting) coils and are connected in series to form the field winding. Copper wire is used for the construction of field coils. When the DC current is passed through the field windings, it magnetizes poles which produce magnetic flux.

- **Armature Core**

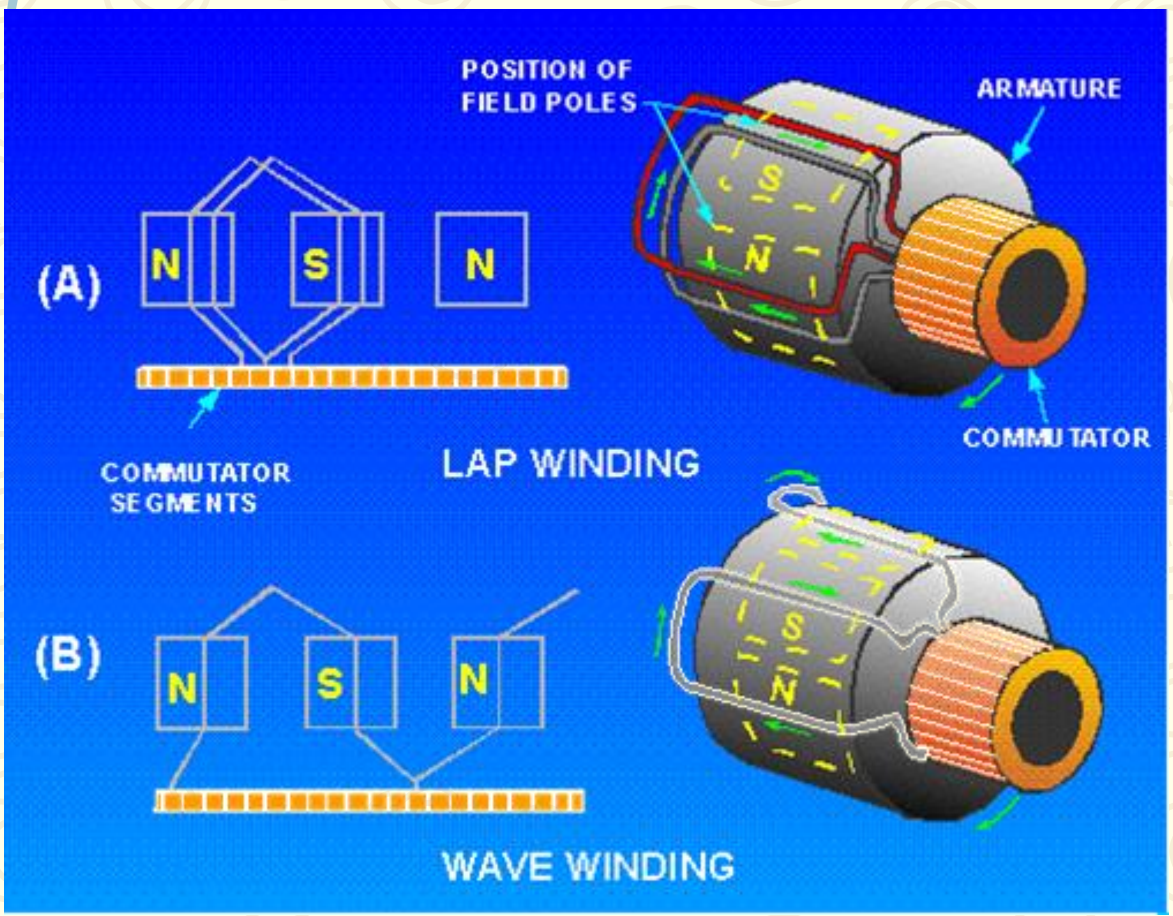
It is a cylindrical drum and keyed to the rotating shaft. A large number of slots are made all over its periphery, which accommodates the armature winding. Low reluctance, high permeability material such as cast iron and cast steel are used for armature core. The laminated construction is used to produce the armature core to minimize the eddy current losses. The air holes are also provided on the armature core for the air circulation which helps in cooling the motor.



Construction of DC motors…

- **Armature Winding**

The armature winding plays very important role in the construction of a DC motor because the conversion of power takes place in armature winding. On the basis of connections, there are two types of armature windings named: Lap winding & Wave Winding



Construction of DC motors…

- **Armature Winding**

LAP WINDING	WAVE WINDING
1. lap winding is high current, low voltage	1.wave winding is low current, high voltage.
2.IN LAP winding,if connection is in started form conductor in slot,then connections overlap each other as winding proceeds till startng point is reached again.	2.IN WAVE type of connection winding always travels ahead avoiding overlapping.it travels like a progressive wave
3.IN LAP winding, no. of parallel paths = holes i.e,A=P=4	3.IN WAVE winding,no. of parallel paths=2
4.LAP winding is preferrable for high current low voltage capacity generator	4.WAVE winding is preferrable for high voltage low current capacity generator
5.Lap windings are also used for applications requiring lower voltages at higher currents	5.Wave windings are used for applications requiring higher voltages at lower currents

Construction of DC motors…

- **Commutator**

The commutator connects the rotating armature conductor to the stationary external circuit through carbon brushes. It converts alternating torque into unidirectional torque produced in the armature.

Carbon Brushes

The current is conducted from voltage source to armature by the carbon brushes which are held against the surface of commutator by springs. They are made of high-grade carbon steel and are rectangular in shape.

Bearings

The ball or roller bearings are fitted in the end housings. The friction between stationary and rotating parts of the motor is reduced by bearing. Mostly high carbon steel is used for making the bearings as it is very hard material.

Back E.M.F in DC Motor

When the armature winding of a DC motor rotates in the magnetic field produced by the field winding, it cuts the magnetic flux. Hence an EMF is induced in the armature winding according to the Faradays law of electromagnetic induction. And as per Lenz's law, this induced EMF acts in opposite direction to the armature supply voltage. Therefore, this EMF is known as the back EMF and it is denoted by E_b.

This back EMF induced in a DC motor can be expressed mathematically as,

$$\boldsymbol{E_b} = \frac{\Phi \boldsymbol{ZNP}}{\boldsymbol{60\ A}}$$

Where P = number of poles

Φ = flux per pole in Wb

N = speed of motor in RPM

Z = number of armature conductors

A = number of parallel paths

Back E.M.F in DC Motor…

- Average emf generated per conductor is given by $d\Phi/dt$ (Volts
- Flux cut by one conductor in one revolution = $d\Phi = P\Phi$ …..(Weber)
- Number of revolutions per second (speed in RPS) = $N/60$
- Therefore, time for one revolution = $dt = 60/N$ (Seconds)

So emf generated per conductor = $d\Phi/dt = P\Phi N/60$ (Volts)
Above equation gives the emf generated in one conductor of the generator.

The conductors are connected in series per parallel path, and the emf across the terminals is equal to the generated emf across any parallel path.

Therefore, $E_b = P\Phi NZ / 60A$

Torque equation of a DC motor

- When armature conductors of a DC Motor carry current in the presence of stator field flux, a mechanical torque is developed between the armature and the stator.
- Torque is given by the product of the force and the radius at which this force acts.
  Torque T = F × r (N-m) …where, F = force and r = radius of the armature
- Work done by this force in once revolution = Force × distance = $F \times 2\pi r$ (where, $2\pi r$ = circumference of the armature)
- Net power developed in the armature = word done / time = (force × circumference × no. of revolutions) / time = $(F \times 2\pi r \times N) / 60$ (Joules per second) …..(A)
- But, $F \times r = T$ and $2\pi N/60$ = angular velocity ω in radians per second. Putting these in the above equation (A)
- Net power developed in the armature = $P = T \times \omega$ (Joules per second)

Torque equation of a DC motor…

Armature torque (Ta)

- The power developed in the armature can be given as, $Pa = Ta \times \omega = Ta \times 2\pi N/60$. The mechanical power developed in the armature is converted from the electrical power,

- Therefore, mechanical power = electrical power

  i.e $Ta \times 2\pi N/60 = Eb.Ia$

  We know, $Eb = P\Phi NZ / 60A$
- Therefore, $Ta \times 2\pi N/60 = (P\Phi NZ / 60A) \times Ia$

  Rearranging the above equation,

  $Ta = (PZ / 2\pi A) \times \Phi.Ia$ (N-m)

- The term $(PZ / 2\pi A)$ is practically constant for a DC machine.
- **Thus, armature torque is directly proportional to the product of the flux and the armature current i.e. $Ta \propto \Phi.Ia$**

Power Equation of a D.C. Motor

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

  $V = Eb + Ia\ Ra$

- Multiplying both sides of the above equation by Ia we get,

  $VIa = Ia\ Eb + I^2a\ Ra$,

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

VIa = Net electrical power input to the armature measured in watts.

$I^2a\ Ra$ = Power loss due to the resistance of the armature called armature copper loss.

So difference between VIa and $I^2a\ Ra$ i.e. input – losses gives the output power.

So Eb Ia is called electrical equivalent of gross mechanical power developed by the armature. This is denoted as Pm.

Gross mechanical power developed in the armature = Power input to the armature – Armature copper loss

Power Equation of a D.C. Motor

Condition for Maximum power

For a motor from power equation it is known that

$$Pm = VIa - I^2a\ Ra$$

For maximum gross mechanical power so $\frac{dPm}{dIa} = 0$

$V - 2\ Ia\ Ra = 0$

$Ia\ Ra = V/2$

But $V = Eb + Ia\ Ra = Eb + V/2$

So Eb = V/2 is condition for maximum power.

Classification of DC Motors

(A). DC Motor (Electromagnet)

- **Separately excited DC motors**
- **Self excited DC motors**
  - **Shunt Motor**
  - **Series Motor**
  - **Compound Motor**
    - **Cumulative compound**
    - **Differential compound**

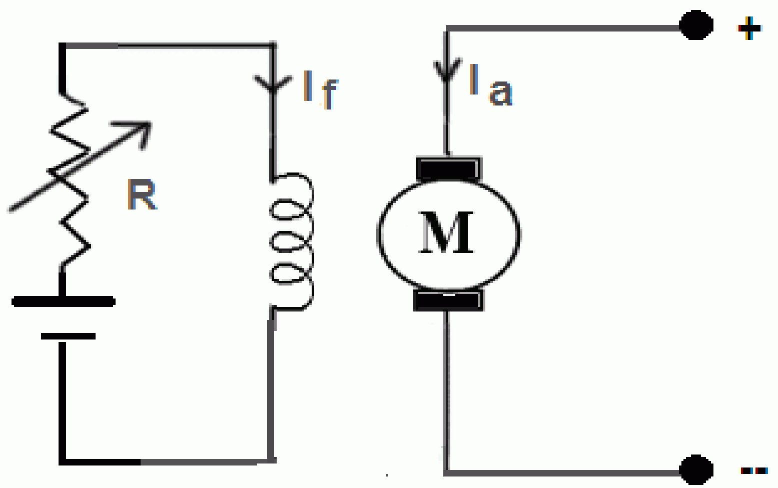
(B). Permanent Magnet DC Motor

In these motors, the magnetic field is produced by small magnets. These motors are made in very small sizes and ratings. These motors are used where very small driving torque is required like toys.

Classification of DC Motors…

- **Separately Excited DC Motor**

In these motors, the armature and field coils are fed from different supply sources.



Circuit diagram of separately excited motor

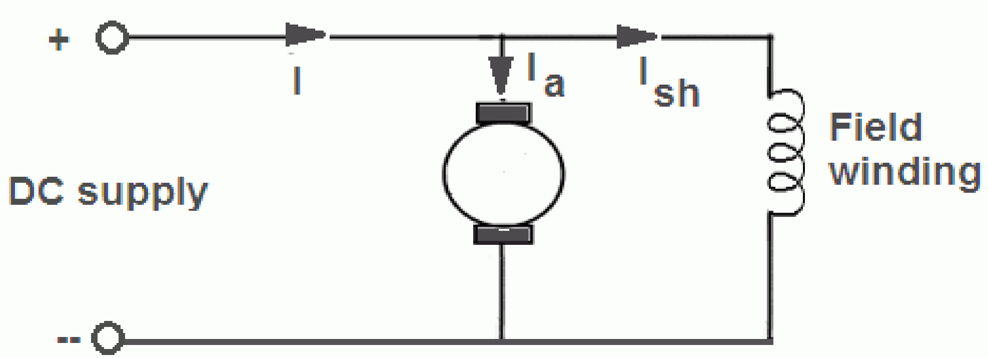
Very accurate speed control can be obtained by these motors.
These motors are best suited for the applications where speed variation is required from very low value to high value.

Classification of DC Motors…

Self excited motors

DC Shunt Motor

In the DC shunt motor , the armature and field winding are connected in parallel as shown in the figure.

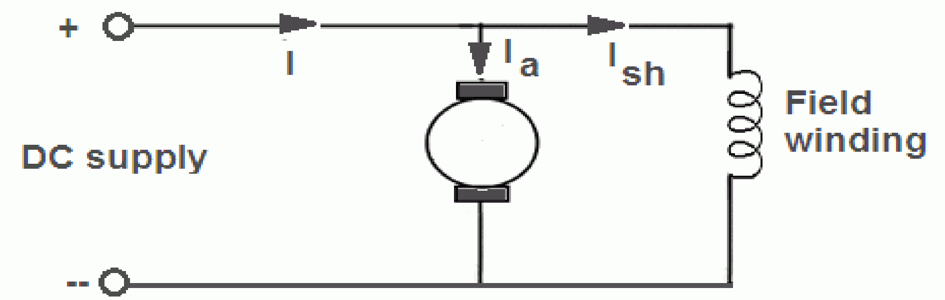


Circuit diagram of shunt motor

The field winding consists of a large number of turns of fine wire. The cross-sectional area of the wire used for field winding of shunt motor is always smaller than that of the wire used for the armature winding. Therefore, the resistance of field winding is more than that of the armature winding.

Classification of DC Motors…

DC Shunt Motor



Circuit diagram of shunt motor

Voltage and Current Relations for DC Shunt Motor

Total current drawn from the voltage source $I = I_a + I_{sh}$ Where I_a = armature current, I_{sh} (field current) = V/R_{sh}

Since the applied voltage (V) and the field resistance (R_{sh}) are almost constant, therefore field current (I_{sh}) remains constant. As the field current is responsible for flux generation so the flux produced in the shunt motor also remains constant. This is why **shunt motor is also known as constant flux motors**.

Therefore **flux, $\varphi \propto I_{sh}$ (constant)**

Supply voltage $\mathbf{V = E_b + I_a R_a}$,

Where E_b = back EMF, R_a = armature resistance.

Classification of DC Motors…

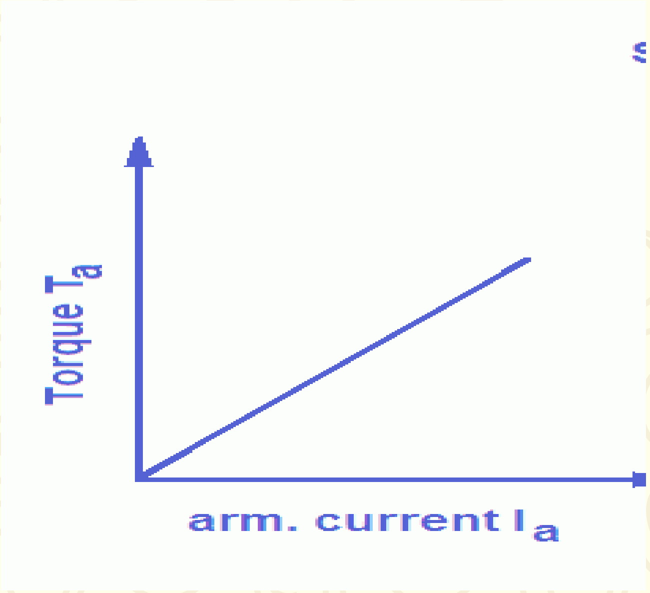
DC Shunt Motor Characteristics and Applications

A. Torque – Current Characteristics (T v/s I_a)

We know that, T α $I_a\varphi$

But flux of a shunt motor is practically constant. Therefore, T α I_a

Therefore, torque current characteristics of a shunt motor is a straight line passing through the origin. Although the field current remains practically constant, yet the field flux becomes slightly weaker at heavy loads, due to armature reaction, hence the curve bends slightly bends at heavy loads.



Classification of DC Motors…

DC Shunt Motor Characteristics and Applications

B. Speed Current Characteristic (N v/s I_a)

Back EMF of shunt motor is given by $E_b = V - I_aR_a = (P\varphi NZ)/60A$

Because P, N, Z and A are constant Therefore

$\mathbf{E_b \; \alpha \; N\varphi}$, or $\mathbf{V - I_aR_a \; \alpha \; N\varphi}$ or $\mathbf{N \; \alpha \; (V - I_aR_a)/\varphi}$ …….(1)

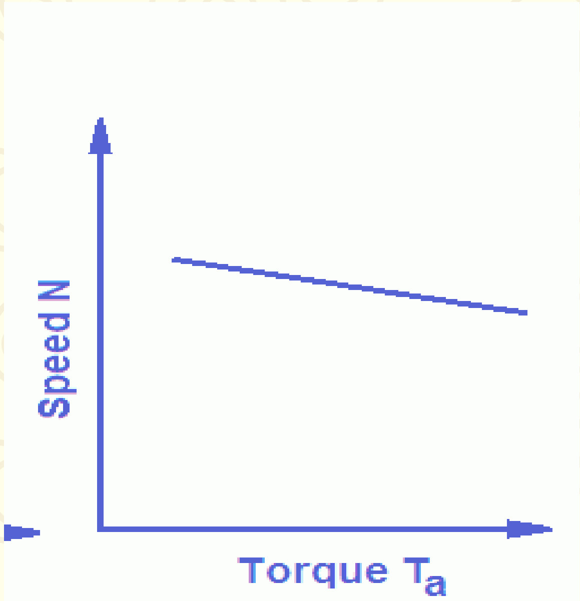
The field flux of shunt motor is almost constant. Therefore, the numerator of RHS of equation (1) decreases with increase in load (or I_a). So there is a little fall in speed with the increase in load, hence the curve bends slightly as the load is increased due to increased I_aR_a voltage drop.

Classification of DC Motors…

DC Shunt Motor Characteristics and Applications

C. Speed – Torque Characteristics (N v/s T)

The speed torque characteristics are similar to speed current characteristics.

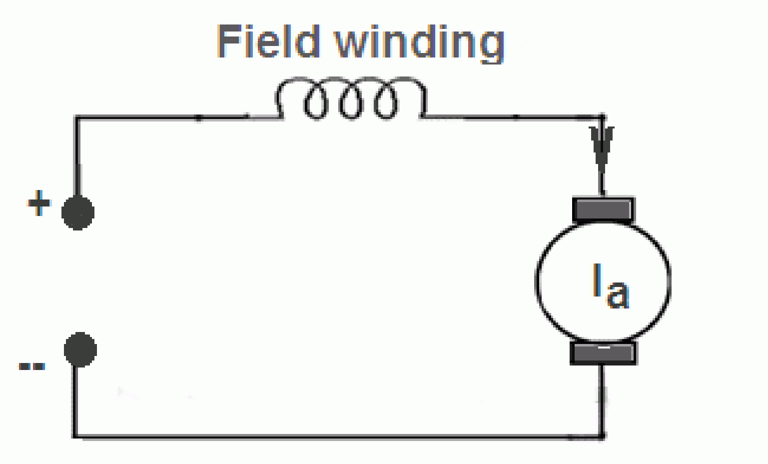


Because there is no appreciable change in the speed of a shunt motor from no-load to full-load, it may be connected to loads which are totally and suddenly thrown off without any fear of excessive speed resulting. Due to the constancy of their speed, shunt motors are suitable for driving shafting, machine tools, lathes, wood-working machines and for all other purposes where an approximately constant speed is required.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

In the DC series motor, the armature and field windings are connected in series with each other. The field winding of DC series motor consists of few turns of thick wire. Therefore, the resistance of the series field winding(R_s) is much smaller as compared to that of the armature resistance.



Circuit diagram of DC series motor

Voltage and Current Relations

As armature and the field winding are in series, therefore,

$I = I_a = I_s$

Where I = total current drawn by the motor

I_a = armature current

I_s = series field current

Total supply voltage V is given by,

$\mathbf{V = E_b + I_a(R_a + R_s)}$

E_b = back EMF

I_a = armature current

R_a = armature resistance

R_s = series field resistance.

In the DC motors flux produced is proportional to the field current. But in the series motor, the field current is same as the armature current. Thus the armature current (I_a) and hence field current is load dependent. So with the increase in load flux also increases. Therefore, **DC series motor is a variable flux motor**.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

A. Torque – Current characteristics (T v/s I_a)

For a series motor,

Torque α Armature current x Field flux

$T \propto I_a \varphi$

Before saturation, $\varphi \propto I_a$, Therefore, $T \propto I_a^2$

After magnetic saturation of core, flux (φ) is independent of I_a i.e. flux does not increase with increase in armature current. Therefore after saturation, $T \propto I_a$

Therefore, on light loads, the torque produced by the series motor is proportional to the square of armature current and hence curve drawn between torque and armature current up to magnetic saturation is a parabola. But after magnetic saturation flux φ is independent of excitation current and so torque is proportional to I_a and hence characteristics become a straight line.

B. **Speed – Current Characteristics (N v/s I_a)**

We know that $E_b = (P\varphi NZ)/60A$ or $N = (60AE_b)/P\varphi Z$

In above equation, all quantities are constant except E_b and φ.

$N \propto E_b / \varphi$

also $E_b = V - I_a R_a$

Classification of DC Motors…

DC Series Motor Characteristics and Applications

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Classification of DC Motors…

DC Series Motor Characteristics and Applications

B. Speed – Current Characteristics (N v/s I_a)

We know that $E_b = (P\varphi NZ)/60A$

or $N = (60AE_b)/P\varphi Z$

In above equation, all quantities are constant except E_b and φ.

$N \propto E_b / \varphi$

also $E_b = V - I_a R_a$ Therefore, $N \propto (V - I_a R_a) / \varphi$

In a DC series motor, initially the field flux φ rises in proportion to the current but after saturation, it is independent of armature current. Consequently, speed N is roughly proportional to the current. The speed may become dangerously high if load reduces to a small value.

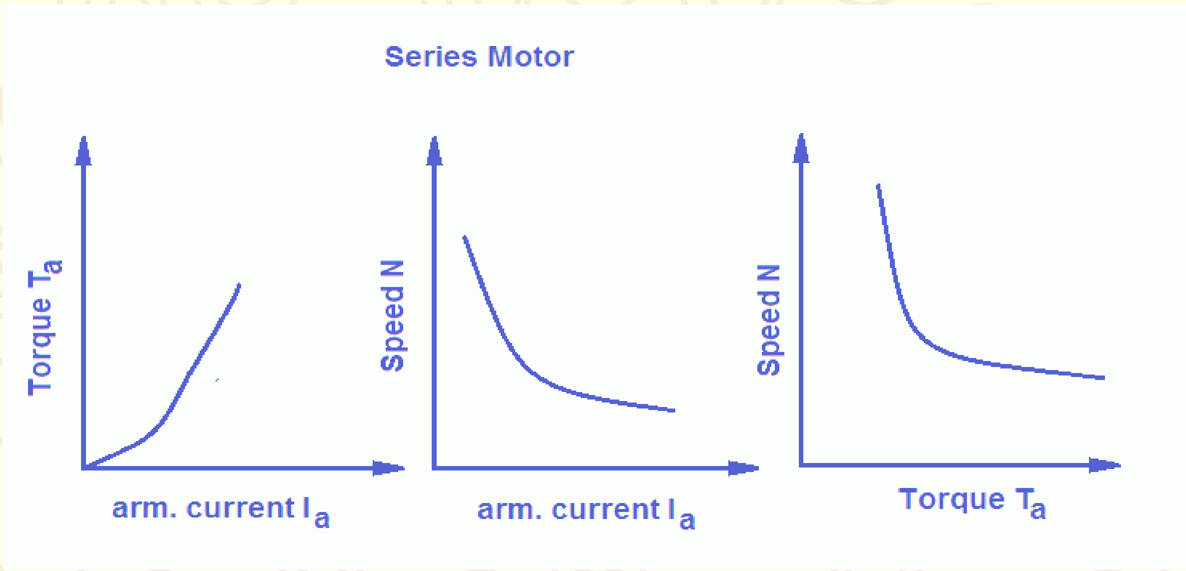
When load is heavy, I_a is large. Hence, speed is low (this decreases E_b and allows more armature current to flow). But when load current and hence I_a falls to a small value, speed becomes dangerously high. Hence, a series motor should never be started without some mechanical (not belt-driven) load on it otherwise it may develop excessive speed and get damaged due to heavy centrifugal forces so produced. It should be noted that series motor is a variable speed motor.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

C. Speed – Torque Characteristics (N v/s T)

Since a series motor develops high starting torques at low speeds and low torque at high speeds, therefore, speed – torque characteristics of a DC series motor is a hyperbola. **High starting torque enables, even a small series motor to start a heavy load.**



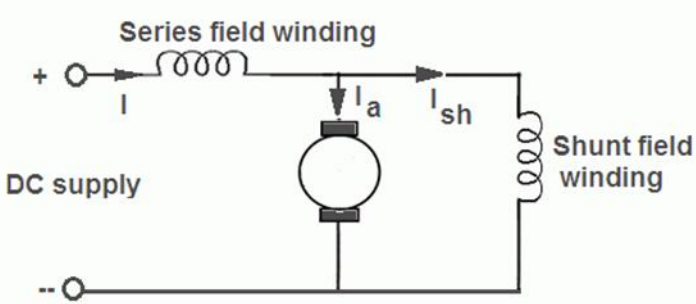
Application of DC Series Motor

DC series motors are used where high starting torque is required like hoists, cranes, electrical locomotives, elevators etc.

Classification of DC Motors…

DC Compound Motors

Shunt and series, both the field windings are present in compound motors. In these motors, a part of the field winding is connected across the armature and remaining field winding is connected in series with the armature. These compound motors are further subdivided into two types, namely, cumulative compound and differential compound.



cumulative compound motor circuit diagram

- In the cumulative compound motor, shunt and series field winding is connected in such a way that the direction of flow of current is same in both the field windings i.e. series field flux strengthens the field due to shunt field winding.

Differential Compound Motor

In the differential compound motor, shunt and series field winding is connected in such a way that the direction of flow of current is opposite in both the field windings i.e. series field flux weakens the field due to shunt field winding.

Classification of DC Motors…

DC Compound Motor Characteristics and Applications

A. Torque – Current Characteristics

In the case of a cumulative compound motor, as the armature current increases, the series flux increases, so flux per pole increases.

But T α Iaφ

Consequently torque also increases; however, this increase in torque is greater than that of the shunt motor.

Whereas in the case of a differential compound motor, series field opposes the shunt field so the total flux of such motor decreases with increase in current (i.e. load). Hence in a differential compound motor, torque increases with increase in current.

B. Speed – Current Characteristics

In cumulative compound motor, series field aids the shunt field, so flux per pole increases as the armature current increase and hence speed decreases.

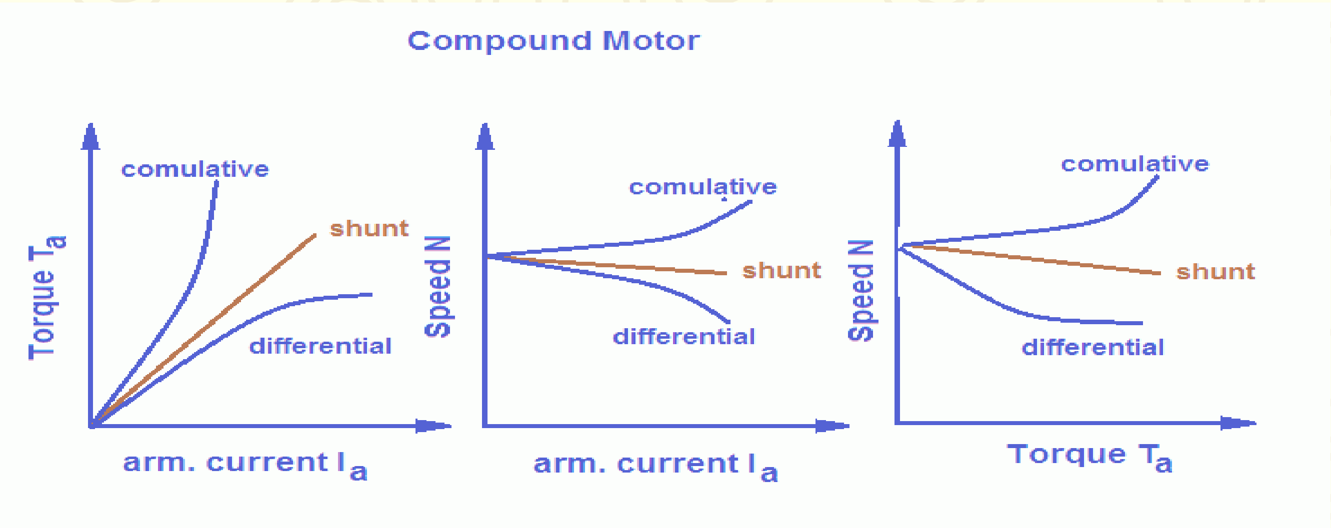
Whereas in a differential compound motor, series field opposes the shunt field, so flux per pole decreases as the armature current increase and hence speed increases.

Classification of DC Motors…

DC Compound Motor Characteristics and Applications

Speed – Torque Characteristics

In a cumulative compound motor, the series excitation helps the shunt excitation hence speed decreases with increase in torque whereas torque increases very slightly with the speed.



Applications of DC Compound Motor

A cumulative compound motor has a fairly constant speed and good starting torque. Such motors are used where series characteristics are required and the load is likely to be removed totally. These motors are used in driving machines which are subject to the sudden application of heavy loads; they are used in rolling mills, punching and shearing machines, mine-hoists etc.

In a differential compound motor, the motor speed will increase with an increase in the load, which leads to an unstable operation. Therefore, a differential compound motor is rarely used for any practical application.