L01

DC Motors

Electrical Machinery

Introduction

An **electrical machine** is a term which collectively refers to motors and generators, both of which can be designed to operate using AC (Alternating Current) power or DC power.

Operation Principle of DC Motor

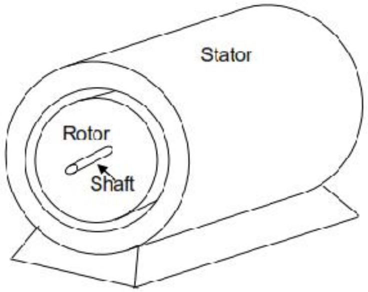
The purpose of an electrical motor is to convert electrical power into mechanical power. DC motors do this by using direct current electrical power to make a shaft spin. The mechanical power available from the spinning shaft of the DC motor can be used to perform some useful work such as turn a fan.

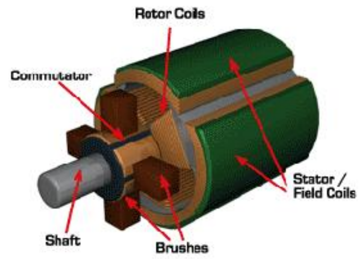
The rotation of the DC motor is accomplished by the force which is developed on a current-carrying conductor in a magnetic field.
The current-carrying conductor is connected to the shaft which is able to rotate relative to the stationary body of the DC motor.

Physical parts of an electrical machine

Using the idea of electromagnetic coupling one can divide any motor into two physical parts:

- one part which rotates **«the rotor»**
- one part which does not rotate **«the stator»**.

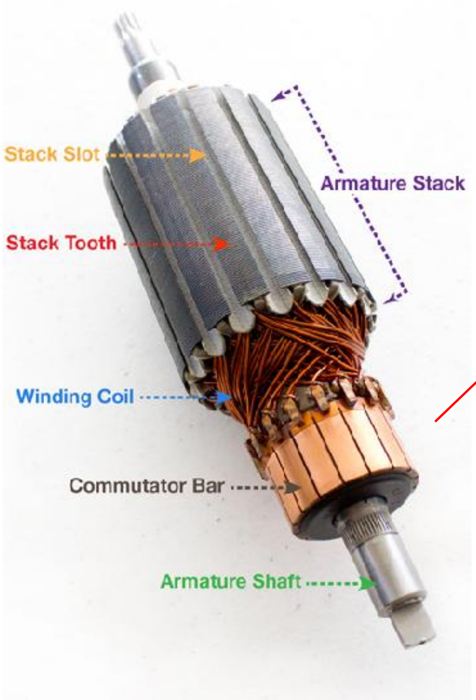


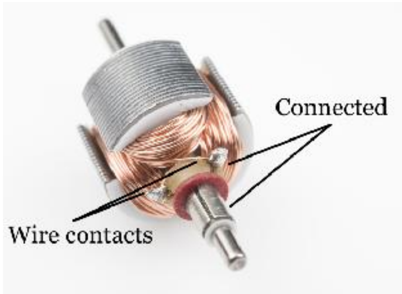


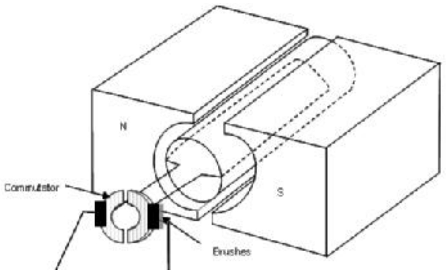
Since DC motors use DC current and voltage to power the motor, it is necessary to change the direction of the DC current that is applied to the current-carrying conductor within the rotor. This is accomplished by utilizing a segmented metal ring, called **a commutator**.

Physical parts of an electrical machine

A commutator is directly connected to the current-carrying conductor, so it will rotate with the rotor.

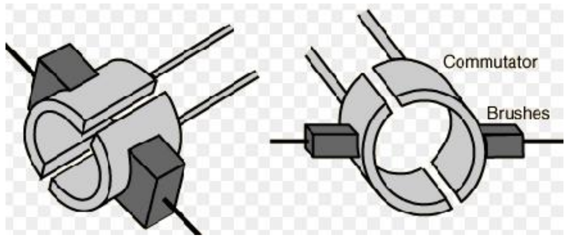


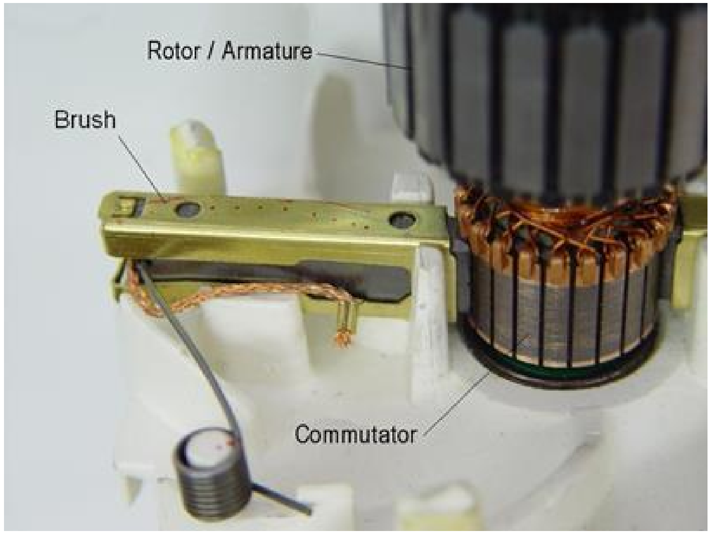




The commutator is made from two round pieces of copper, one on each side of the spindle. A piece of carbon (graphite) is lightly pushed against the copper to conduct the electricity to the armature. The carbon brushes against the copper when the commutator spins.

<u>The *commutator* </u>maintains electrical contact with its external DC electrical power source by using metal or hard <u>carbon *brushes*</u>





Functional parts of an electrical machine

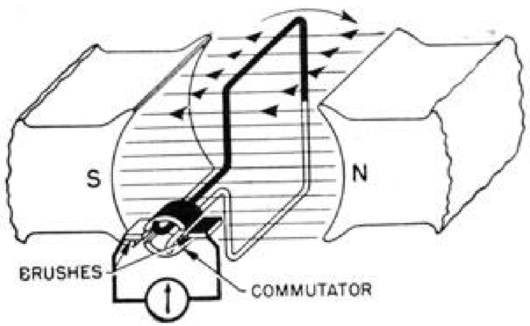
Electrical machines can also be divided into two functional parts.

- One functional part is the magnetic field, simply called *the field*, and
- the other functional part is the conductor, which is called *the armature.*

In a given machine, one functional part is associated with one physical part, and the other functional part is then associated with theother physical part. So there are two possible configurations for electrical machines:

1. The field rotates with the rotor and the armature is on the stator, or
2. The armature rotates with the rotor while the field is on the stator.

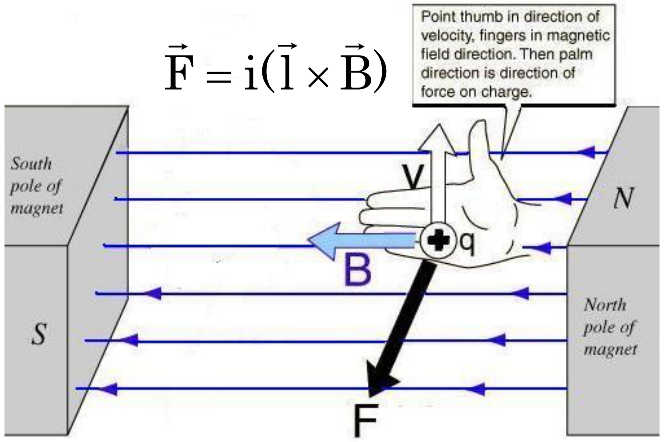
The DC motor will use a rotating armature inside a magnetic field, which is developed within the stator as shown



Operation of a DC Motor

A DC motor operates by using the force described by the Magnetic force law.

The current passing through the stator coil creates an electro-magnet with a North/South pole



DC voltage is applied across the armature and the current carrying armature moves in the magnetic field generated in the stator.

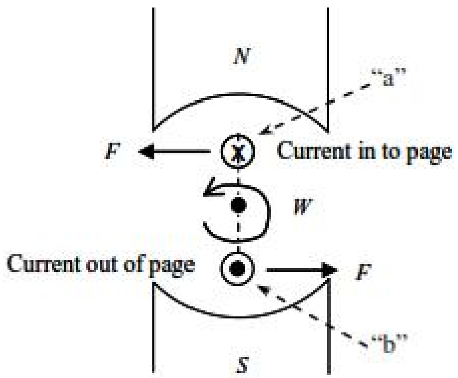
Operation of a DC Motor

$$\vec{F} = i(\vec{l} \times \vec{B})$$

The magnetic Force is a result of a cross product, it can be seen that the magnetic force acts

- to pull the top conductor (“a”) of the armature loop towards the left,
- to pull the lower conductor (“b”) towards the right.

These two forces rotate the armature that is attached to the rotor.



The armature current is always in the same direction, the conductor (“a”) shown on the top in Figure will always be pulled towards the left and the conductor (“b”) shown on the bottom in Figure will always be pulled towards theright

At best, this motor would only rotate through one-half (180º) of a rotation andwould stop when the “a” conductor is in the 9 o’clock position and the “b” conductor is in the 3 o’clock position

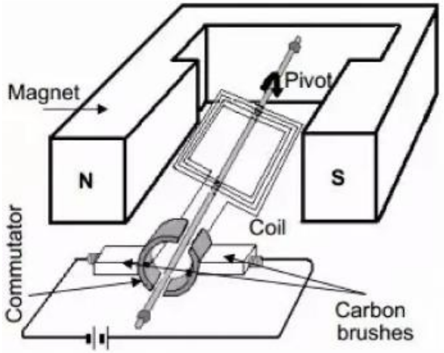
In order to provide continuous rotation, the armature current (Ia) must change direction every 180 degrees of rotation.
This process (commutation) is accomplished by brushes and a segmented commutator bar.

The force is now directed to pull the “a” conductor towards the right and the “b” conductor towards the left, allowing the motor to rotate through more than one-half of a rotation.

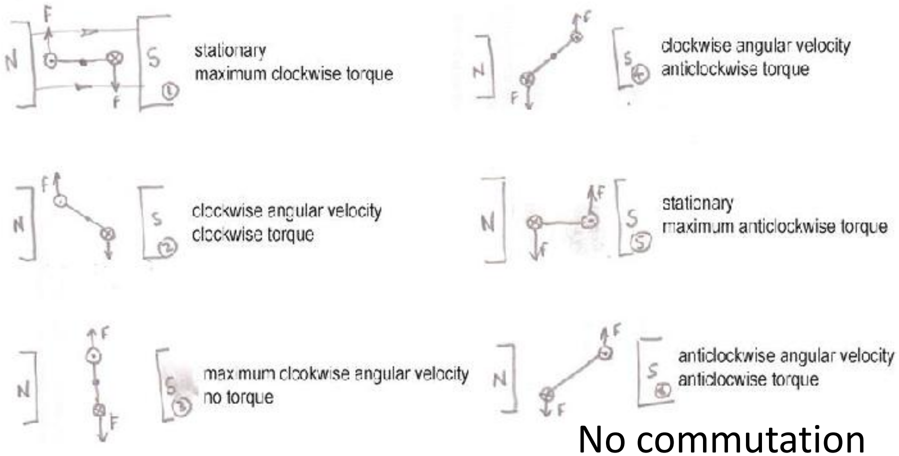
By changing the current direction every half-rotation (when the conductors are in the 3 and 9 o’clock positions), the Lorentz force is always acting to keep the motor spinning 360 degrees in one direction.

Electrical Machinery

How commutation works



A split - ring commutator (sometimes just called a commutator)is a simple and clever device for reversing the current direction through an armature every half turn



No commutation

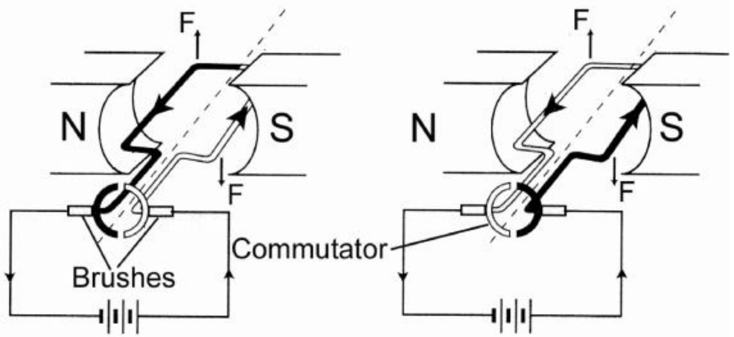


Fig. 3-2a

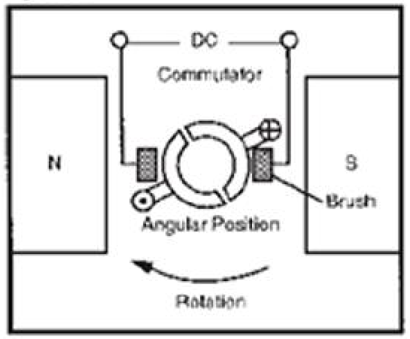
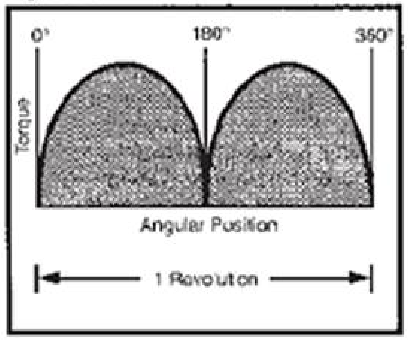


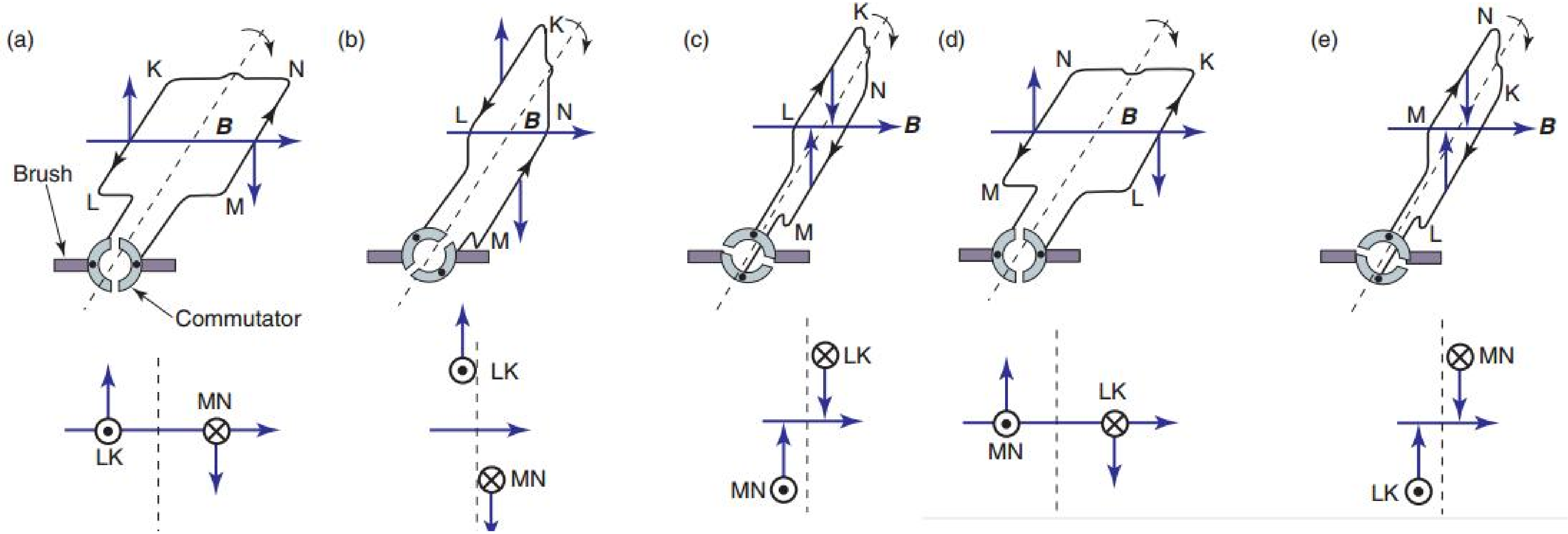
Fig. 3-2b.



As the motor rotates, first one piece of copper, then the next connects with the brush every half turn. The wire on the left side of the armature always has current flowing in the same direction, and so the armature will keep turning in the same direction

As the coil becomes perpendicular to the magnetic field, the direction of current in the coil reverses, causing the forces acting on the coil to switch their direction. The coil then continues to rotate in a clockwise direction.

Operation of a DC Motor



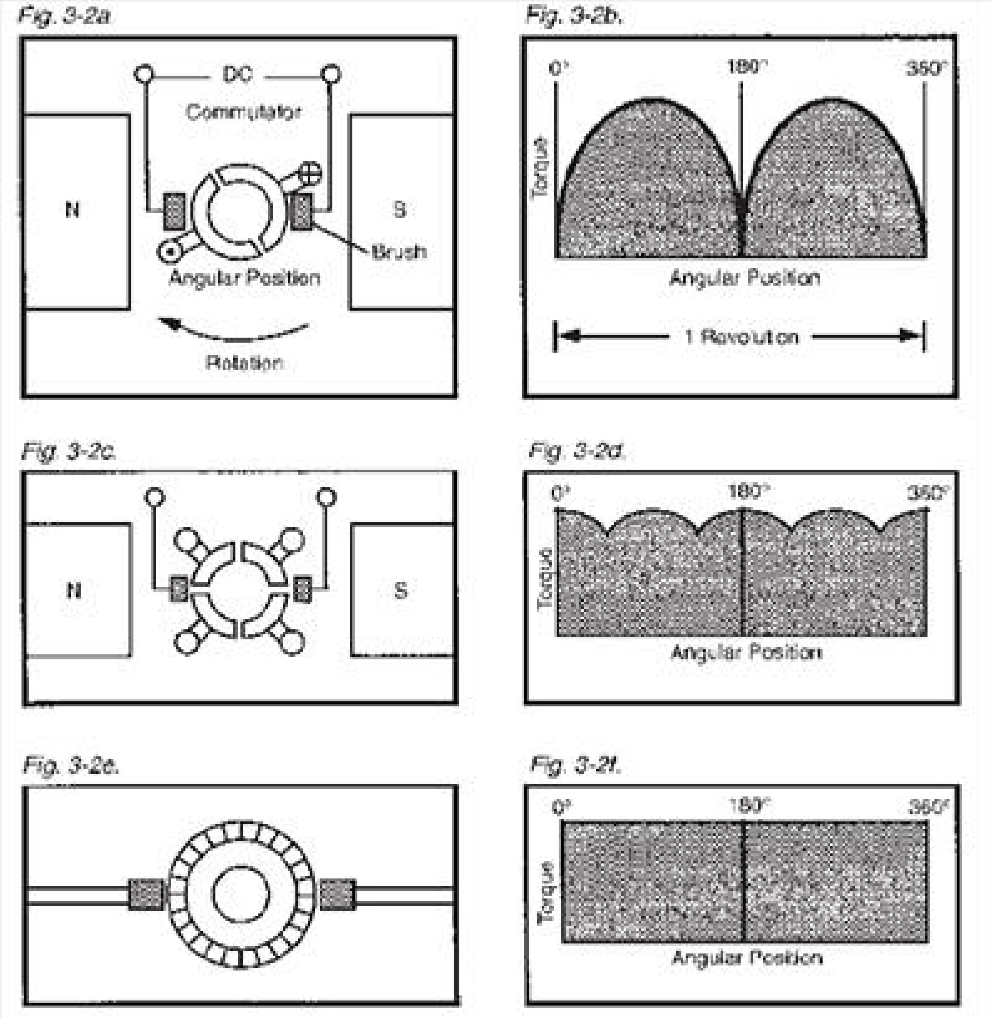
Electrical Machinery

How commutation works

The torque produced on the armature is proportional to the sine of the angle between the magnetic field and the plane of the rotating coil. The torque will produce a ripple type waveform as shown below (b). This figure shows that the resulting torque reaches zero at the two vertical positions during the armature (loop) rotation. This simple motor relies on the inertia of the armature to carry it through the zero torque points to continue its rotation

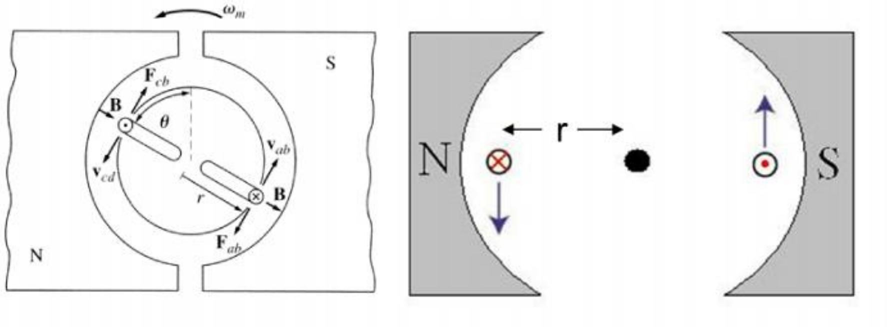
To eliminate this effect and keep a level of torque always at some point above zero. a four-segment commutator and two armature coils may be used (see figure below - c). This arrangement staggers forces to keep the torque at an acceptable level. The torque/position curve will then look like the figure below (d).

The more segments added to the coils and corresponding commutator armature, the closer the torque curve will approximate a straight line characteristic. See the figure below (e and f).



32-segment commutator

Developed Force and Torque



The force between the rotating electromagnet and the stationary magnetic field is given by the Lorentz Force Law.

$$\vec{F}_d = I_a \vec{L} x \vec{B}$$

Torque=Force x Distance: $T = F_D r = (I_a \vec{L} x \vec{B}) r \quad (\mathrm{N \cdot m})$

where r = radius from central axis

If power is only applied to the armature wire in the optimum position, the cross product becomes simple multiplication: $T = BLI_a r$

2 wires being acted upon $T = 2BLI_a r$

Torque can be significantly increased by increasing:

- The magnetic field
- The current
- The number of wires being acted upon

The most practical way to increase torque is to increase the number of wires being acted upon: $T = 2NBLI_a r$

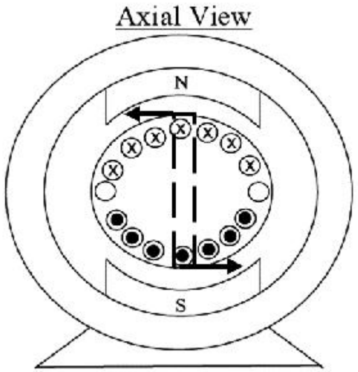
where N = number of turns of wire

*This equation is greatly simplified by using the torque Constant (K_t) [V*sec].*

$$\mathrm{T} = \mathrm{K_t I}$$ *where Kt=2NBLr*

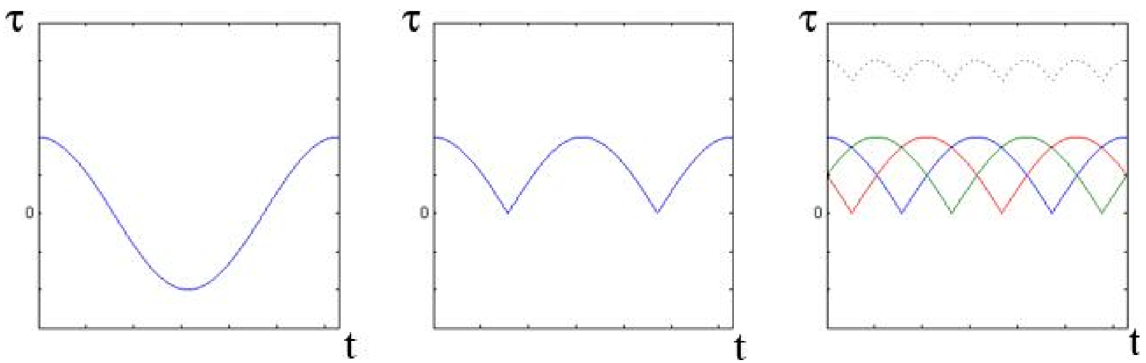
Developed Force and Torque

Multiple sets of windings are used on the rotor to ensure that torque is applied smoothly throughout the rotation of the motor.



Each winding is only briefly supplied current when it is at the position where it would apply maximum torque to the rotor.

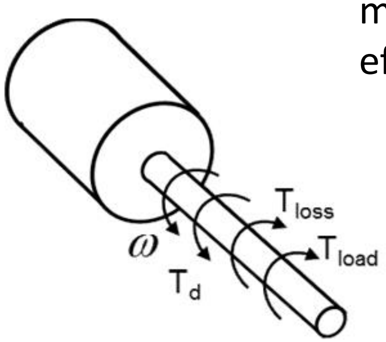
This ensures maximum efficiency of the motor, since power isn’t wasted on forces which try to pull the rotor apart.



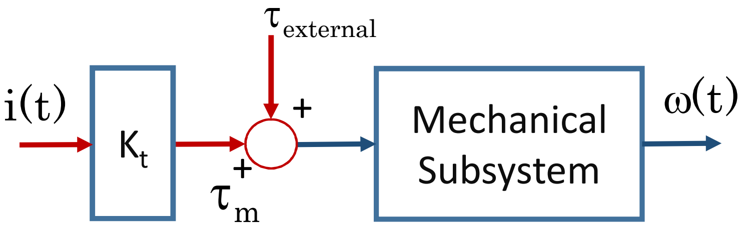
Electrical Machinery

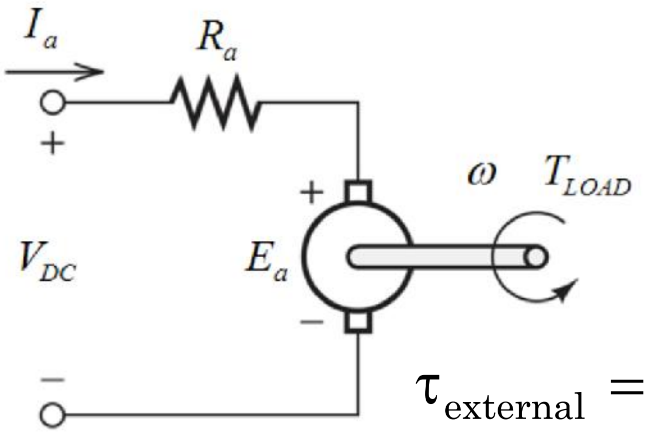
DC Motors

Torque Balance



With developped torque and moving mechanical parts and other disturbance effects, a torque balance is settled.

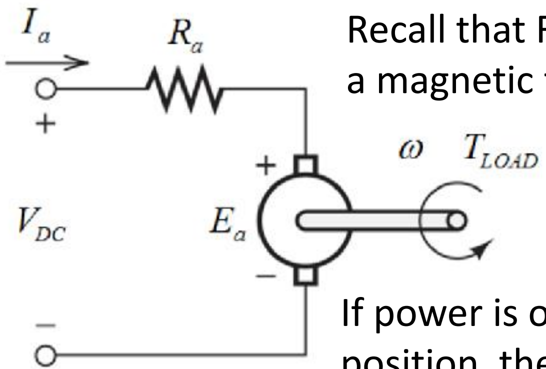




$$\tau_{external} = \tau_{load} + \tau_{loss}$$

$$Watt = \frac{N \cdot m}{sec} \quad \rightarrow \quad N \cdot m = Watt \cdot sec = V \cdot A \cdot sec$$

Armature circuit



Recall that Faraday's Law states that a voltage is induced in a circuit when a conductor is moved through a magnetic field. The induced voltage is given by

$$E_a = l(\vec{v} \times \vec{B})$$

Turning now to a rotating machine, where angular velocity is related to linear velocity

$$v = wr$$

If power is only applied to the armature wire in the optimum position, the cross product becomes simple multiplication:

$$E_a = 2NBlrw$$

$$E_a = K_v w$$

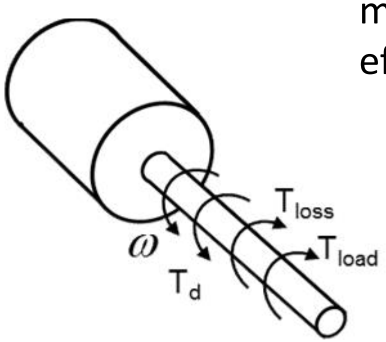
where Kv=2NBLr

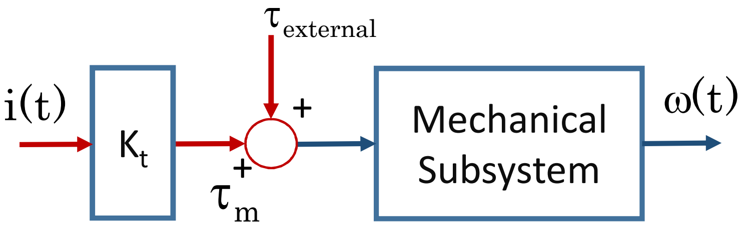
$$V_{DC} - I_a R_a - E_a = 0$$

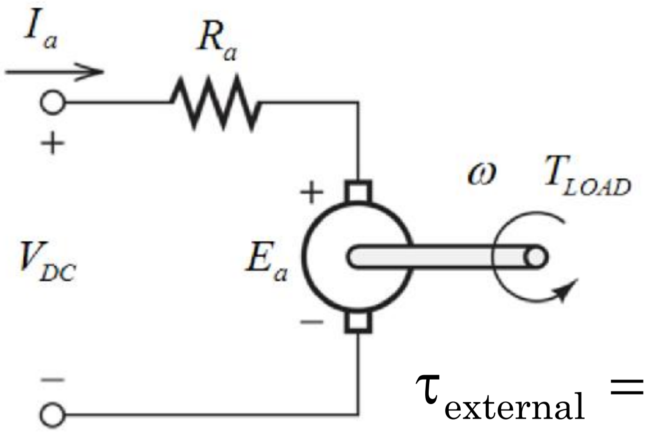
Electrical Machinery

Torque Balance

With developped torque and moving mechanical parts and other disturbance effects, a torque balance is settled.







$$\tau_{\text{external}} = \tau_{\text{load}} + \tau_{\text{loss}}$$

$$Watt = \frac{N \cdot m}{\sec} \quad \rightarrow \quad \mathrm{N \cdot m = Watt \cdot sec = V \cdot A \cdot sec}$$

Developed Power

Developed power (Pd) is given by

$$P_d = E_a I_a = T_d \mu = K_v I_a \mu$$, where is the angular velocity

Also, the power into the DC motor is given by: $P_{in} = V_{DC} I_a$

And the electrical losses in the armature (due to R_a) are given by: $P_{elecloss} = I_a^{\ 2} R_a$

Ignoring rotational losses, developed power is the mechanical output, from which machine efficiency can be calculated as:

¦ $$= \frac{P_{out}}{P_{in}} 100 = \frac{P_D}{P_{in}} 100 \quad (T_{loss} = 0)$$

$$Watt = \frac{N \cdot m}{\sec} \quad \rightarrow \quad \mathrm{N \cdot m = Watt \cdot sec = V \cdot A \cdot sec}$$

Review of concepts

Torque Developed:

$$T_d = K_v I_a$$

Mechanical Power Developed:

$$P_d = E_a I_a = T_d \omega = K_v I_a \omega$$

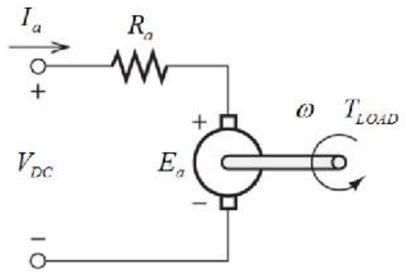
Angular velocity:

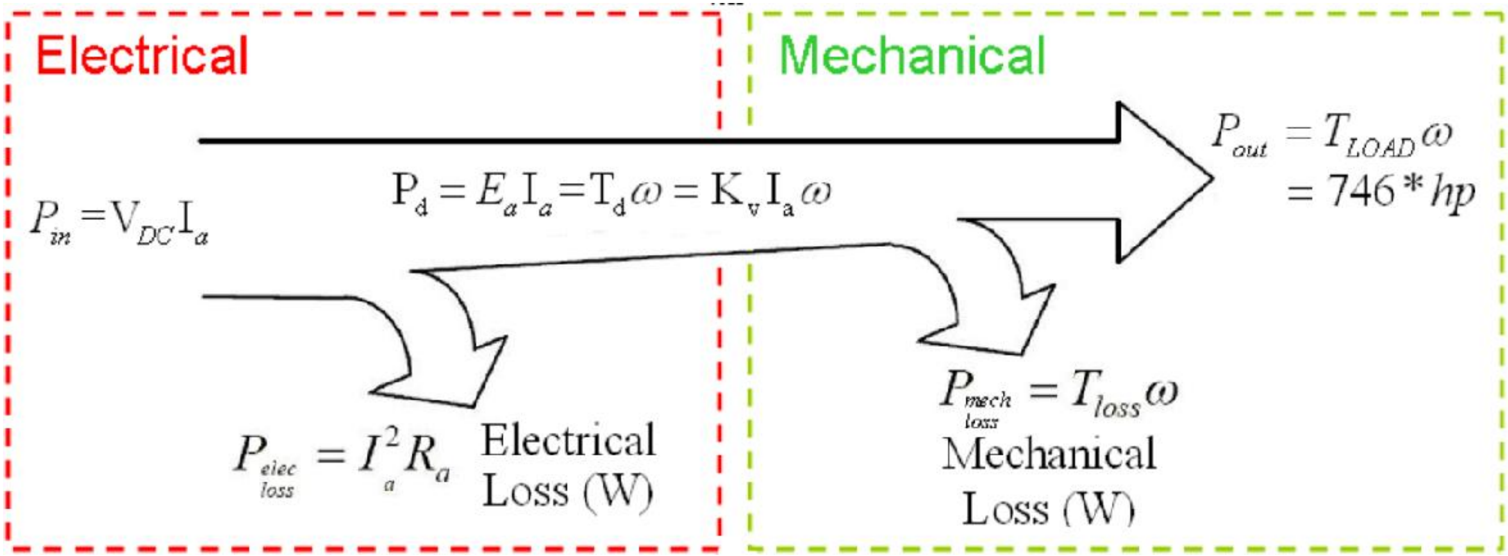
$\omega = 2$ ® $(RPM/60)$

Back EMF:

$$E_a = K_v \omega$$

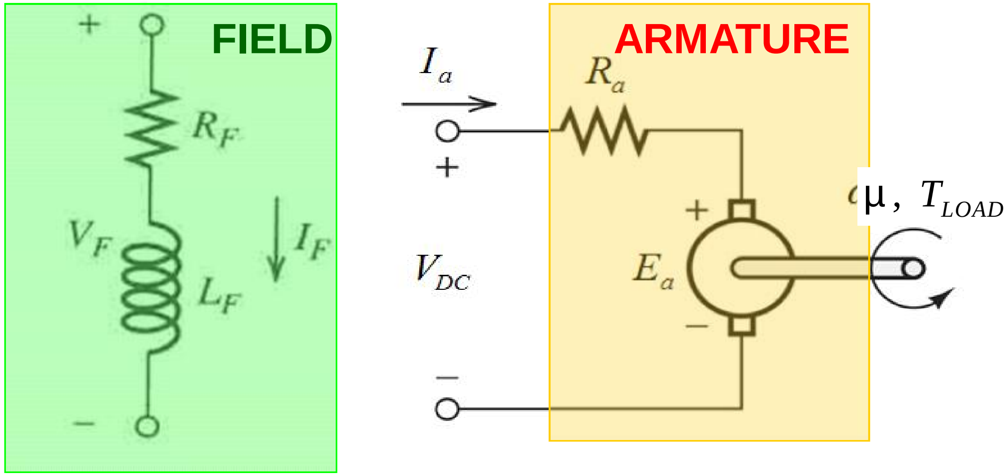
$$V_{DC} - I_a R_a - E_a = 0$$





Types of DC Motors

Types of a DC Motors

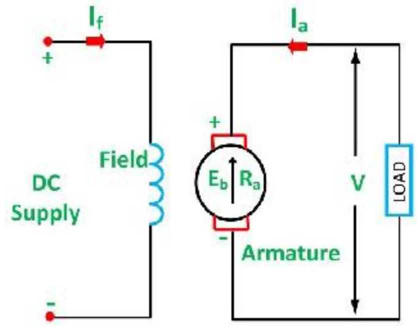


A Direct Current Motor is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors.

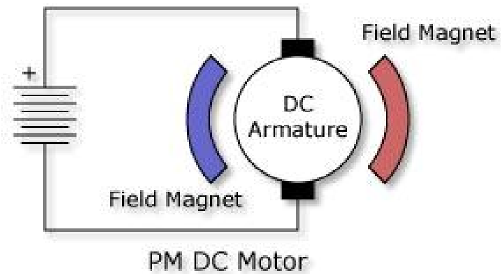
1. Separately Excited DC Motor
2. Self-excited DC Motor. The self-excited motors are further classified as
   a. Shunt wound or shunt motor,
   b. Series wound or series motor and
   c. Compound wound or compound motor

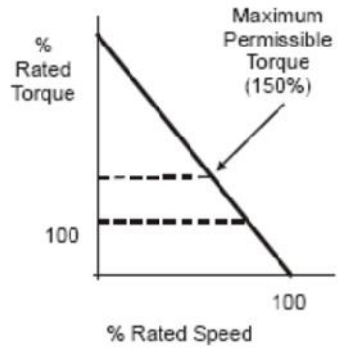
Seperately Excited motors

The field coils or field windings are energised by a separate DC source



Permanent Magnet DC Motor



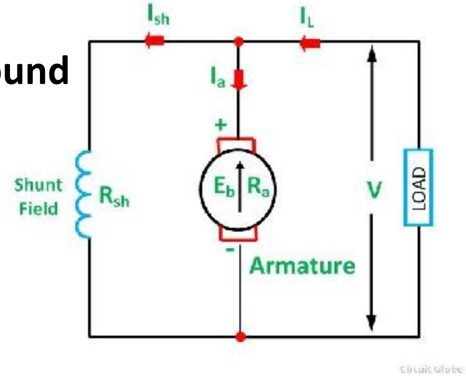


The permanent magnet motor is a DC-only commutated motor that uses permanent magnets to provide the stationary field poles. Power is applied only to the DC rotor (armature) through a set of carbon brushes

Types of DC Motors

Self-excited DC Motor: Shunt wound

The field winding is connected in parallel with the armature

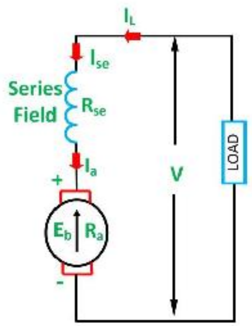


the electrical power supplied

$$\boxed{VI_a} = \boxed{EI_a} + I_a^2R$$

mechanical power developed

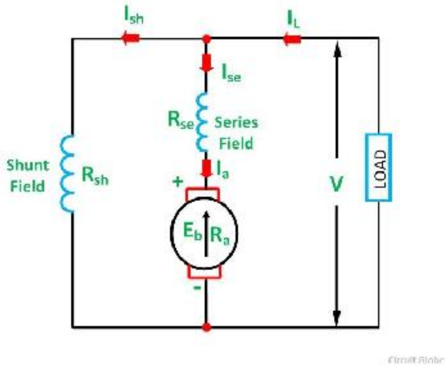
Self-excited DC Motor: Series Wound



The field winding is connected in series with the armature winding.

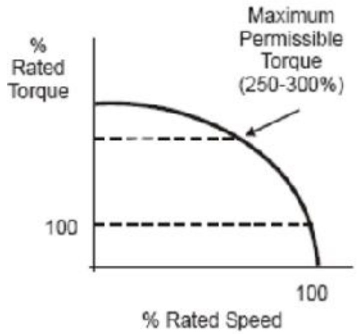
$$VI = EI + I^2(R_{se} + R_a)$$

Self-excited DC Motor: compound Wound

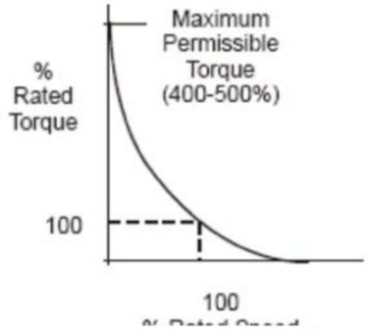


A DC Motor having both shunt and series field windings is called a Compound Motor

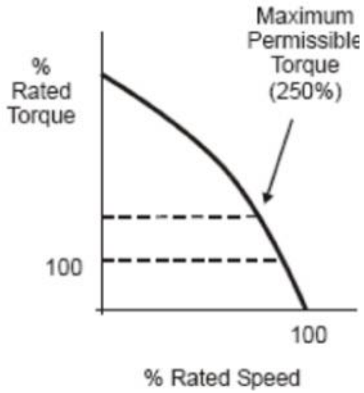
Speed - Torque characteristics



Shunt motor gives almost constant speed for over wide range of mechanical load torques.



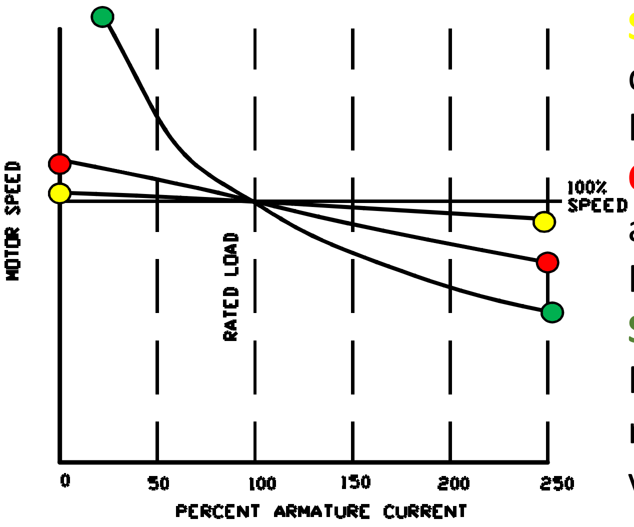
A characteristic of series motors is the motor develops a large amount of starting torque. However, speed varies widely between no load and full load. Series motors cannot be used where a constant speed is required under varying loads.



A compound wound DC offers the high starting torque of a series wound motor. In addition, it offers constant speed regulation (speed stability) under a given load.

Types of DC Motors

Speed-Torque Characteristics Compared

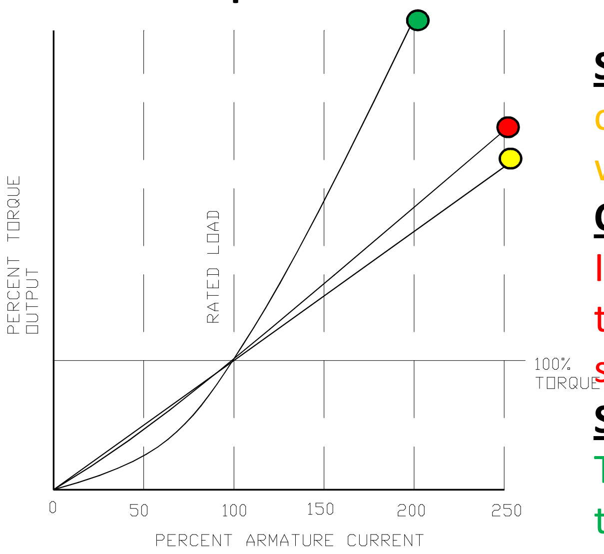


Shunt - constant speed due to constant flux. Regulation approx. 5%

Compound - speed varies as load changes Regulation approx 15-25%

Series - variable speed. No load condition causes motor to accelerate to very high speeds

Current-Torque Characteristics Compared



Shunt - constant field flux causes torque to vary linearly with the armature current.

Compound - higher torques at I_a values above rated. Higher toques developed at lower speeds.

Series - High starting torques. Torque is proportional to the square of I_a. Require load torque to prevent run away.

- Shunt Motor:

  Applications Centrifugal pumps, Fans, Conveyors, Machine tools Characteristics Constant speed,Moderate starting torque

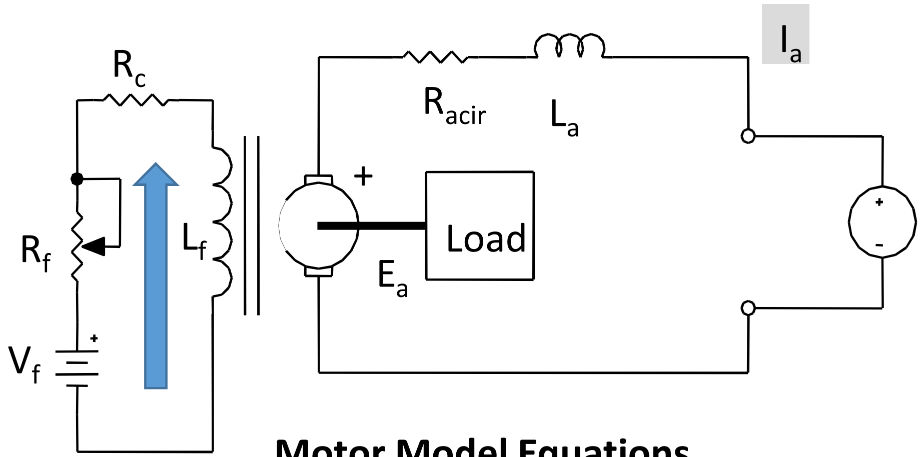
- Series Motor:

  Applications Hoists, Locomotives. Characteristics High starting torques, Wide speed range from no-load to full-load

- Compound Motor:

  Applications Centrifugal pumps, Fans, Conveyors, Machine tools Characteristics Constant speed,Moderate starting torque

Separately Excited Dc Motor Model



Motor Model Equations

Inducted EMF Equation: $E_a = k_G \cdot \omega \cdot \Phi_p$

Solving for ω gives: $\omega = \dfrac{E_a}{k_G \cdot \Phi_p}$

KVL around armature loop gives:

$V_t = E_a + I_a \cdot R_{acir}$ for armature current $I_a = \dfrac{V_t - E_a}{R_{acir}}$

Back EMF, E_a, proportional to speed

Motor with constant field current $\Phi_p \cdot k_G = K_e$

Where K_e is the back EMF constant

Previous E_a equation simplifies to: $E_a = K_v \cdot \omega$ $\qquad \omega = \dfrac{E_a}{K_e}$

V_t

Developed torque related to the field strength and the armature current.

$T_D = k_m \cdot B_p \cdot I_a$

Where: T_D = developed torque
B_p = flux density of field poles
I_a = armature current
k_m = motor design constant

k_m depends on number of turns, effective conductor length, # poles

pole flux density to the motor field current

$B_p = \dfrac{\Phi_p}{A}$ $\quad \Phi_p = \dfrac{N \cdot I_f}{\mathfrak{R}}$ $\quad B_p = \dfrac{N \cdot I_f}{A \cdot \mathfrak{R}}$

So now developed torque is given by $k_F = \dfrac{N}{A \cdot \mathfrak{R}}$

$T_D = k_F \cdot I_f \cdot I_a$

R:reluctance

Types of DC Motors

Steady-State Operation of Separately Excited Dc Motors

Developed Torque

$$T = K_T \cdot i_a - T_f \text{ [Nm]}$$

T = motor torque
K_T = torque constant
T_f = motor friction torque
i_a = armature current

Back EMF

$$e_b = K_e \cdot \omega_m \text{ [V]}$$

ω_m= shaft speed (rad/s)
e_b = back emf
K_e = back emf constant

KVL in Armature Circuit

$$e_a = i_a \cdot R_a + e_b \text{ [V]}$$

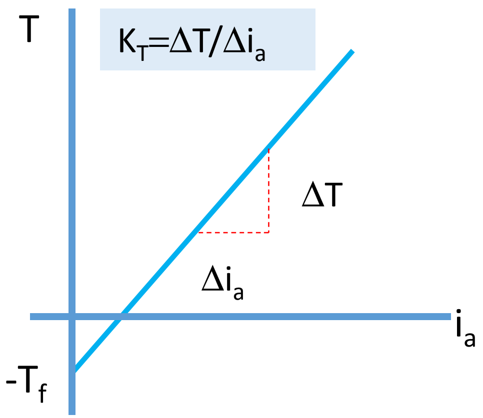
e_a= armature voltage
e_b = back emf
R_a = armature resistance

Developed Power

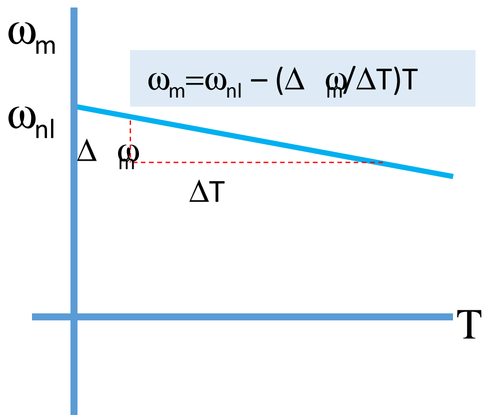
$$P = \omega_m \cdot T \text{ [W]}$$

P = shaft power

Torque-Current Curve

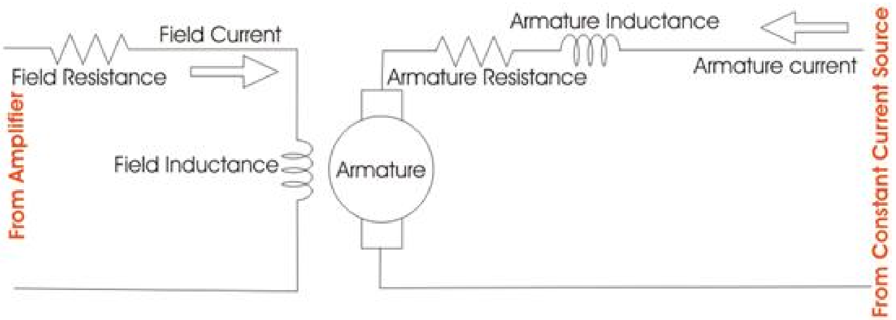


Speed-Torque Curve



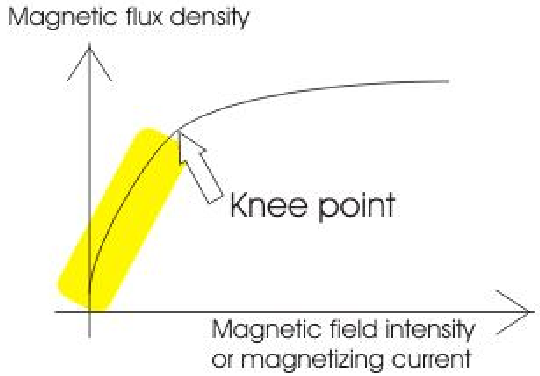
Types of DC Motors

Field Controlled Self-excited DC Motor



In field controlled DC servo motor arrangement:

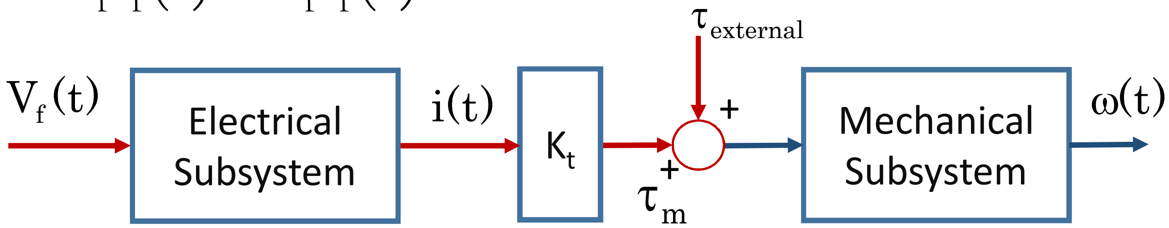
- the field of DC motor is excited be the amplified error signal and
- armature winding is energized by a constant current source .



The field is controlled below the knee point of magnetizing saturation curve. At that portion of the curve the mmf linearly varies with excitation current. That means torque developed in the DC motor is directly proportional to the field current below the knee point of magnetizing saturation curve.

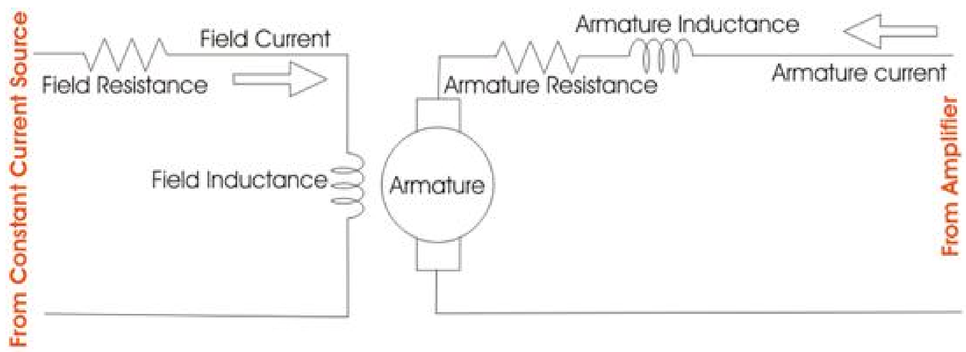
$$i_a = \text{constant} \qquad K_t = K_a K_f i_a \qquad T_m(t) = K_t i_f(t)$$

$$V_f = V_f(t) \quad V_f(t) = R_f i_f(t) + L_f \frac{di_f(t)}{dt} = R_f i_f(t) + L_f \dot{i}_f(t)$$



Types of DC Motors

Armature Controlled Self-excited DC Motor

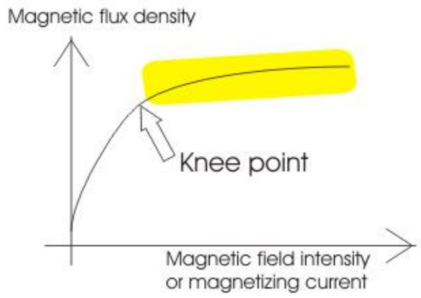


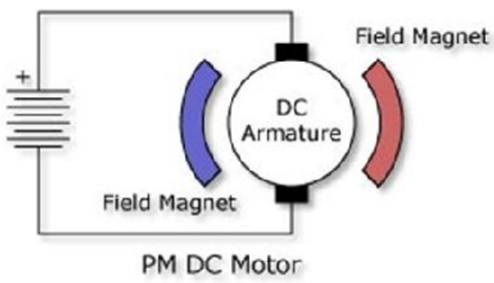
the armature is energized by amplified error signal and field is excited by a constant current source

$$i_f = sbt \qquad V_a = V_a(t)$$

little change in armature current Ia there will be a prominent changer in motor torque. That means servo motor becomes much sensitive to the armature current.

The field is operated at well beyond the knee point of magnetizing saturation curve. In this portion of the curve, for huge change in magnetizing current, there is very small change in mmf in the motor field. This makes the servo motor is less sensitive to change in field current. Actually for armature controlled DC servo motor, we do not want that, the motor should response to any change of field current.





Permanent Magnet DC Servo Motor is the case of permanent magnet DC motor as the field is a permanent magnet here. DC motor working principle in that case is similar to that of armature controlled motor.

The direction of rotation of the motor can easily be changed by reversing the polarity of the error signal.

Types of DC Motors

Armature Controlled Self-excited DC Motor

Since we are working in armature circuit then we should also take the generator operation in to account

Motor Action $K_t = K_a K_f i_f \quad T_m(t) = K_t i_a(t)$

Generator Action $\varepsilon_b(t) = K_b \omega(t)$

$$V_a(t) - V_b(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} = R_a i_a(t) + L_a \dot{i}_a(t) \qquad T_m(t) - T_L(t) = J\dot{\mu}(t) + C\mu(t)$$