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

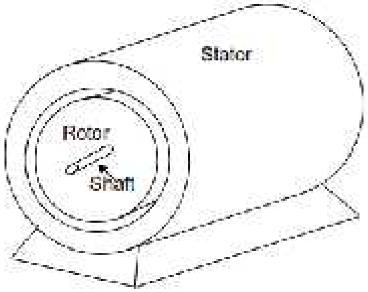
The purpose of an electrical motor is to convert electrical power into mechanical power. DC motors do this by using direct current electrical power to make a shaft spin. The mechanical power available from the spinning shaft of the DC motor can be used to perform some useful work such as turn a fan.

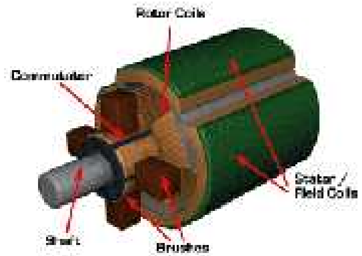
The rotation of the DC motor is accomplished by the force which is developed on a current-carrying conductor in a magnetic field.
The current-carrying conductor is connected to the shaft which is able to rotate relative to the stationary body of the DC motor.

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**.

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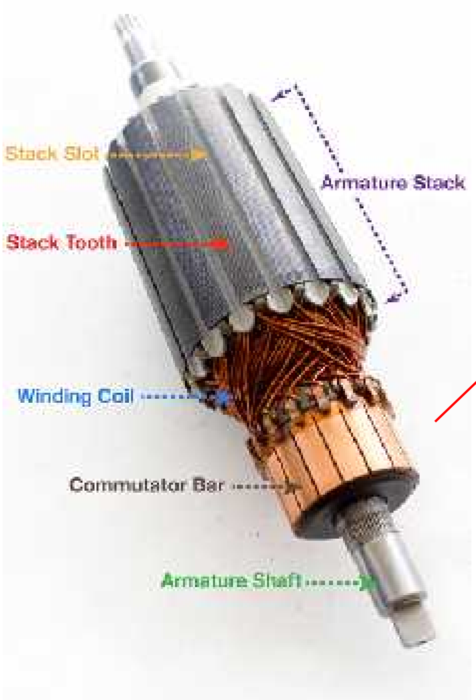
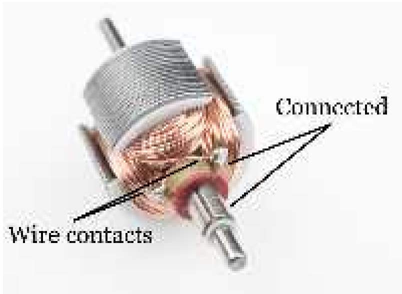
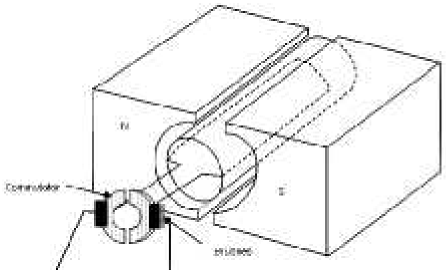
Physical parts of an electrical machine

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

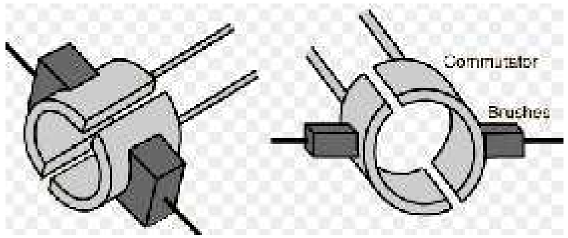


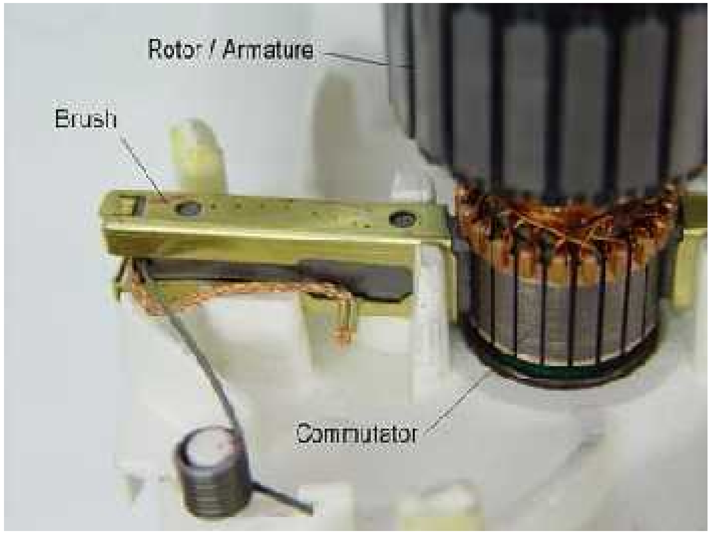




The commutator is made from two round pieces of copper, one on each side of the spindle. A piece of carbon (graphite) is lightly pushed against the copper to conduct the electricity to the armature. The carbon brushes against the copper when the commutator spins.

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





Functional parts of an electrical machine

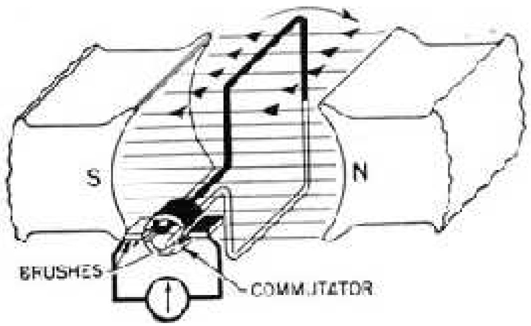
Electrical machines can also be divided into two functional parts.

- 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

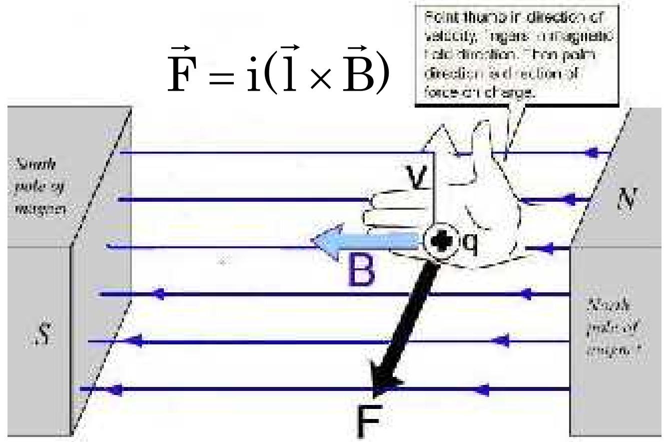


Operation of a DC Motor

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

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



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

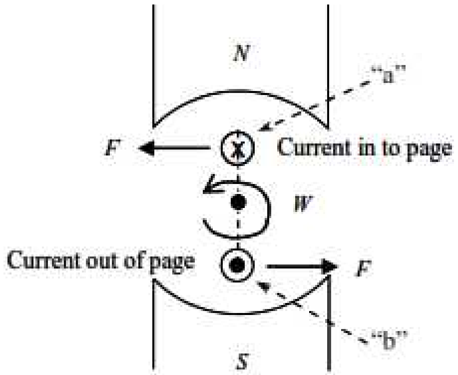
Operation of a DC Motor

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

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.

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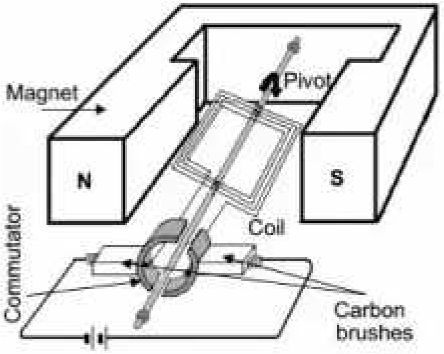
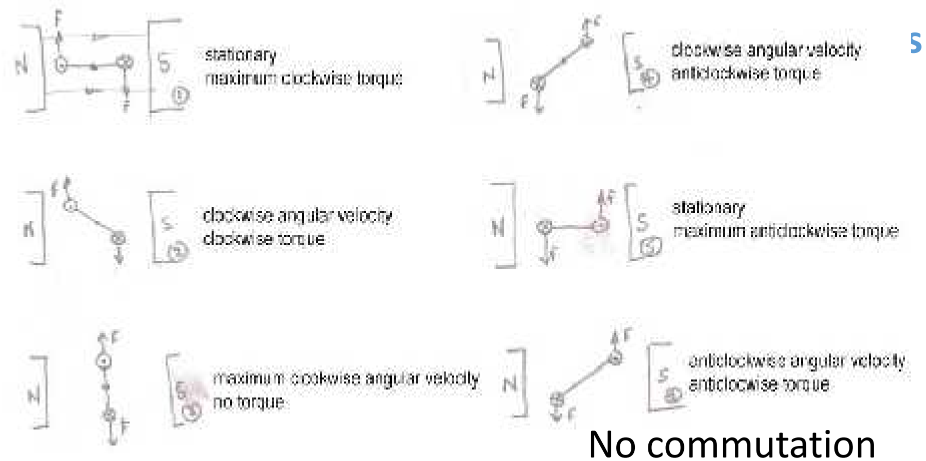
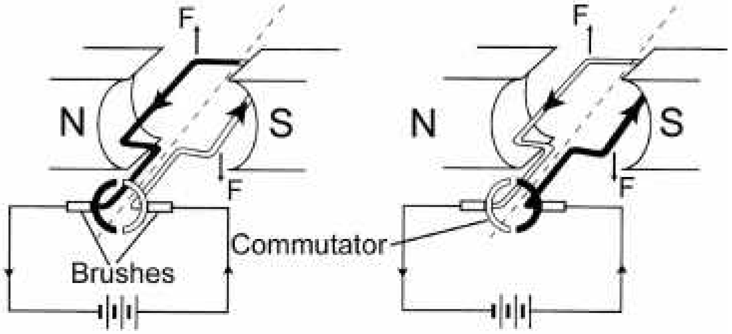
How commutation works

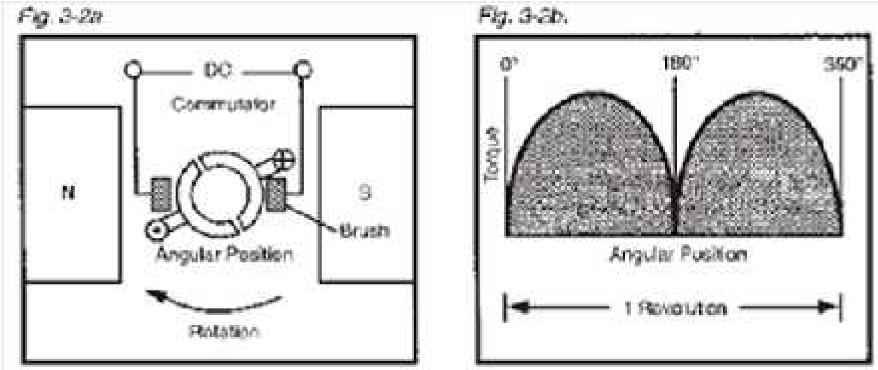


A split - ring commutator (sometimes just called a commutator)is a simple and clever device for reversing the current direction through an armature every half turn



No commutation



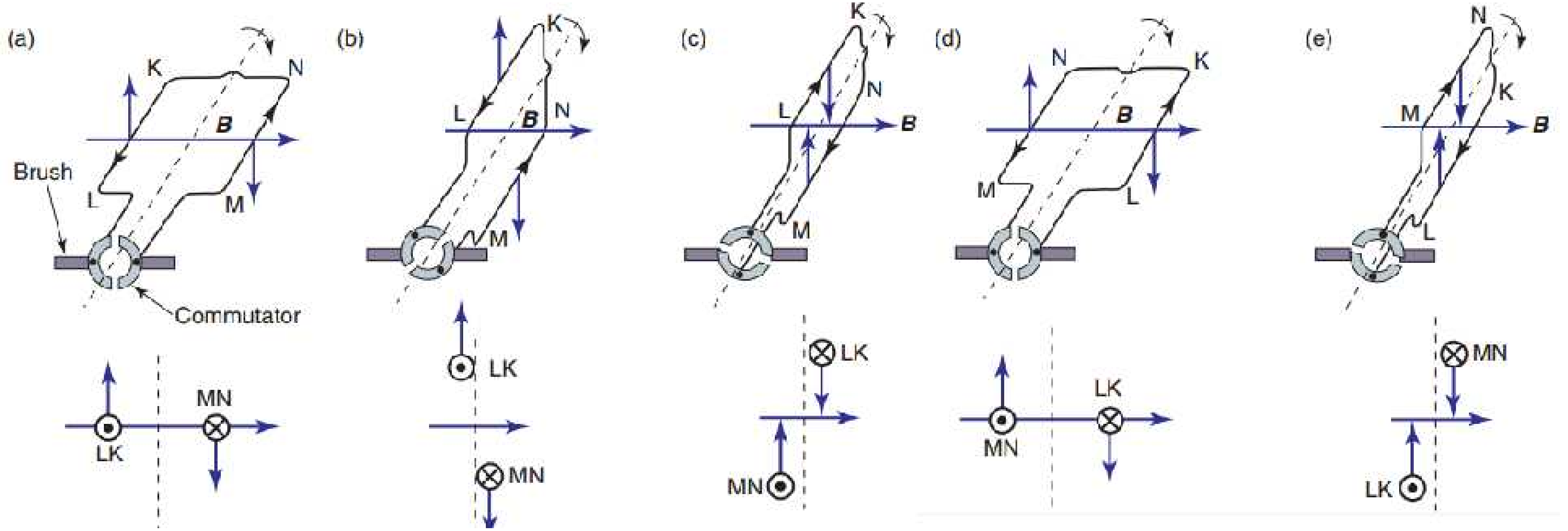


As the motor rotates, first one piece of copper, then the next connects with the brush every half turn. The wire on the left side of the armature always has current flowing in the same direction, and so the armature will keep turning in the same direction

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.

Electrical Machinery

Operation of a DC Motor



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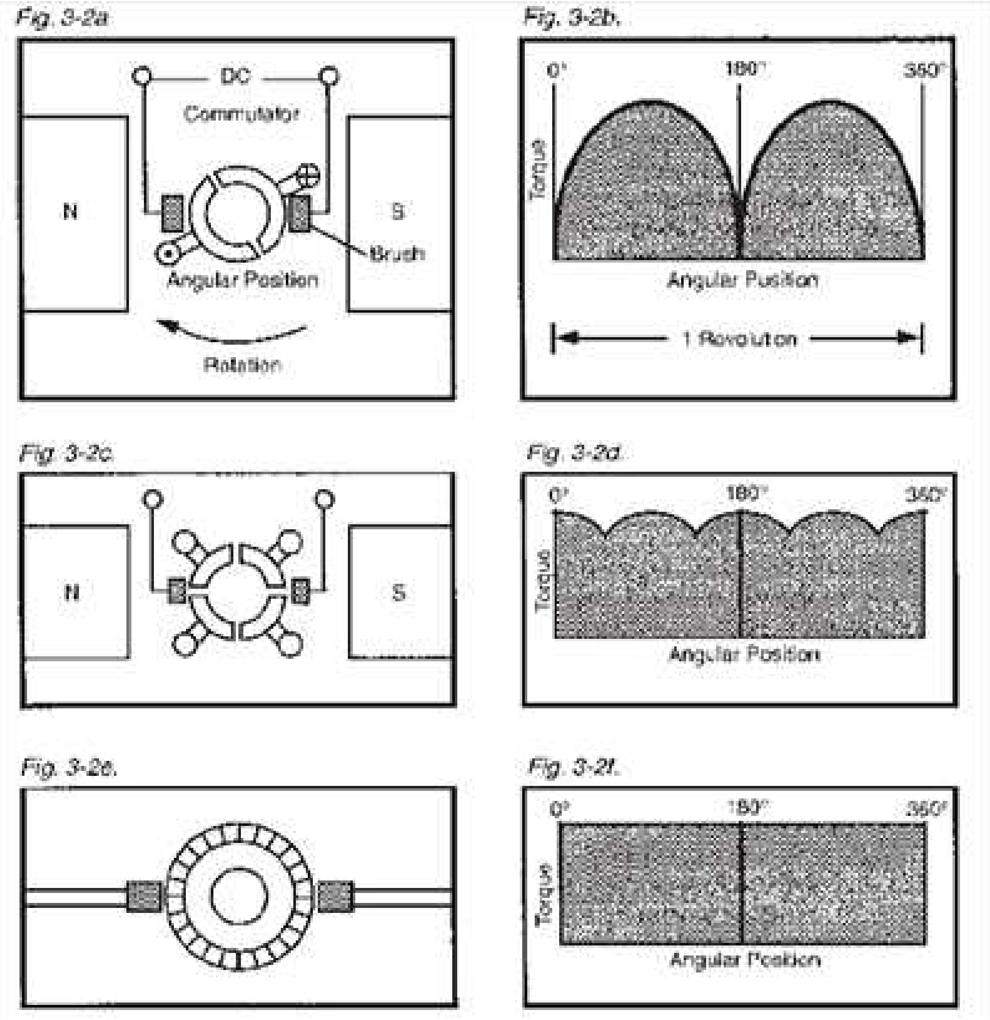
How commutation works

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).

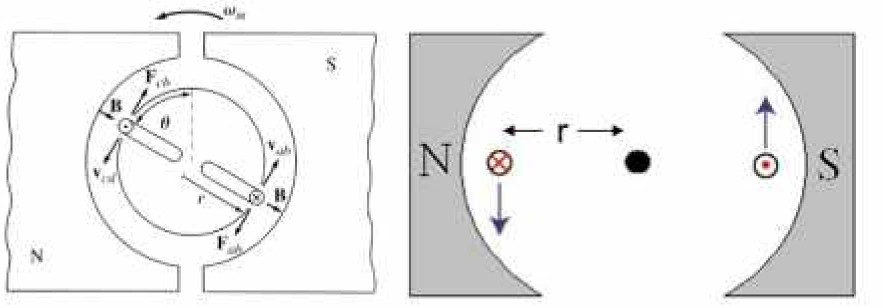
The more segments added to the coils and corresponding commutator armature, the closer the torque curve will approximate a straight line characteristic. See the figure below (e and f).



32-segment commutator

Electrical Machinery

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:

$$T = BLI_a r$$

Torque can be significantly increased by increasing:

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

2 wires being acted upon

$$T = 2BLI_a r$$

The most practical way to increase torque is to increase the number of wires being acted upon:

$$T = 2NBLI_a r$$

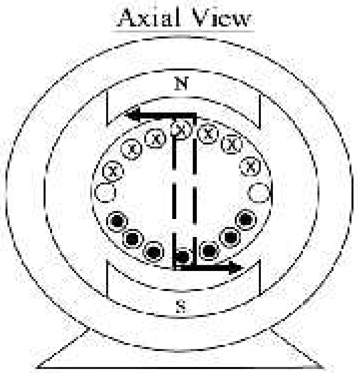
where N = number of turns of wire

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

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

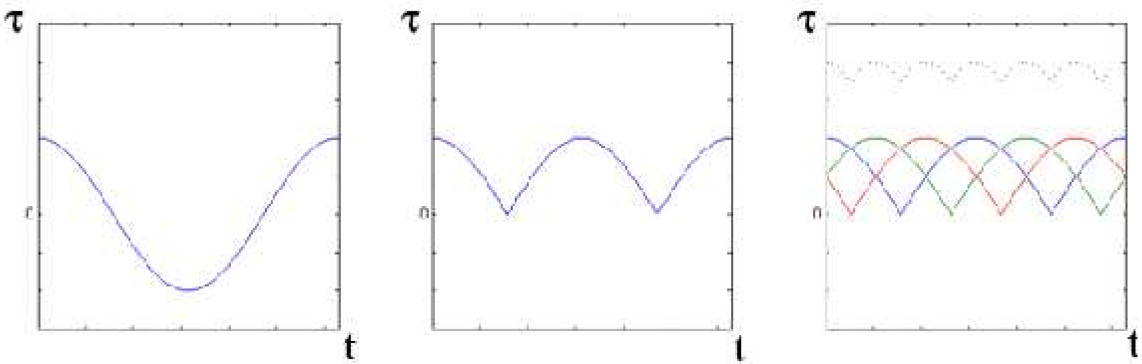
Developed Force and Torque

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.



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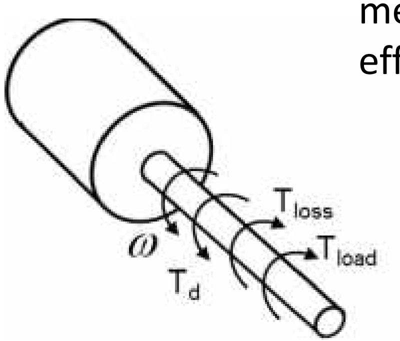
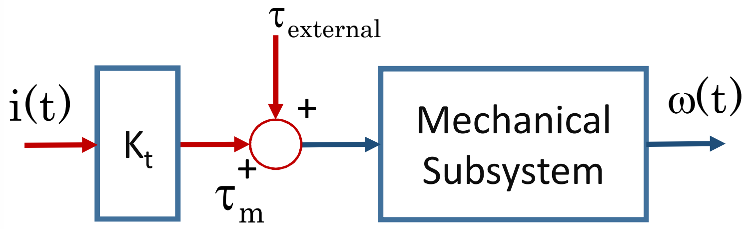
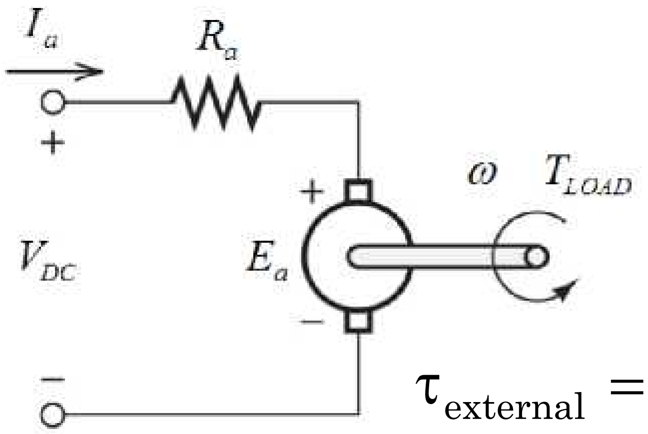
Torque Balance



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

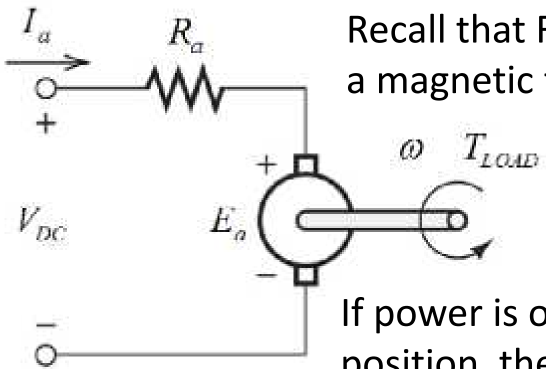




$$\tau_{\text{external}} = \tau_{\text{load}} + \tau_{\text{loss}}$$

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

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

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

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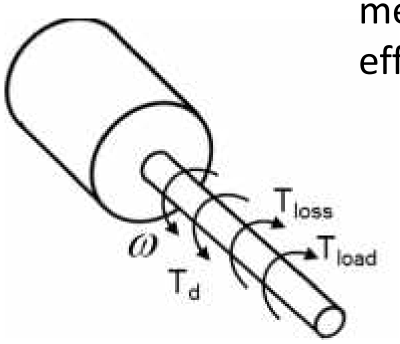
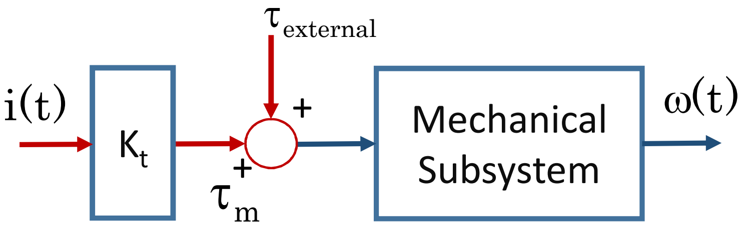
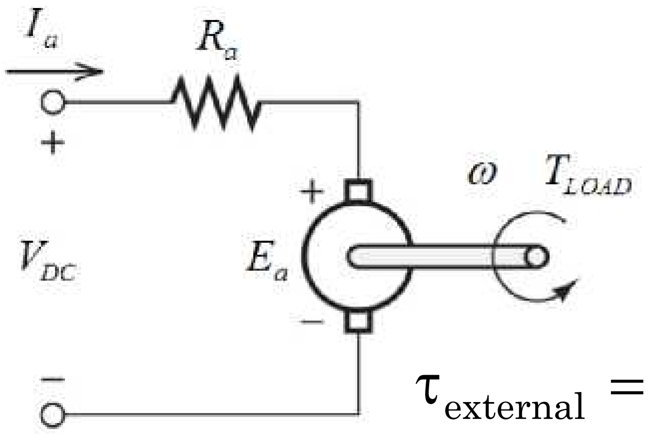
Torque Balance

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:

$$¦ = \frac{P_{out}}{P_{in}} 100 = \frac{P_D}{P_{in}} 100 \quad (T_{loss} = 0) \qquad Watt = \frac{N \cdot m}{sec} \quad \rightarrow \quad \mathrm{N \cdot m = Watt \cdot sec = V \cdot A \cdot sec}$$

Review of concepts

Torque Developed:

$T_d = K_v I_a$

Mechanical Power Developed:

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

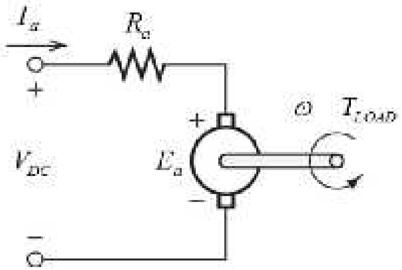
Angular velocity:

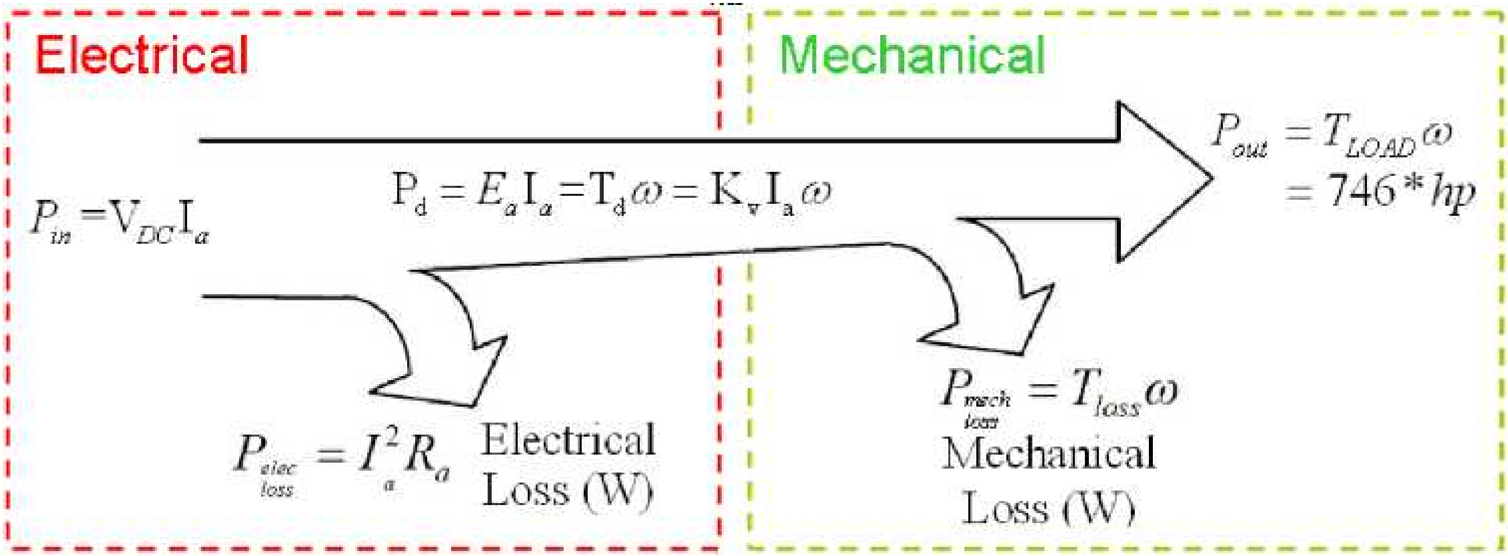
$\omega = 2$ ® $(RPM/60)$

Back EMF:

$E_a = K_v \omega$

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





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Operation of a DC Motor