DC Motors

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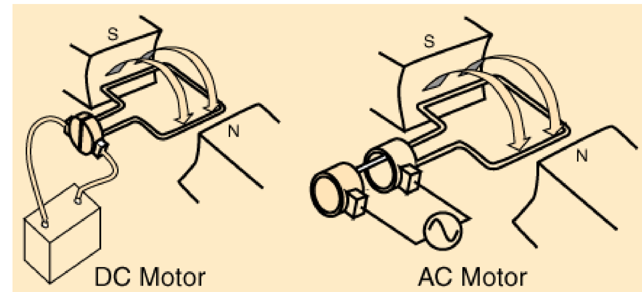
ME 475: Mechatronics

AC Motors vs DC Motors



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- AC motors are smaller in size, reliable and less costly.
- AC motors run at fixed speed set by the line frequency.
- Easy speed, torque & direction controls in DC motors.
- DC motors are generally operate at lower voltages which makes these easier to interface with control electronics.

DC Motor Classification

DC motors can be divided into two general categories:

1. **Brush-type DC Motor**: has a mechanical brush pair on the motor frame & makes contact with a commutator ring assembly on the rotor in order to communicate current, i.e. to switch current from one winding to another, as a function of rotor position so that the magnetic fields of the rotor & stator are always at a 90^o angle relative to each other.
2. **Brushless DC Motor**: is an inside-out version of the brush-type DC motor, i.e. the rotor has the permanent magnets & the stator has the winding. Hence, magnetic fields of the rotor & stator must be perpendicular to each other at all rotor positions. Communication is done by solid-state power transistors based on a rotor position sensor, hence it is considered a **servo** motor.

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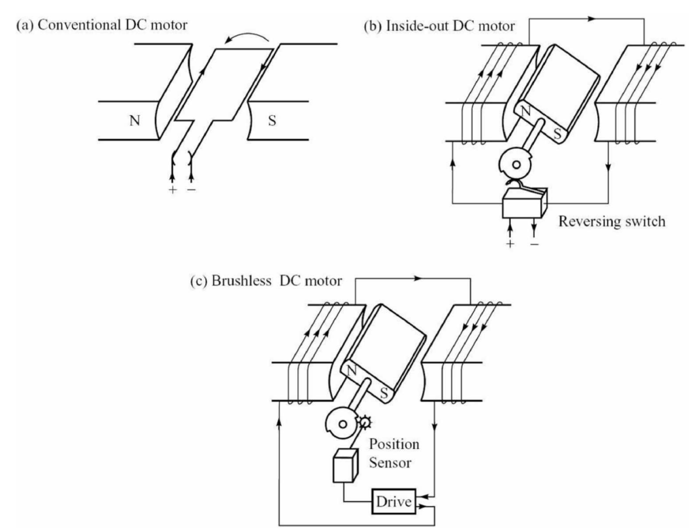

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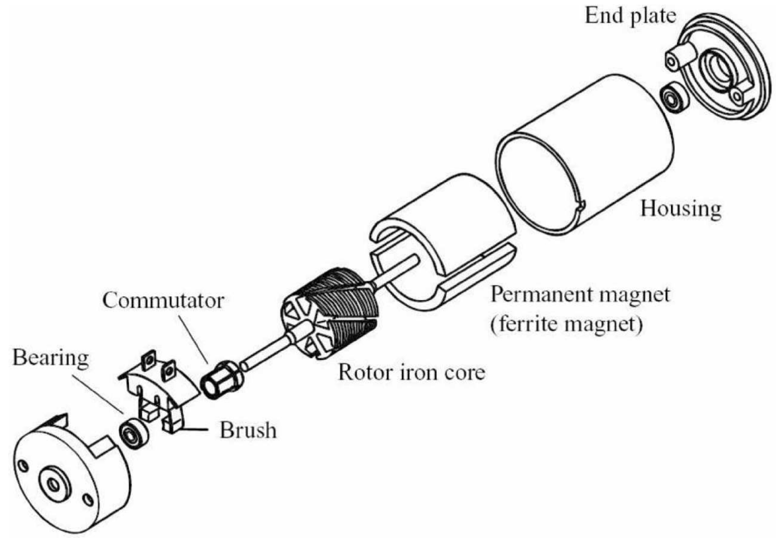
- Brush-type DC motors have the permanent magnet (PM) as the stator (typically 2-pole or 4-pole configuration) & the windings on the iron core rotor.
- Almost identical mechanical components exist in the brushless DC motors with **3** exceptions:
  1. There are no commutator or brushes since commutation is done electrically by the drive.
  2. The rotor has the permanent magnets glued to the surface of the rotor, and the stator has the winding.
  3. The rotor has some form of position sensor which is used for current commutation.

PM DC Motor



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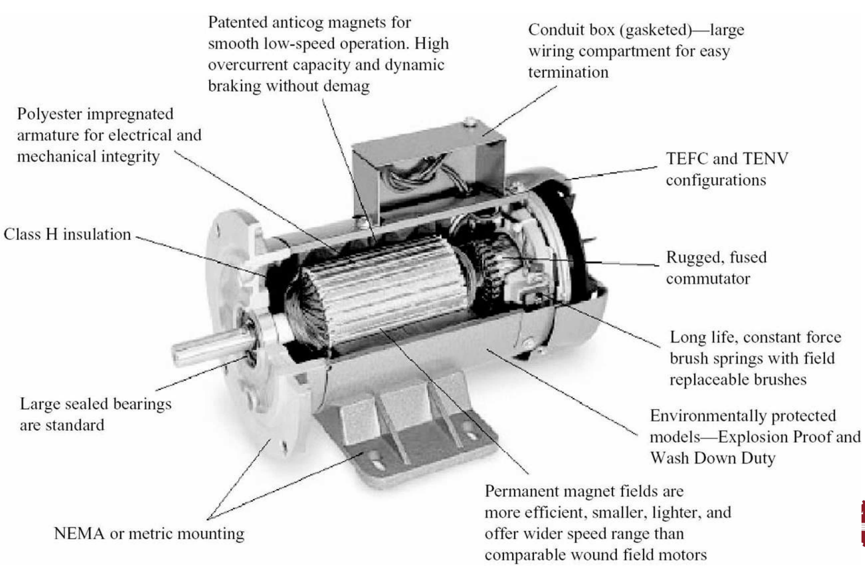
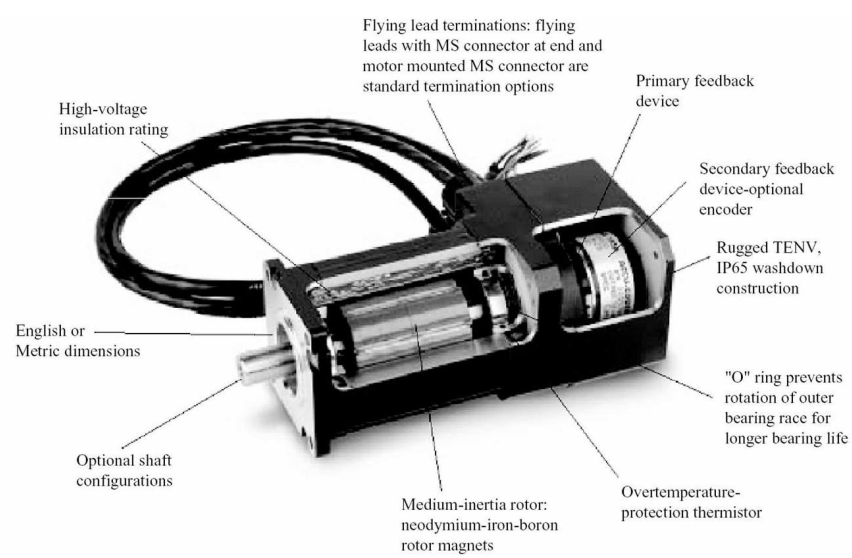
PM Brush-type Iron-core DC Motor



PM Brushless DC Motor



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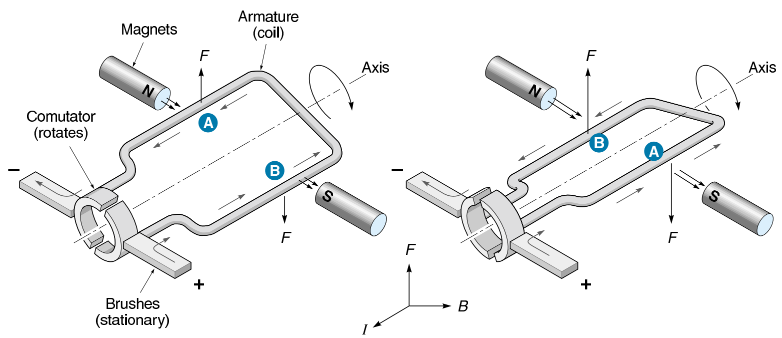
Motor Action



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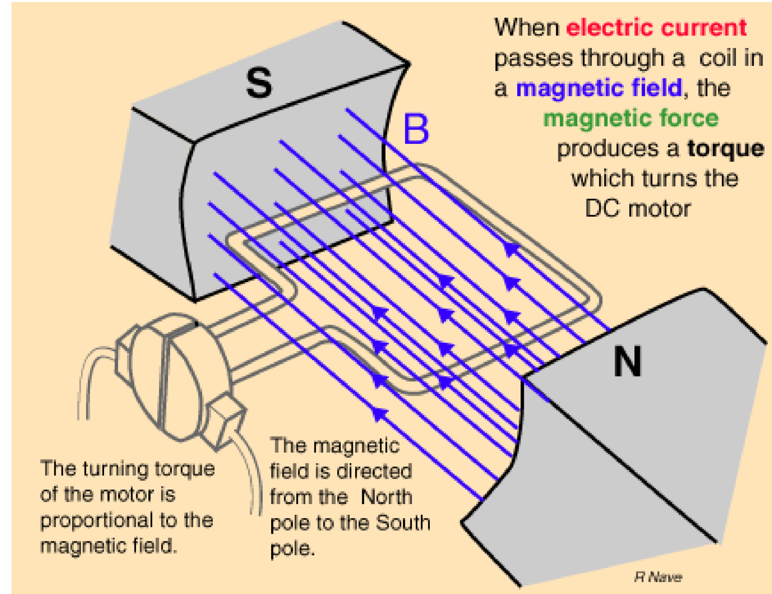
In electric motor, wire loop is formed which is allowed to rotate about the axis and is called **armature winding**. The armature is placed in a magnetic field called **field**. The **commutator** and **brushes** supply current while allowing it rotate.



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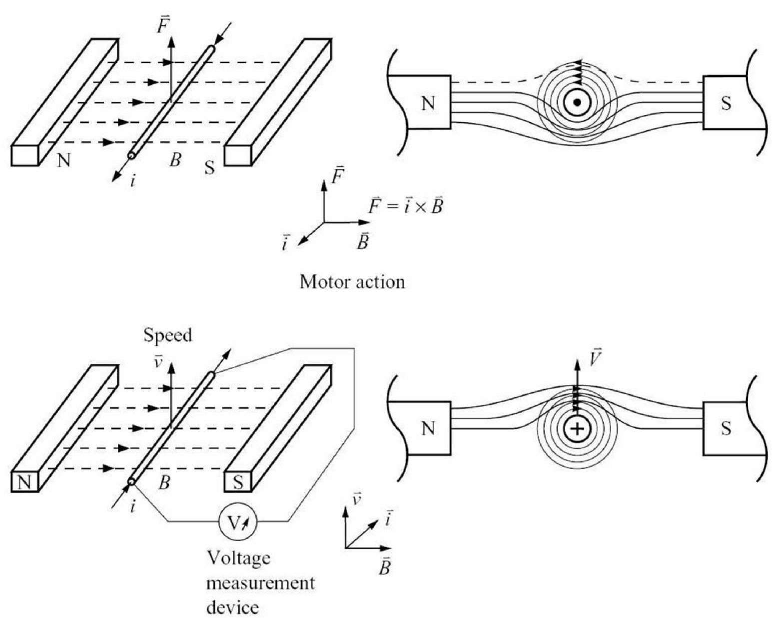

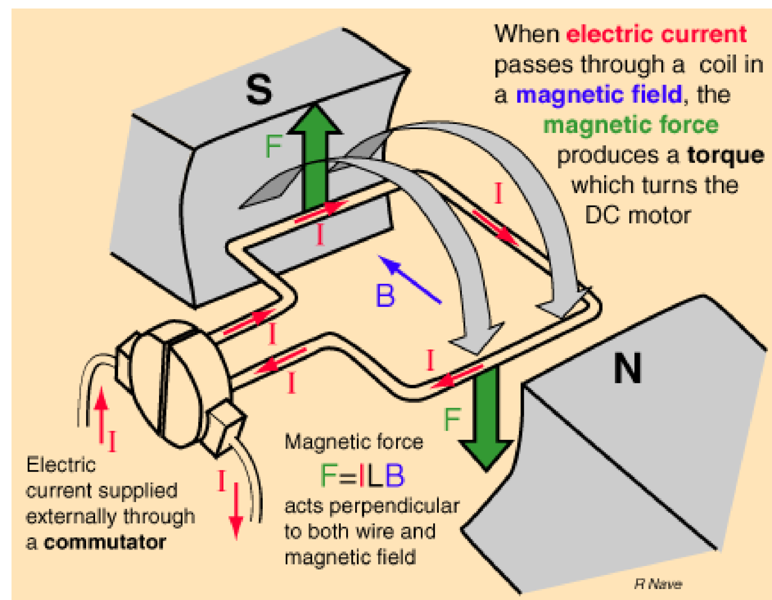

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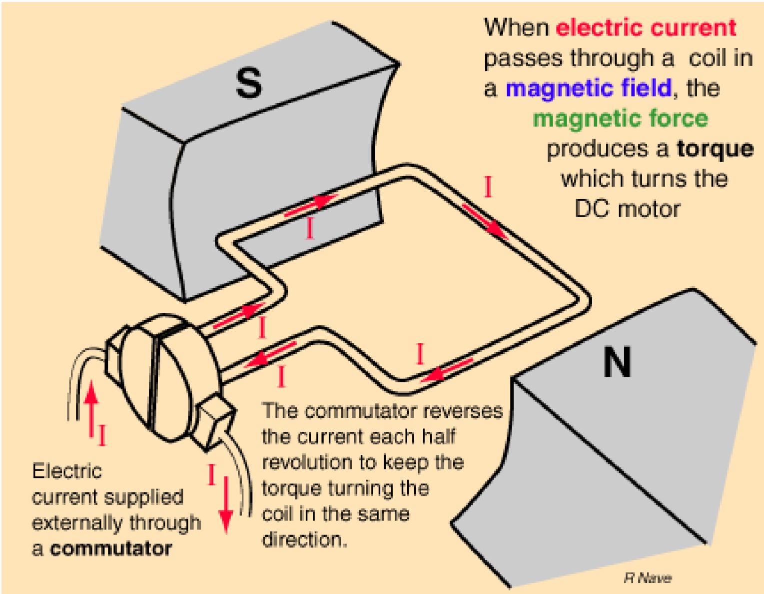

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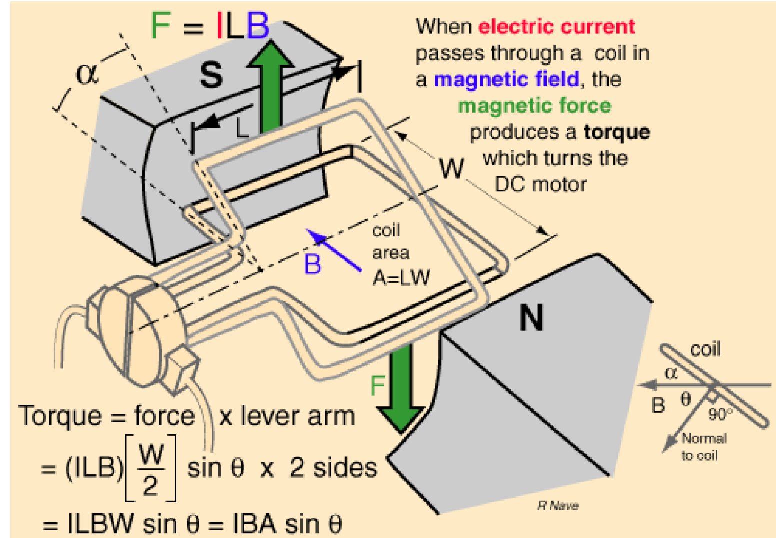

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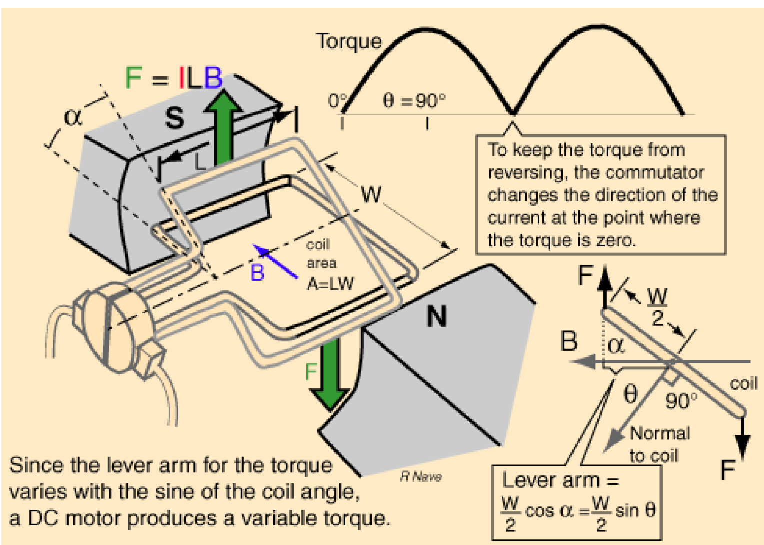

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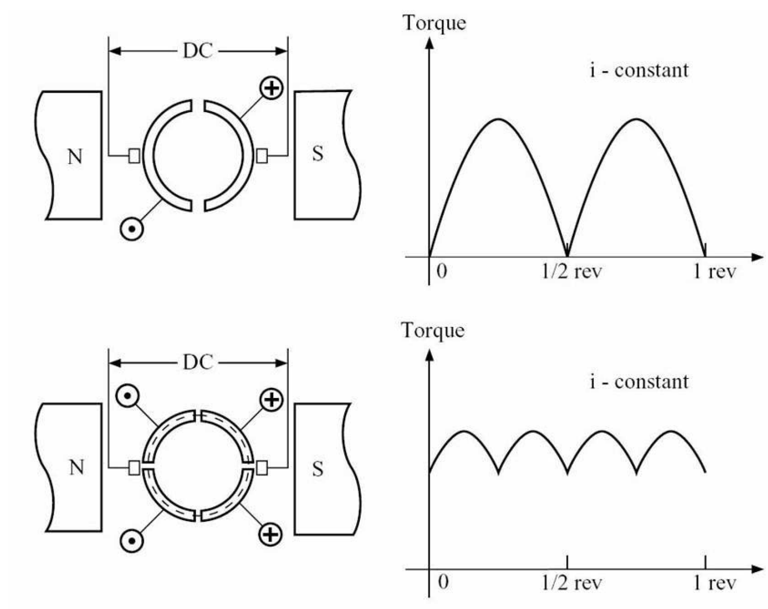

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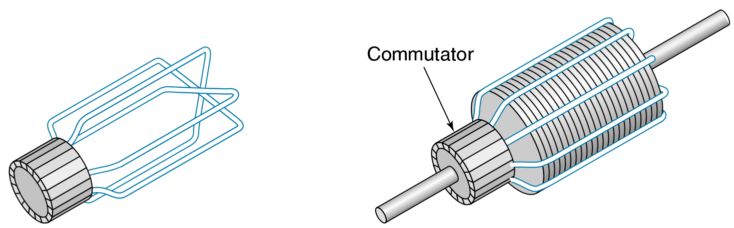

(a) Simplified armature showing multiple loops

(b) An actual armature (many loops)

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- In actual motors, there are multiple coils and each coil experiences forces and so contributes to the overall torque.
- Each coil is connected to a separate pair of commutator segments, causing the current in each coil to switch directions at the proper time for that individual coil.
- The overall effect is to provide approximately the same torque for any armature location.

- **Torque,** T is the rotational force a motor can exert.

$$T = K_T I_A \phi$$

K_T = a constant based on the motor construction
I_A = armature current
ϕ = magnetic flux

- If the armature coil were rotated in the magnetic field by some external force, a voltage [called the **electromotive force (EMF)**] would appear on the commutator segment.

$$EMF = K_E S \phi$$

K_E = a constant based on the motor construction
S = motor speed (rpm)

- EMF is generated even when the motor is running on its own power, but it has the opposite polarity of the line voltage; hence is called the **counter-EMF (CEMF)**. Its effect is to cancel out some of the line voltage, V_{ln}. So, actual voltage available to the armature, V_A is

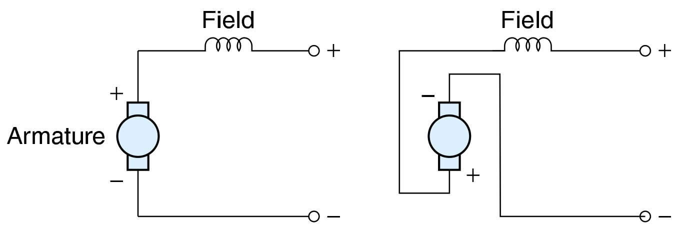
$$V_A = V_{ln} - CEMF \quad \Longrightarrow \quad I_A = \frac{V_{ln} - CEMF}{R_A}$$

- Because CEMF increases with motor speed, the faster the motor runs, the less current the motor will draw, and consequently its torque will diminish. As a result, if the motor keeps going faster, the CEMF will nearly cancel out line voltage and armature current will approach zero.

- $$S = \frac{CEMF}{K_E \phi}$$

  The motor speed is directly proportional to the CEMF and inversely proportional to the field flux.
- DC motors have a property called **Speed regulation** which is the ability of a motor to maintain its speed when the load is applied. When motor's load is increased, the speed tends to decrease, but the lower speed reduces CEMF, which allows more current into the armature. The increased current results in increased torque, which prevents the motor from slowing further.
- $$\%\ Speed\ regulation = \frac{S_{NL} - S_{FL}}{S_{FL}}$$

Series-Wound Motors



(a) Series motor circuit (b) Series motor reversed

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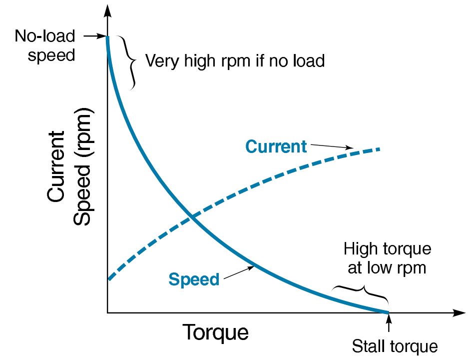
- When motor is stopped, there is no CEMF and full voltage is available at the armature. So, high initial armature current and large magnetic flux creates high initial torque.
- It tends to “run-away” under no-load conditions.



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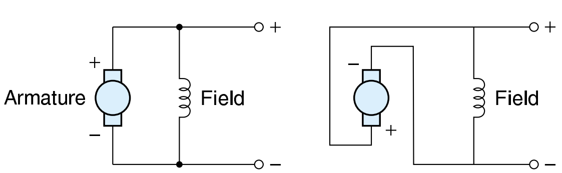
- Motor speed decreases as torque increases.
- **Stall torque:-** is the maximum torque delivered occurs when the motor is loaded so much as it comes to a stop.
- **No-load speed:-** is the attained when the motor is allowed to run without any external load.

Shunt-Wound Motors



(d) Shunt motor circuit (e) Shunt motor reversed

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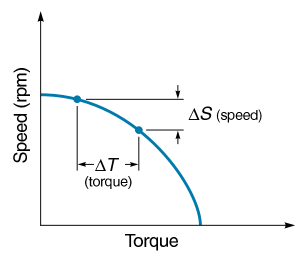

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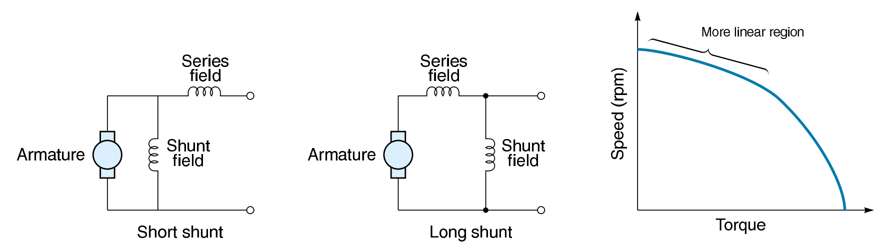
- Field current is dependent only the supply voltage.
- Stall-torque and no-load speed values are relatively low.
- Motor tends to run at a relatively constant speed. Its speed can be varied
  - by putting a rheostat in series with the field winding
  - by changing line voltage

Compound Motors



(a) Compound motor circuit (b) Torque-speed curve

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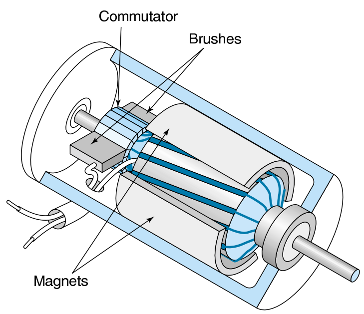
The compound motor has both shunt and series field windings. The main purpose of the series winding is to give the motor a higher starting torque. Once the motor is running, the CEMF reduces the strength of the series field, leaving the shunt winding to be the primary source of field flux and thus providing some speed regulation.

Permanent-Magnet Motors



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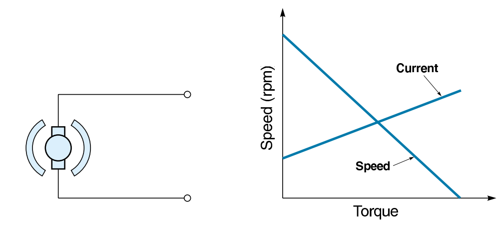
PM motors use permanent magnets to provide the magnetic flux for the field.Three types of magnets are used:

1. Alnico magnet, iron based alloy
2. Ferrite magnets
3. Rare-earth magnets



(a) PM motor symbol (b) PM motor torque-speed curve

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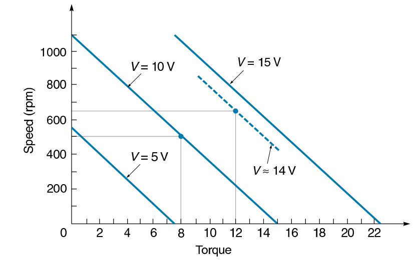

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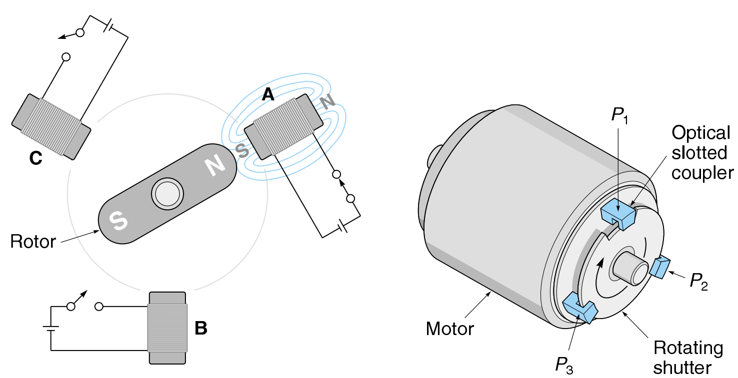
- Field flux of a PM motor remains constant, hence a very desirable linear torque-speed curve is achieved.
- PM motor is easily reversed by reversing the polarity of applied voltage.
- As the voltage increases, the stall torque and no-load speed also rise.

Brushless DC (BLDC) Motors



(a) Field coil arrangement (b) Rotating shutter and sensors

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In BLDC motor, armature (called the rotor) is a permanent magnet which is surrounded by field coils. By switching the coils ON/OFF in sequence, the rotor is dragged around to provide rotational motion.

- BLDC motors operates without brushes by taking advantage of modern electronic switching techniques. Although it adds some complexity, the result is a motor that is very reliable, very efficient and easily controlled.
- Stepper motor is used when it is necessary to step to precise positions and then stop; BLDC is used a source of rotary power.
- BLDC motor exhibits excellent speed control. Some models actually come with built-in tachometer that feeds back to the control unit.
- BLDC motors have higher power efficiency; these are smaller and lighter than any other types of motors.
- Unlike a brushed DC motor, the BLDC motor has a minimum operating speed (around 300 rpm) below which the individual pulses can be felt (called cogging).

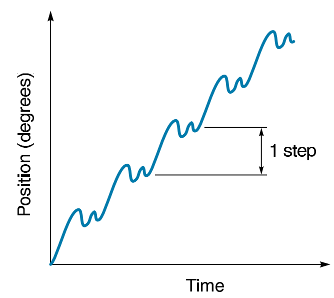
Stepper Motors

- A stepper motor is a unique type of DC motor that rotates in fixed steps of certain number of degrees. Step size can range from 0.9 to 90^o.
- Stepper motors are particularly useful in control applications because the controller can know the exact position of the shaft without the need of position sensors.
- Step size is determined by the number of rotor and stator poles, there is no cumulative error.
- Steppers have inherently low velocity and therefore are frequently used without gear reductions.
- There are three types of steppers: permanent magnet, variable reluctance, and hybrid.

Modes of Operation of Steppers

Steppers have **two** modes of operations:

1. **Single-step:-** frequency of the steps is slow enough to allow the rotor to come to stop between steps.
2. **Slew-mode:-** the rotor does not have the time to come to stop; these cannot be stopped or reversed direction instantaneously. The step-count integrity might be lost.



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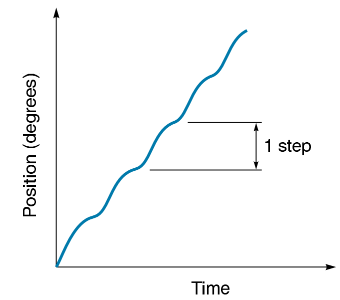

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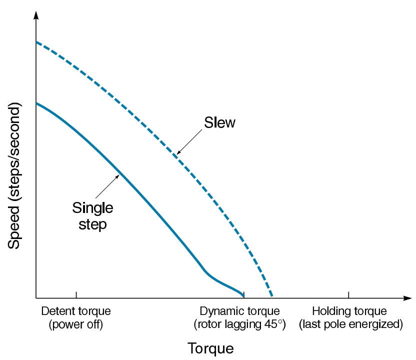
Torque-speed Characteristics



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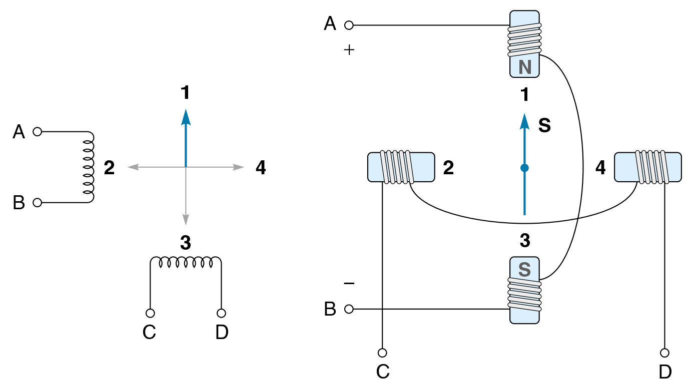
- **Detent torque:-** is the torque required to overcome the forces of the permanent magnets when the power is off.
- **Dynamic torque:** is the maximum running torque.
- **Holding torque:-** is the stall torque, results when the motor is completely stopped but with the last pole still energized.

PM Stepper Motors

Phase refers to the number of separate winding circuits.

1. **Two-phase (bipolar) Stepper Motor:-** has only two circuits but actually consists of four field poles. The term bipolar applies to this motor because the current is sometimes reversed. The simplest way to step this motor is to alternately energize the winding such a way as to pull the rotor from pole to pole.
2. **Four-phase (unipolar) Stepper Motor:-** is the most common type of stepper motor. The term four-phase is used as the motor has four field coils that can be energized independently, and the term unipolar is applied because the current always travel in the same direction through the coils. The simplest way to operate is to energize one phase at a time in sequence (known as wave drive).

Two-Phase (bipolar) PM Stepper Motor



(a) Symbol (b) Wiring diagram

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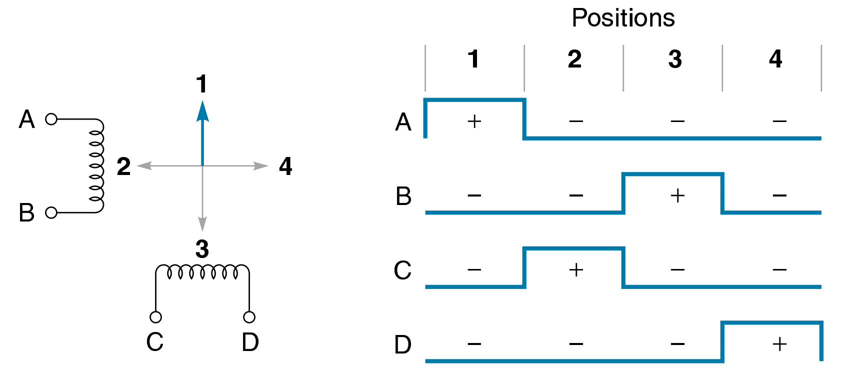
Control of Two-Phase (bipolar) PM Stepper Motor



(a) Rotor positions

(b) Timing diagram
(for CCW stepping “single excitation”)

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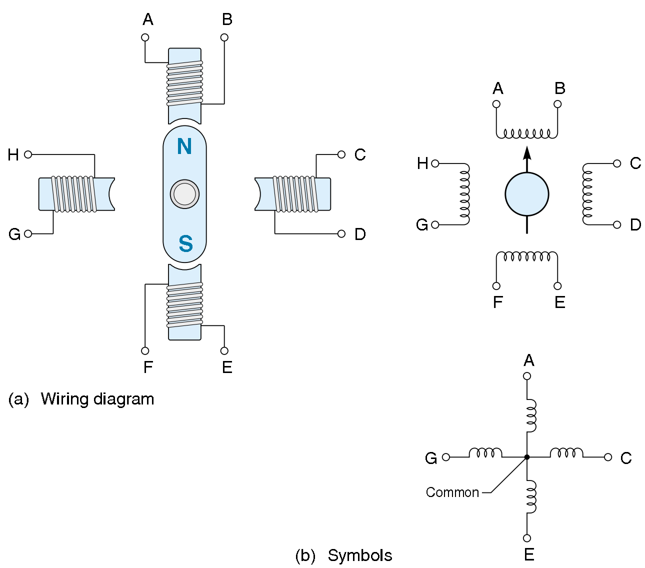
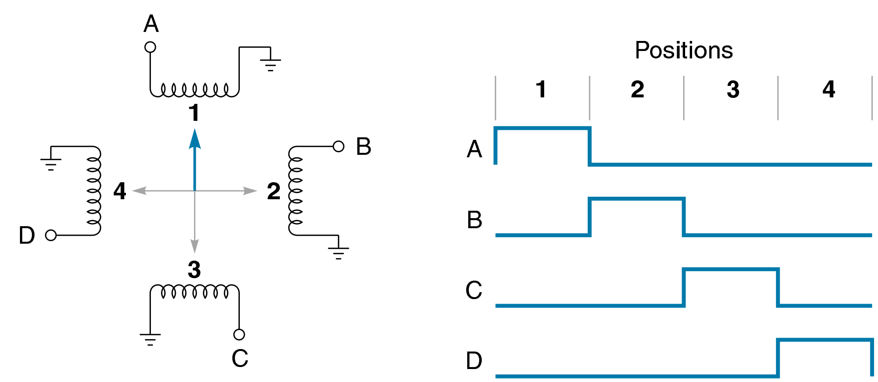
Four-Phase (unipolar) PM Stepper Motor



(a) Wiring diagram

(b) Symbols

Control of Four-Phase (unipolar) PM Stepper Motor



(a) Rotor positions (b) Timing diagram for CW stepping

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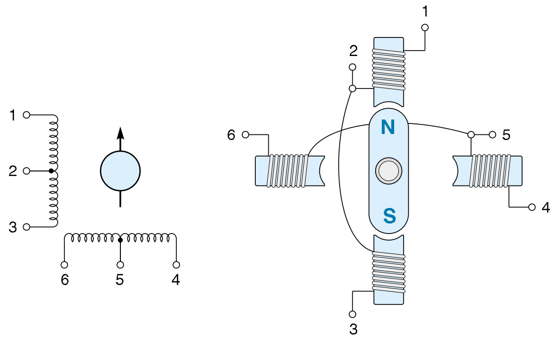
Four-Phase PM Stepper Motor with Center Tap



(a) Symbol (b) Wiring diagram

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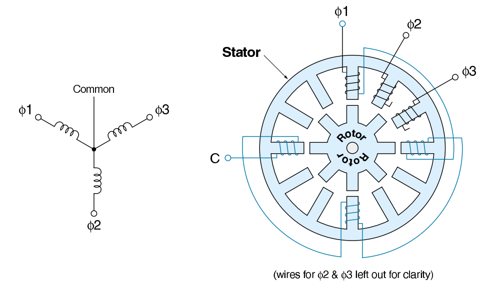
4ϕ steppers with center tap is done by bringing out 2 additional wires that are internally connected to points between the opposite field coils. When such a motor is used in 2ϕ mode, the center taps are not used; when operated in 4ϕ mode, the center taps become a common return.

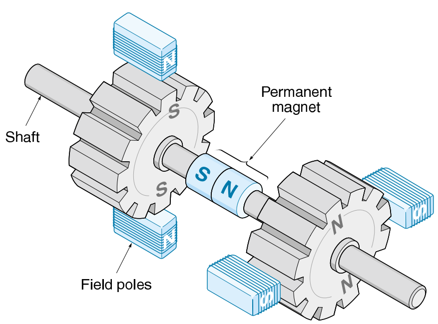
Variable Reluctance Stepper Motor



(a) Symbol (b) Construction

e161.eps VR steppers does not use PM for the rotor; instead, it uses a toothed iron wheel. The advantage of not requiring the rotor to be magnetized is that it can be made any shape. Being iron, each rotor tooth is attracted to the closest energized field pole in the stator, but not with the same force as in the PM motor. This gives VR motor less torque than the PM motor.

Hybrid Stepper Motor



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Hybrid motors combine the features of PM and VR stepper motors and is the type in most common use today. The rotor is toothed, which allows for very small step angles (typically 1.8^{o}), and it has a permanent magnet providing a small detent torque even when the power is off.