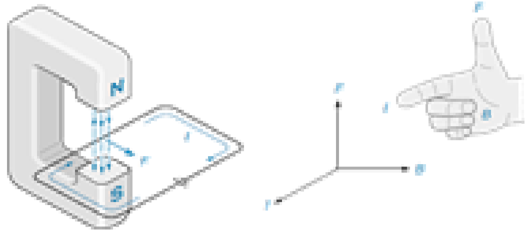
Actuators

- Most mechatronic systems involve motion or action of some sort. This motion or action can be applied to anything from a single atom to a large articulated structure. It is created by a force or torque that results in acceleration and displacement.
- **Actuators** are the devices used to produce this motion or action.
- Actuators produce physical changes such as linear and angular displacement.
- They also modulate the rate and power associated with these changes.
- An important aspect of mechatronic system design is selecting the appropriate type of actuator.
- Some of the most important actuators:
  - solenoids and relays,
  - electric motors,
  - hydraulic cylinders and pneumatic cylinders
  - control valves

Electromagnetic Principles

- Many actuators rely on electromagnetic forces to create their action.
- *When a current carrying conductor is moved in a magnetic field, a force is produced in a direction perpendicular to the current and magnetic field directions*



(a) Experimental setup

(b) Directions of I, F, and B are mutually orthogonal (conventional current flow)

Figure 3.1 Action of force on a wire in a magnetic field.

Electric Motor

- Electric motors are by far the most ubiquitous of the actuators, occurring in virtually all electromechanical systems.
- Electric motors can be classified either
  - by function or
  - by electrical configuration
- In the functional classification, motors are given names suggesting how the motor is to be used.
  - Examples of functional classifications include
    - torque, gear, servo, instrument servo, and stepping.
- It is necessary to know about the electrical design of the motor to make judgments about its application for delivering power and controlling position.

Electric Motor: classification

- Figure 3.2 provides a configuration classification of electrical motors found in mechatronics applications.
- The differences are due to motor winding and rotor designs, resulting in a large variety of operating characteristics.

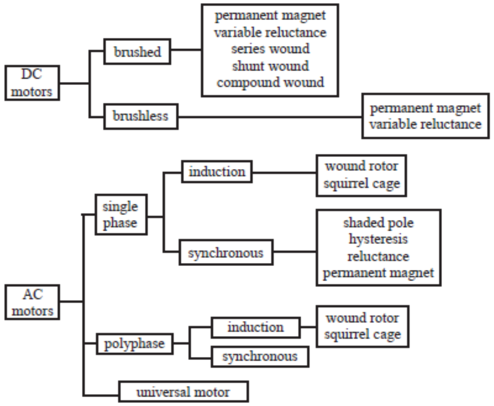


Figure 3.2 Configuration classification of electric motors.

DC Motors

- An electric motor must harness a force in such a way as to cause a rotary motion.
- This can be done by forming the wire in a loop and placing it in the magnetic field (Figure 3.3).

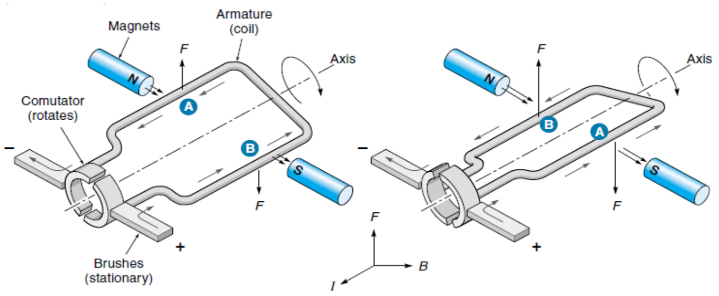


Figure 3.3 A simple DC motor action (conventional flow).

DC Motors

- The loop (or *coil*) of wire is allowed to rotate about the axis shown and is called the **armature** winding.
- The armature is placed in a magnetic field called the **field.**
- The **commutator** and **brushes** supply current to the armature while allowing it to rotate.
- To understand how the motor works, look at Figure 3.3(a). Notice that wire segments A and B of the coil are in the same magnetic field, but the current in wire segment A is coming out of the page, whereas the current in wire segment B is going in.
- Applying the force diagram from Figure 3.1(b), we see that wire segment A of the coil would be forced up, whereas wire segment B would be forced down. These forces would cause the coil to rotate clockwise.

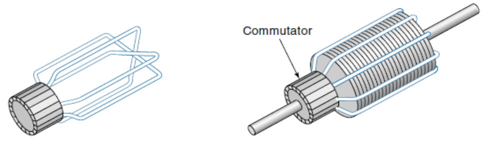
DC Motors

- Figure 3.3(b) shows the situation after the coil has rotated about 90°. The current has now reversed direction in the coil because the commutator contacts have rotated and are now making contact with the opposite brush. Now wire segment A of the coil will be forced down and wire segment B up, which causes the armature to continue rotating clockwise.
- **Video :** 1. DC motor principle

- Reversing the direction of rotation of the motor
  - polarity of the voltage to the commutator is reversed.
  - This causes the forces on the armature coil to be reversed, and
  - the motor would then run in the opposite direction

DC Motors

- Figure 3.4 shows the armature of a practical motor.
- Notice that there are multiple coils and each coil experiences the forces described in the before and so contributes to the overall torque of the motor.
- 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 position (like a multipiston engine).



(a) Simplified armature showing multiple loops

(b) An actual armature (many loops)

Video: DC motor

Figure 3.4 DC motor armature

DC Motors

- **Torque: -**is the rotational force a motor can exert.
  - One of the most important operating parameters of any motor is torque.
  - Electric motor torque is directly proportional to the force on the armature wires.
  - the motor torque can be expressed as $T = K_T I_A \varphi$

Where, K_T = a constant based on the motor construction

I_A = armature current, φ = magnetic flux

- the very same device (motor) is also capable of converting mechanical energy to electrical energy, in which case it is called a generator.
- For example, if the armature coil of Figure 3.3 were rotated in the magnetic field by some external force, a voltage [called the *electromotive force* (EMF)] would appear on the commutator segments.
- The magnitude of the EMF is given as

$$\text{EMF} = K_E \varphi S$$

Where, K_E = a constant based on motor construction, φ = magnetic flux,

S = speed of motor (rpm)

DC Motors

- Although it may seem strange, this EMF voltage is being generated even when the motor is running on its own power, but it has the opposite polarity of the line voltage;
- hence, it is called the **counter-EMF** (CEMF). *Its effect is to cancel out some of the line voltage*. In other words, the actual voltage available to the armature is the line voltage minus the CEMF:

$$V_A = V_{ln} - \text{CEMF}$$

where, V_A = actual voltage available to the armature

V_{ln} = line voltage supplied to the motor

CEMF = voltage generated within the motor

DC Motors

- We can not directly measure V_A with a voltmeter because it is an effective voltage inside the armature.
- However, there is physical evidence that the CEMF exists because the armature current is also reduced, as indicated in Equation $I_A = \dfrac{V_{ln} - \text{CEMF}}{R_A}$

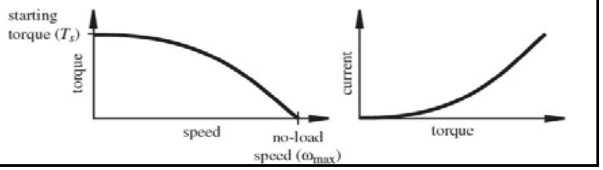
where, I_A = armature current, V_{ln} = line voltage to the motor

R_A = armature resistance, CEMF = voltage generated within the motor

- Above equation tells us that the armature current is a function of the applied voltage minus the CEMF.
- Because CEMF increases with motor speed, the faster the motor runs, the less current the motor will draw, and consequently its torque will diminish. This explains why most DC motors have a finite maximum speed; eventually, if the motor keeps going faster, the CEMF will nearly cancel out the line voltage, and the armature current will approach zero.

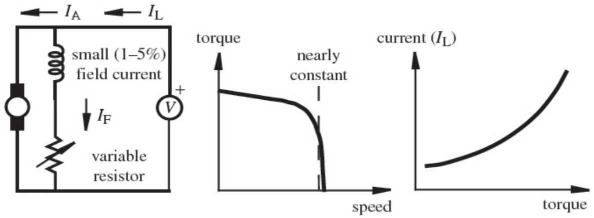
DC Motors: Wound-field DC motors

- use an electromagnet called the **field winding** to generate the magnetic field.
- The speed of wound-field motors is controlled by varying the voltage to the armature or field windings.
- **rated speed:** the speed when the motor is supplying the rated (horse)power.
- **starting torque:** maximum torque the motor can produce, at zero speed, associated with starting the motor.
- **stall torque:** *maximum torque the DC motor can deliver when the motor is loaded so much it comes to a stop.*
- **no-load speed**: maximum sustained speed the motor can attain.
  - This speed can be reached only when no load or torque is applied to the motor (i.e., only when it is free running).



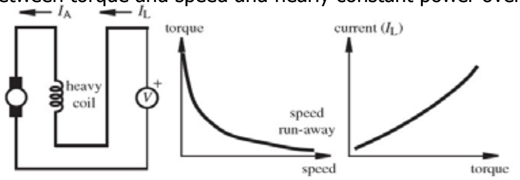
DC Motors: Shunt motors

- have armature and field windings connected in parallel, which are powered by the same supply. The total load current is the sum of the armature and field currents.
- exhibit nearly constant speed over a large range of loading,
- have starting torques about 1.5 times the rated operating torque,
- have the lowest starting torque of any of the DC motors, and
- can be economically converted to allow adjustable speed by placing a potentiometer in series with the field windings.



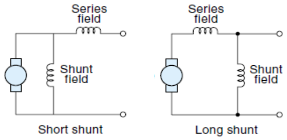
DC Motors: Series motors

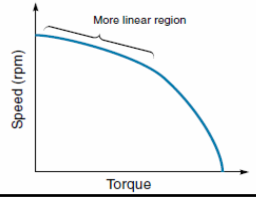
- have armature and field windings connected in series so the armature and field currents are equal.
- exhibit very high starting torques, highly variable speed depending on load, and
  - very high speed when the load is small.
  - In fact, large series motors can fail catastrophically when they are suddenly unloaded (e.g., in a belt drive application when the belt fails) due to dynamic forces at high speeds. This is called **run-away.**
  - As long as the motor remains loaded, this poses no problem.
- The torque speed curve for a series motor is hyperbolic in shape, implying an inverse relationship between torque and speed and nearly constant power over a wide range.



DC Motors: Compound motors

- include both shunt and series field windings.
- There are two configurations of the compound motor, the short shunt and the long shunt.
- 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.
- The combination of both fields acting together tends to straighten out (linearize) a portion of the torque speed curve



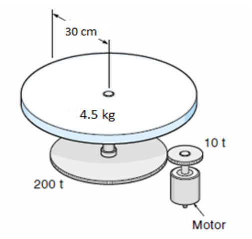


DC Motors: **Problem 1**

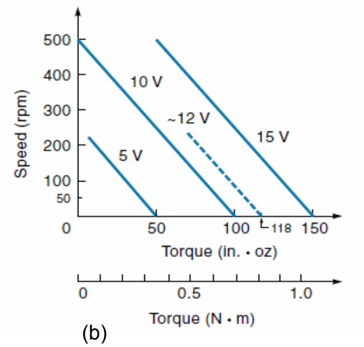
An old 90 Vdc shunt motor on a conveyer belt needs to be replaced. The identification plate on the old motor is unreadable, but you know it was turning at about 1750 rpm. Using your ingenuity and common measuring instruments, determine the specifications for a new motor.

DC Motors: **Problem 2**

A PM motor turns a large 60 cm diameter, 4.5 kg turntable through a 20 : 1 gear train Figure (a). A particular requirement is that the turntable must be able to accelerate from a rest position to 90° in 0.2 s. Determine the necessary motor voltage. The torque speed curves of the motor are given in Figure (b).



(a)



(b)

DC Motors: Permanent magnet motor

- **Permanent-magnet (PM) motors** use permanent magnets to provide the magnetic flux for the field.
- The armature is similar to those in the wound-field motors discussed earlier.
- Three types of magnets are used:
  (1) The Alnico magnet (iron based alloy) has a high-flux density but loses its magnetization under some conditions such as a strong armature field during stalled operation;
  (2) ferrite (ceramic) magnets have a low flux density, so they have to be larger, but they are not easily demagnetized;
  (3) the newer, so-called rare-earth magnets, made from samarium-cobalt or neodymium-cobalt, have the combined desirable properties of high-flux density and high resistance to demagnetization.

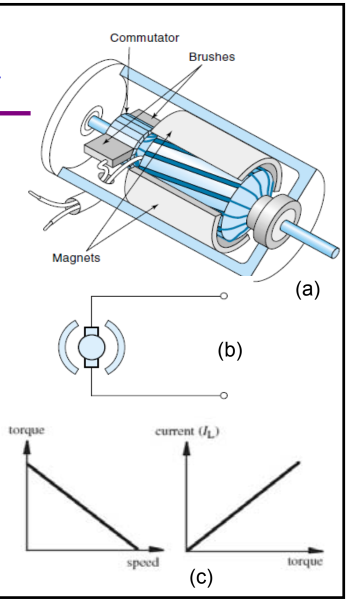


Figure 3.5 (a) Cut-away diagram of a Permanent magnet motor, (b) it's symbol, (c) Torque-speed curve.

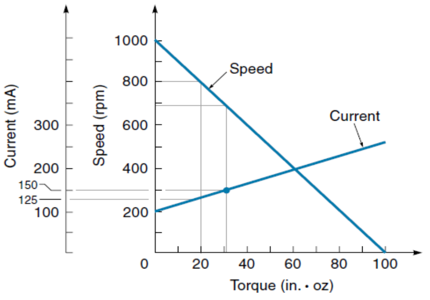
DC Motors: Permanent magnet motor

- requires no external power source for fields, therefore produce no I^2R heating.
- lighter and smaller than other, equivalent DC motors because the field strength of permanent magnets is high.
- ideal in control applications because of the linearity of its torque speed relation. The design of a controller is always easier when the actuator is linear since the system analysis is greatly simplified.
- When a motor is used in a position or speed control application with sensor feedback to a controller, it is referred to as a **servomotor.**
- used only in low power applications since their rated power is usually limited to 5 hp (3728 W) or less, with fractional horsepower ratings being more common.
- PM DC motors can be brushed, brushless, or stepper motors.
- Small PM motors are used extensively in office machines such as printers and disk drives, toys, equipment such as VCRs and cameras (for zoom and autofocus), and many places in industry. Larger PM motors are used in control systems such as industrial robots.

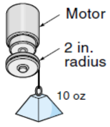
DC Motors: **Problem 3**

Figure (a) shows the torque speed curve of a PM motor. Find the speed and motor current for the following:

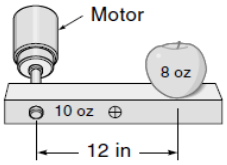
a. No load and stall conditions, **b.** Lifting a 10 oz load with a 2 in. radius pulley
c. A motor driving a robot arm with a weight



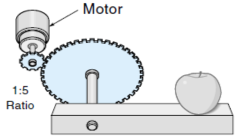
(a)



(b)



(c)



(d)

DC Motors: Brushless DC motor (BLDC)

- The weak point in the mechanical design of the DC motor is the brushes rubbing against the rotating commutator (to get current into the armature). Brushes wear out, get dirty, cause dust, and are electrically noisy.
- The **brushless DC motor** (BLDC) operates without brushes by taking advantage of modern electronic switching techniques. Although this adds some complexity, the result is a motor that is extremely reliable, very efficient, and easily controlled. The BLDC is becoming increasingly popular, particularly in those cases where the motor must be operated from a DC source such as a battery.

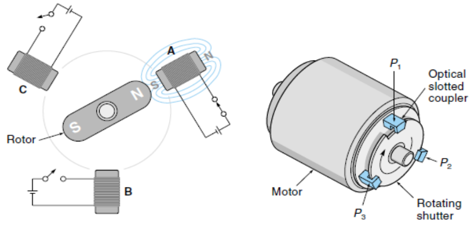


Figure 3.6 Brushless DC motor

(a) Field coil arrangement

(b) Rotating shutter and sensors

DC Motors: Brushless DC motor (BLDC)

- Figure 3.6(a) shows a diagram of a three-phase BLDC. The armature (called the **rotor**) is a permanent magnet, and it is surrounded by three field coils.
  - Each field coil can be switched on and off independently.
  - When a coil is on, such as coil A in Figure 3.6(a), the north pole of the rotor magnet is attracted to that coil.
  - By switching the coils on and off in sequence (A, B, C), the rotor is "dragged" around clockwise—that is, the field has rotated electronically.
- have much in common with stepper motors. The major difference between these two types of motors is that the BLDC is used as a source of rotary power, like a regular electric motor, whereas the stepper motor is used when it is necessary to step to precise positions and then stop.
- Figure 3.6(b) shows the 3-phase BLDC with 3 optical slotted couplers and a rotating shutter (Hall-effect sensors can also be used for this application).
  - These position sensors control the field windings.
  - When the shutter is open for sensor P_1 as shown, field coil A [Figure 3.6(a)] is energized.

DC Motors: Brushless DC motor (BLDC)

  - When the rotor actually gets to field coil A, sensor P_1 is turned off and P_2 is turned on, energizing field coil B and pulling the rotor on around to coil B, and so on. In this manner, the rotor is made to rotate with no electrical connection between the rotor and the field housing.

- BLDC motors exhibit excellent speed control. In fact, some models come with a built-in tachometer that feeds back to the control unit, allowing a perfect speed regulation.

- BLDC motors have higher power efficiency (they use less power for the same horsepower) and are smaller and lighter than other types of motors with the same horsepower.

Stepper Motors:

- A **stepper motor** is a unique type of DC motor that rotates in fixed steps of a certain number of degrees. Step size can range from 0.9 to 90°.
- It can rotate in both directions,
  - move in precise angular increments,
  - sustain a holding torque at zero speed, and
  - be controlled with digital circuits.
- It moves in accurate angular increments in response to digital pulses sent to an electric drive circuit.
- The number and rate of the pulses control the position and speed of the motor shaft. Generally, stepper motors are manufactured with steps per revolution of 12, 24, 72, 144, 180, and 200, resulting in shaft increments of 30, 15, 5, 2.5, 2, and 1.8 per step.
- Special **micro-stepping** circuitry can be designed to allow many more steps per revolution, often 10,000 steps/rev or more.

Stepper Motors:

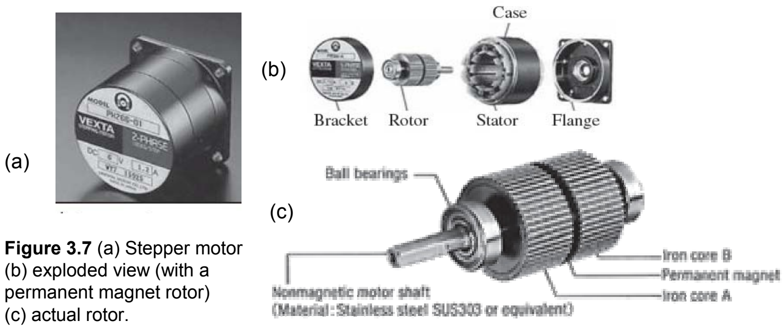


Figure 3.7 (a) Stepper motor (b) exploded view (with a permanent magnet rotor) (c) actual rotor.

- There are three types of stepper motors:
  - permanent magnet,
  - variable reluctance, and
  - hybrid.

Stepper Motors: PM

- a basic stepper motor consists of a **rotor** and **stator.**
- rotor is a permanent magnet, and stator is made up of four poles (electro-magnets).
- The motor works in the following manner: Assume the rotor is in the position shown with the south end up.
  - When field coil 1 is energized, the south end of the rotor is attracted to coil 1 and moves toward it.
  - Then field coil 1 is de-energized, and coil 2 is energized.
  - The rotor pulls itself into alignment with coil 2.
  - Thus, the rotor turns in 90° steps for each successive excitation of the field coils.
- The motor can be made to reverse by inverting the sequence

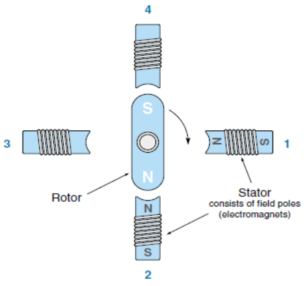


Figure 3.8 A PM 90 stepper motor.

Stepper Motors: mode of operation

- two modes of operation: single step and slew.
- **single step mode** or bidirectional mode:
  - frequency of the steps is slow enough to allow the rotor to (almost) come to a stop between steps.
  - Figure 3.9(a) shows a graph of position versus time for single step operation.
  - For each step, the motor advances a certain angle and then stops.
  - If the motor is only lightly loaded, overshoot and oscillations may occur at the end of each step as shown in the figure.
  - the motion is slow and "choppy."

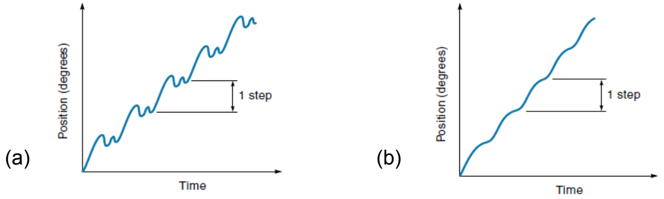


Figure 3.9 Position versus time for (a) single step mode and (b) slew mode

---

Stepper Motors: mode of operation

- **slew mode,** or unidirectional mode,
  - frequency of the steps is high enough that the rotor does not have time to come to a stop.
  - This mode approximates the operation of a regular electric motor—that is, the rotor is always experiencing a torque and rotates in a smoother, continuous fashion.
  - the motion is much less choppy than in single step mode.
  - in slew mode, the motor cannot stop or reverse direction instantaneously.
  - If attempted, the rotational inertia of the motor would most likely carry the rotor ahead a few steps before it came to rest. The step count integrity would be lost. It is possible to maintain the step count in the slew mode by slowly ramping up the velocity from the single step mode and then ramping down at the end of the slew. This means the controller must know ahead of time how far the motor must go.
  - Typically, the slew mode is used to get the motor position in the "ballpark," and then the fine adjustments can be made with single steps.
  - Slewing moves the motor faster but increases the chances of losing the step

Stepper Motors: mode of operation

- three different kinds of torques.
- **detent torque:** the torque required to overcome the force of the permanent magnets (when the power is off).
  - It is the little tugs you feel if you manually rotate the unpowered motor.
- **dynamic torque**: the maximum running torque, is obtained when the rotor is lagging behind the field poles by half a step.
- **holding torque**: The highest stall torque shown in Figure 3.10
  - results when the motor is completely stopped but with the last pole still energized.
  - This is really a detent type of torque because it represents the amount of external torque needed to rotate the motor "against its wishes."

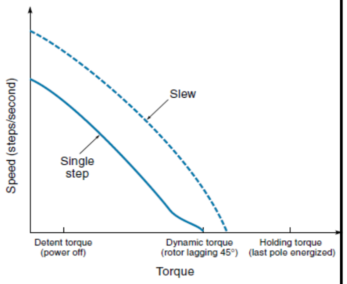


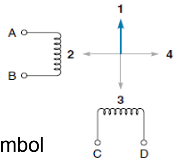
Figure 3.10:Torque–speed curves for single-step and slew modes.

Stepper Motors: Excitation mode (for PM)

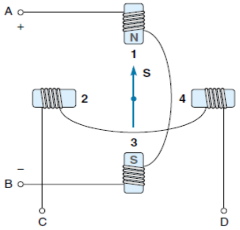
- Stepper motors come with a variety of winding and rotor combinations.
- there are different ways to sequence energy to the field coils.
- All these factors determine the size of each step.
- **Phase** refers to the number of separate winding circuits.
- There are 2-, 3-, and 4-phase steppers.

Two Phase (Bipolar) Stepper Motors

- has only two circuits but actually consists of four field poles.
- In Figure 3.11(b), circuit AB consists of two opposing poles such that when voltage is applied (+A –B), the top pole will present a north end to the rotor and the bottom pole will present a south end. The rotor would tend to align itself vertically (position 1) with its south pole up (because, opposite magnetic poles attract).



(a) Symbol



(b) Wiring diagram

Figure 3.11 Two-phase (bipolar) stepper motor.

Stepper Motors: Excitation mode (for PM)

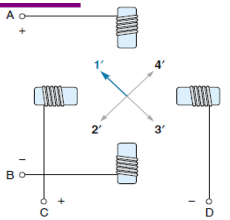
- The simplest way to step this motor is to alternately energize either AB or CD in such a way as to pull the rotor from pole to pole.
  - If the rotor is to turn CCW from position 1, then circuit CD must be energized with polarity C+ D–. This would pull the rotor to position 2.
  - Next, circuit AB is energized again, but this time the polarity is reversed (–A +B), causing the bottom pole to present a north end to the rotor, thereby pulling it to position 3.
- The voltage sequence needed to rotate the motor one full turn is shown below.
  - Reading from top to bottom gives the sequence for turning CCW, reading from bottom up gives the CW sequence:

Circuit	**Position**
A+ B–	1
C+ D–	2
A– B+	3
C– D+	4

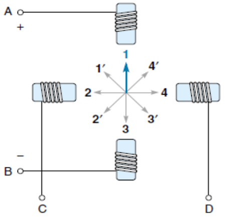
Stepper Motors: Excitation mode (for PM)

- Another way to operate the two phase stepper is to energize both circuits at the same time.
- In this mode, the rotor is attracted to two adjacent poles and assumes a position in between.
- Figure 8.9(a) shows the four possible rotor positions.
- The excitation sequence for stepping in this dual mode is as follows:

Circuits	**Position**
A+ B– and C+ D–	1′
A– B+ and C+ D–	2′
A– B+ and C– D+	3′
A+ B– and C– D+	4′



(a) Dual excitation (energized for position 1)



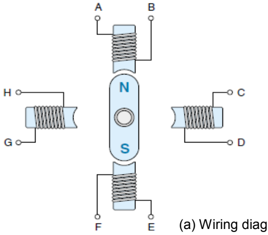
(b) Eight-step drive using "half-steps"

Figure 3.12 Additional operating modes for stepper motors.

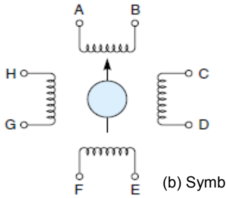
Stepper Motors: Four-Phase (Unipolar) Stepper Motors

- is the most common type of stepper motor
  - the term four-phase is used because the motor has four field coils that can be energized independently, and
  - the term **unipolar** is applied because the current always travels in the same direction through the coils.
- The simplest way to operate the four-phase stepper motor is to energize one phase at a time in sequence (known as wave drive).
- To rotate CW, the following sequence is used:

  A B, C D, E F, G H
- Compared with the two-phase bipolar motor, the four-phase motor has the advantage of simplicity.
- The control circuit of the four-phase motor simply switches the poles on and off in sequence; it does not have to reverse the polarity of the field coils.



(a) Wiring diagram

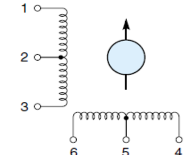


(b) Symbol

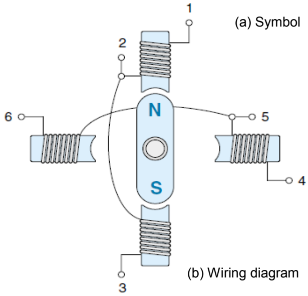
Figure 3.13 Four-phase (unipolar) stepper motor.

Stepper Motors: center tap windings

- (However, the two-phase motor produces more torque because it is pushing and pulling at the same time.)
- Constructing motors so they can be used in either a 2- or 4-phase mode is common practice.
  - done by bringing out two additional wires (from the two phase motor) that are internally connected to points between the opposing field coils.
- When such a motor is used in the 2-phase mode, the center taps (terminals 2 and 5) are not used.
- When the motor is operated in the 4-phase mode, the center taps become a common return, and power is applied to terminals 1, 4, 3, and 6 as required.



(a) Symbol



(b) Wiring diagram

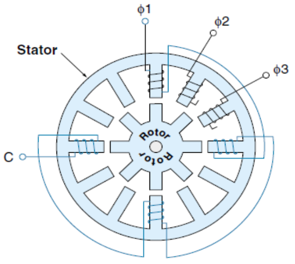
Figure 3.14 Four-phase stepper with center tap windings.

Stepper Motors: Variable reluctance SM

- The **variable-reluctance (VR) stepper motor** does not use a magnet for the rotor;
  - uses a toothed iron wheel.
  - The advantage of not requiring the rotor to be magnetized is that it can be made in any shape.
  - VR motor gives less torque than the PM motor.
- A VR motor usually has 3- or 4-phases.
- Figure 3.15(a) shows a typical 3-phase stepper motor.
  - The stator has 3 field pole circuits:

    Ø1, Ø2, and Ø3.
  - the actual motor has 12 field poles, where each circuit energizes 4 windings
  - the rotor has only 8 teeth even though there are 12 teeth in the stator
  - Therefore, the rotor teeth can never line up

    “one for one” with the stator teeth, a fact that plays an important part in the motor’s operation.

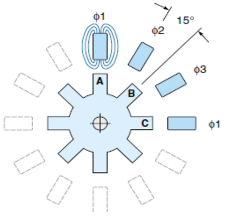


(wires for ϕ2 & ϕ3 left out for clarity)

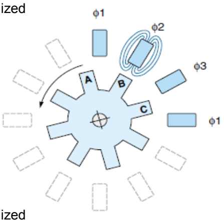
Figure 3.15 A 3-phase VR stepper motor (15 step).

Stepper Motors: Variable reluctance SM

- When circuit Ø1 is energized, the rotor will move to the position shown in Figure 3.16(a)—that is, a rotor tooth (A) is lined up with the Ø1 field pole.
- Next, circuit Ø2 is energized. Rotor tooth B, being the closest, is drawn toward it [Figure 3.16(b)].
- Notice that the rotor has to move only 15° for this alignment.
- If circuit Ø3 is energized next, the rotor would continue CCW another 15° by pulling tooth C into alignment.
- The step angle of the VR motor is the difference between the rotor and stator angles.
  - the angle between the field poles is 30°, and the angle between the rotor poles is 45°.
  - Therefore, the step is 15° (45° – 30° = 15°).
- By using this design, the VR stepper motor can achieve very small steps (less than 1°).



(a) Pole Ø1 energized



(b) Pole Ø2 energized

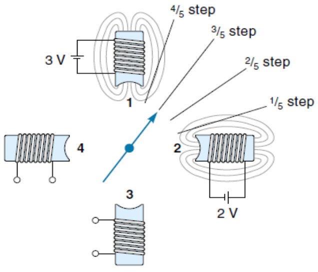
Figure 3.16 Operation of a 15° three-phase VR stepper motor

Stepper Motors: Hybrid Stepper Motors

- The **hybrid stepper motor** combines the features of the PM and VR stepper motors
- is the type in most common use today.
- The rotor is toothed, which allows for very small step angles (typically 1.8°), and it has a permanent magnet providing a small detent torque even when the power is off.
- the step size of a PM motor is limited by the difficulty in making a multipole magnetized rotor. There is simply a limit to the number of different magnetizations that can be imposed on a single iron rotor. The VR stepper motor gets around this by substituting iron teeth (of which there can be many) for magnetized poles on the rotor.
- This approach allows for a small step angle, but it sacrifices the strength and detent torque qualities of the PM motor.
- The hybrid motor can effectively magnetize a multitoothed rotor and thus has the desirable properties of both the PM and VR motors.

Stepper Motors: Microstepping

- a technique that allows a stepper motor to take fractional steps,
  - works by having two adjacent field poles energized at the same time, similar to half-steps described earlier.
- the adjacent poles are driven with different voltage levels.
- Eg., pole 1 is supplied with 3 V and pole 2 with 2 V, which causes the rotor to be aligned as shown—that is, 3/5 of the way to pole 1.
- The different voltages could be synthesized with pulse width modulation (PWM).
- The most commonly used microstep increments are 1/5, 1/10, 1/16, 1/32, 1/125, and 1/250 of a full step.



Pole 1	Pole 2	Position
5 V	0 V	Pole 1 (full step)
4 V	1 V	$^{4}/_{5}$ step
3 V	2 V	$^{3}/_{5}$ step
2 V	3 V	$^{2}/_{5}$ step
1 V	4 V	$^{1}/_{5}$ step
0 V	5 V	Pole 2 (full step)

Figure 3.17 Microstepping.

Stepper Motors: Microstepping

- Another benefit of microstepping (for delicate systems) is that it reduces the vibrational "shock" of taking a full step—that is, taking multiple microsteps creates a more "fluid" motion.
- it does not require a special stepper motor, only special control circuitry,
- the actual position of the rotor (in a microstepping system) is very dependent on the load torque.

Stepper Motors: Problem 4

A stepper motor has the following properties:

Holding torque: 50 in.·oz
Dynamic torque: 30 in.·oz
Detent torque: 5 in.·oz

The stepper motor will be used to rotate a 1-in. diameter printer platen as shown in the Figure. The force required to pull the paper through the printer is estimated to not exceed 40 oz. The static weight of the paper on the platen (when the printer is off) is 12 oz.

Will this stepper motor do the job?

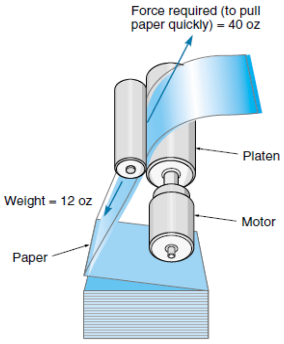


Figure: A stepper motor driving a printer platen

Stepper Motors: Problem 4 Solution

The torque required to rotate the platen during printing can be calculated as follows:

Torque = force × radius = 40 oz × 0.5 in. = 20 in. · oz

Therefore, the motor, with 30 in. · oz of dynamic torque, will be strong enough to advance the paper.

The torque on the platen from just the weight of the paper is calculated as follows:

Torque = force × radius = 12 oz × 0.5 in. = 6 in · oz

When the printer is on, the powered holding torque of 50 in. · oz is more than enough to support the paper.

However, when the printer is off, the weight of the paper exceeds the detent torque of 5 in. · oz, and the platen (and motor) would spin backward.

Therefore, we conclude that this motor is not acceptable for the job

(unless some provision such as a ratchet or brake is used to prevent back spinning).

AC Motors

- AC motors are primarily used as a source of constant-speed mechanical power but are increasingly being used in variable speed control applications.
- They are popular because they can provide rotary power with high efficiency, low maintenance, and exceptional reliability—all at relatively low cost.
- These desirable qualities are the result of two factors:
  - (1) AC motors can use the AC power "right off the lines."—DC motors require the added expense of a rectifier circuit;
  - (2) most AC motors do not need brushes as DC motors do.

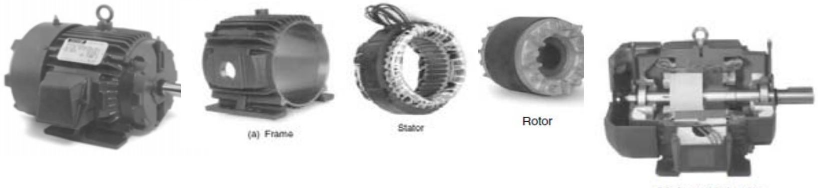


Figure 3.18 Induction motor

AC Motors: induction motor

- By far the most commonly used type of AC motor is the induction motor, the simple, reliable, "workhorse" that powers most domestic and industrial machines.
- The basic parts of the induction motor are the **frame, stator,** and **rotor.**
  - The stator consists of the stationary field coil windings.
  - The rotor is positioned inside the stator and rotates as a result of electromagnetic interaction with the stator.
  - The frame supports the stator and rotor in the proper position.
- Theory of operation:
  - has some similarities to that of the stepper motor or BLDC (brushless DC motor).
  - Two-phase AC consists of two individual phase voltages (Figure 3.19).
  - phase B is lagging behind phase A by 90°—i.e, phase A peaks at 0°, and phase B peaks 90° later.
  - when phase A energizes the top and bottom poles and phase B energizes the left and right poles.
  - The action of two-phase AC on the motor is to cause the stator magnetic field to effectively rotate clockwise (called a **rotating field**), even though the coils themselves are stationary.

AC Motors: induction motor

- In Figure 3.19, at 0° phase A is at peak voltage while phase B is 0 V.
  - At this point, phase A has all the voltage, and phase B has none;
  - the windings connected to phase A (top and bottom) will be energized, and the windings connected to phase B (left and right) will be off.
  - The polarity of the applied voltage causes the top winding to present a north (N) magnetic pole to the rotor and the bottom winding to present a south (S) magnetic pole to the rotor.
- At 90° later in the power cycle, phase A voltage has gone to 0 V (deenergizing the top and bottom windings), and phase B has risen to peak voltage, energizing the left and right windings.
- Specifically, the positive phase B voltage will cause the rightside winding to present a north magnetic pole to the rotor and the left winding to present a south magnetic pole.

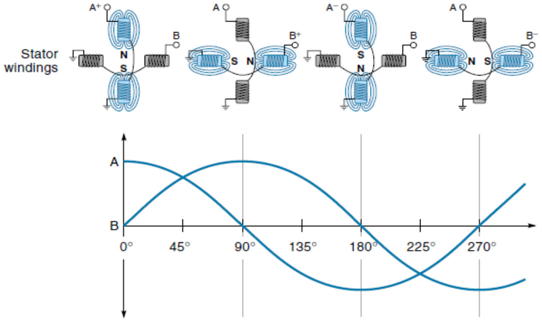


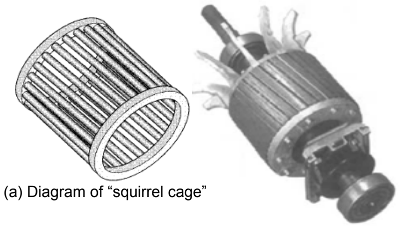
Figure 3.19 How two-phase AC causes a rotating field.

AC Motors: induction motor

- At 180°, phase B voltage has gone back to 0 V (deenergizing the left and right windings), and phase A has descended to a negative peak voltage.
  - Once again, the top and bottom windings are energized but this time with the opposite polarity from what they were at 0°, causing the magnetic poles to be reversed. Now the bottom winding presents a north magnetic pole to the rotor, and the top winding presents a south magnetic pole.
- At 270°, phase A has ascended to 0 V (deenergizing the top and bottom windings), and phase B has gone to a negative peak.
  - Once again, the left and right windings are energized but this time with the left winding presenting a north magnetic pole to the rotor and the right winding a south magnetic pole.
- the rotation of the field is smooth and continuous - it doesn't jump from pole to pole as might be inferred from the discussion.
  - For example, consider the situation at 45°. From Figure 3.19, we can see that both sets of poles are partially energized, causing the resultant N-S magnetic field to be halfway between the two poles.

AC Motors: Squirrel cage rotor

- consists of a number of aluminum or copper bars connected with two end rings.
- Because this configuration reminded someone of a squirrel cage, it is called a **squirrel cage rotor.**
- The squirrel cage rotor has no magnetic properties when the power is off.
- when AC power is applied to the stator windings and the stator field starts rotating, the rotor becomes magnetized by induction.
- Working principle:
  - As the stator field rotates past an individual bar, field strength in the bar rises & falls.
  - This changing magnetic field induces a voltage in the bar, and the voltage causes a current to flow.
  - current flows through the bar, through the end rings, and back through other bars.
  - This current causes the bar to have a magnetic field, and it is this field, interacting with the rotating stator field, that produces the mechanical torque.



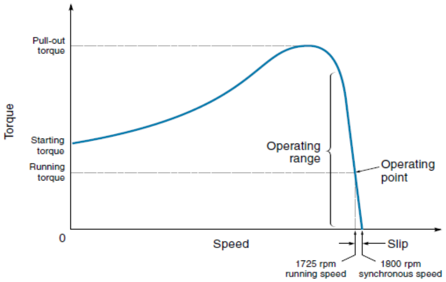
(a) Diagram of "squirrel cage"

Figure 3.20 An induction motor "squirrel cage" rotor.

AC Motors: Torque Speed curve

- Mechanical rotation of the rotor is the result of the rotor being pulled around in a CW direction, "chasing" the rotating field.
- The rotor is magnetized by an "induced" current from the field
- The field makes one complete revolution per cycle; thus, for a line frequency of 60 Hz, the field would rotate at 3600 rpm

  (60 cycle/s) × (60 s/min) =3600 rpm.
- The speed of the rotating field (3600 rpm in this case) is called the **synchronous speed.**
- For an induction motor, the rotor speed does not exactly match the synchronous speed, it's slightly lower.



Torque–speed curve of an induction motor.

AC Motors: AC Servomotors

- high-slip, high torque motor, designed specifically for control systems.
- has a relatively linear torque-speed curve.
- When the motor is running, the speed is inversely proportional to the load torque
  - the lighter the load, the faster the motor runs.
  - This is very similar to the way a DC motor behaves.
- The main winding is connected to an AC source.
- The control winding is driven by an electronic circuit that
  - (1) causes the phase to be either leading or lagging the main winding (thereby controlling the motor direction) and
  - (2) sets the magnitude of the control-winding voltage, which determines the speed.
- If the control winding has 0 V, the motor will coast to a stop, even though the main winding is still connected to the line voltage. This is different from a normal induction motor that *will* continue to run on a single phase.

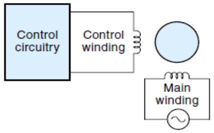
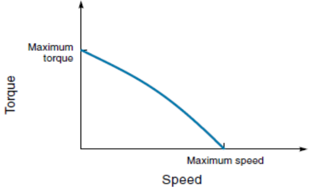


Diagram of an AC servomotor.



Torque–speed curve of an AC servomotor.

AC Motors:

Synchronous Motors

- The rotor in the synchronous motor rotates at exactly the speed of the rotating field — there is no slip.
  - – the speed of the synchronous motor is always an exact multiple of the line frequency.

Universal Motors

- The **universal motor** is so named because it can be powered with either AC or DC.
- Basically, it is a series-wound DC motor that has been specifically designed to operate on AC.
- Like its DC counterpart, it is reversible by changing the polarity of either the field or the rotor windings, but not both.
- Physically, the universal motor is similar to a DC motor except that more attention is paid to using laminations (thin sheets of lacquered metal) for the metal parts (to reduce the AC eddy currents) and the inductance of the windings is minimized as much as possible.

Motor Selection

- When selecting a motor for a specific mechatronics application, the designer must consider many factors and specifications, including speed range, torque speed variations, reversibility, operating duty cycle, starting torque, and power required.
- the torque speed curve provides important information, helping to answer many questions about a motor’s performance.

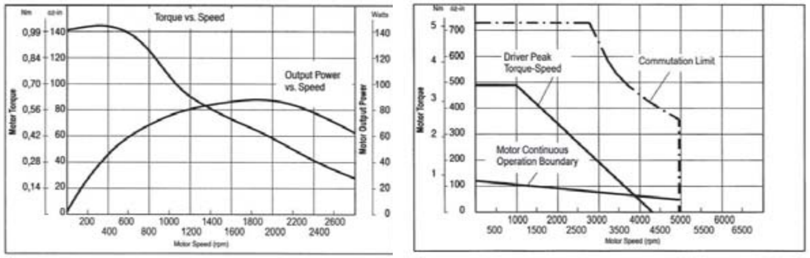


Figure 3.20 Typical motor performance curves: Stepper motor (left figure), servomotor (right figure)

Motor Selection

Some of the salient questions a designer may need to consider when choosing a motor for an application include the following:

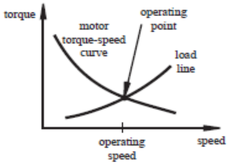
1. Will the motor start and will it accelerate fast enough?
2. What is the maximum speed the motor can produce?
3. What is the operating duty cycle?
   - – When a motor is not operated continuously, one must consider the operating cycle of the system.
   - – The **duty cycle** is defined as the ratio of the time the motor is on with respect to the total elapsed time.
   - – If a load requires a low duty cycle, a lower-power motor may be selected that can operate above rated levels but still perform adequately without overheating during repeated on-off cycles.
4. How much power does the load require?
5. What power source is available?
6. What is the load inertia?
   - – for fast dynamic response, it is desirable to have low motor rotor and load inertia I.

Motor Selection

7. Is the load to be driven at constant speed?
   - – For constant speed, select an AC synchronous motor or a DC shunt motor which runs at a relatively constant speed over a significant range of load torques.
   - – Stepper motors and servomotors can also be driven at constant and accurate speeds, but involves more cost and might not be available in larger sizes.
8. Is accurate position or speed control required?
   - – In the cases of angular positioning at discrete locations and incremental motion, a stepper motor is a good choice.
   - – For some complex motion requirements, where precise position or speed profiles are required (e.g., in automation applications where machines need to perform prescribed programmed motion), a servomotor may be the best choice.
   - – A **servomotor** is a DC, AC, or brushless DC motor combined with a position sensing device (e.g., a digital encoder).
   - – The servomotor is driven by a programmable feed back controller that processes the sensor input and generates amplified voltages and currents to the motor to achieve specified motion profiles.
   - – A servomotor is typically more expensive than a stepper motor, but it can have a much faster and smoother response.

Motor Selection

9. Is a transmission or gearbox required?
    - Often loads require low speeds and large torques. Since motors usually have better performance at high speed and low torque, a speed-reducing transmission (gear box or belt drive) is often needed to match the motor output to the load requirements.
    - The term **gear motor** is used to refer to a motor-gearbox assembly sold as a single package.
10. Is the motor torque speed curve well matched to the load?
11. For a given motor torque speed curve and load line, what will the operating speed be?
    - for a given motor torque-speed curve and a well-defined load line, the system settles at a fixed speed operating point.
    - the operating point is self-regulating.
    - At lower speeds, the motor torque exceeds the load torque and the system accelerates toward the operating point,



Motor operating speed.

Motor Selection

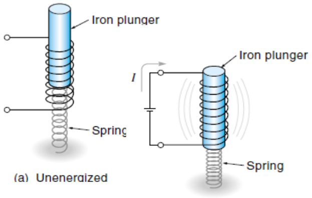
- but at higher speeds, the load torque exceeds the motor torque, reducing the speed toward the operating point.
- The operating speed can be actively changed by adjusting the voltage supplied to the motor, which in turn changes the torque-speed characteristic of the motor.

12. Is it necessary to reverse the motor?
    - Some motors are not reversible due to their construction and control electronics, and care must be exercised when selecting a motor for an application that requires rotation in two directions.

13. Are there any size and weight restrictions?
    - Motors can be large and heavy, and designers need to be aware of this early in the design phase.

Solenoids

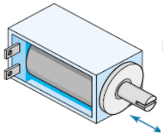
- A **solenoid** is a simple electromagnetic device that converts electrical energy directly into linear mechanical motion, but it has a very short **stroke** (length of movement), which limits its applications.
- consists of a coil of wire with an iron plunger that is allowed to move through the center of the coil.
- at unenergized state, the plunger is being held about halfway out of the coil by a spring. When the coil is energized [Figure 3.21(b)], the resulting magnetic field pulls the plunger to the middle of the coil.
- The magnetic force is unidirectional—a spring is required to return the plunger to its unenergized position.
- The main limitation of the solenoid is its short stroke, which is usually under an inch.
- Examples:
    - Activating electric car-door locks,
    - opening and closing valves, and



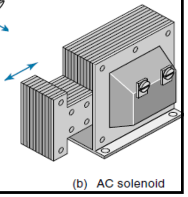
(a) Unenergized

(b) Energized

Figure 3.21 solenoid



(a) DC solenoid



(b) AC solenoid

Solenoids

- Most applications use the solenoid as a on or off device—that is, the coil is either completely energized or switched off.
- However, variable-position control is possible by varying the input voltage.
- Both AC and DC solenoids are used,
- the major difference being that AC solenoids use a plunger and frame made from laminations instead of solid iron.
- **Laminations** are thin sheets of lacquered iron that are riveted together to form the frame and plunger.
    - Laminations prevent power-consuming *eddy currents* (induced by the AC) from circulating in the metal parts of the solenoid.