15. CONTINUOUS ACTUATORS

Topics:
- Servo Motors; AC and DC
- Stepper motors
- Single axis motion control
- Hydraulic actuators

Objectives:
- To understand the main differences between continuous actuators
- Be able to select a continuous actuator
- To be able to plan a motion for a single servo actuator

15.1 INTRODUCTION

Continuous actuators allow a system to position or adjust outputs over a wide range of values. Even in their simplest form, continuous actuators tend to be mechanically complex devices. For example, a linear slide system might be composed of a motor with an electronic controller driving a mechanical slide with a ball screw. The cost for such actuators can easily be higher than for the control system itself. These actuators also require sophisticated control techniques that will be discussed in later chapters. In general, when there is a choice, it is better to use discrete actuators to reduce costs and complexity.

15.2 ELECTRIC MOTORS

An electric motor is composed of a rotating center, called the rotor, and a stationary outside, called the stator. These motors use the attraction and repulsion of magnetic fields to induce forces, and hence motion. Typical electric motors use at least one electromagnetic coil, and sometimes permanent magnets to set up opposing fields. When a voltage is applied to these coils the result is a torque and rotation of an output shaft. There are a variety of motor configuration the yields motors suitable for different applications. Most notably, as the voltages supplied to the motors will vary the speeds and torques that they will provide.

- Motor Categories
  - AC motors - rotate with relatively constant speeds proportional to the frequency of the supply power
    - induction motors - squirrel cage, wound rotor - inexpensive, efficient.
    - synchronous - fixed speed, efficient
  - DC motors - have large torque and speed ranges
    - permanent magnet - variable speed
    - wound rotor and stator - series, shunt and compound (universal)
  - Hybrid
    - brushless permanent magnet -
    - stepper motors

- Contactors are used to switch motor power on/off

- Drives can be used to vary motor speeds electrically. This can also be done with mechanical or hydraulic machines.

- Popular drive categories
  - Variable Frequency Drives (VFD) - vary the frequency of the power delivered to the motor to vary speed.
  - DC motor controllers - variable voltage or current to vary the motor speed
  - Eddy Current Clutches for AC motors - low efficiency, uses a moving iron drum and windings
  - Wound rotor AC motor controllers - low efficiency, uses variable resistors to adjust the winding currents

A control system is required when a motor is used for an application that requires continuous position or velocity. A typical controller is shown in Figure 15.1. In any controlled system a command generator is required to specify a desired position. The controller will compare the feedback from the encoder to the desired position or velocity to determine the system error. The controller with then generate an output, based on the system error. The output is then passed through a power amplifier, which in turn drives the motor. The encoder is connected directly to the motor shaft to provide feedback of position.

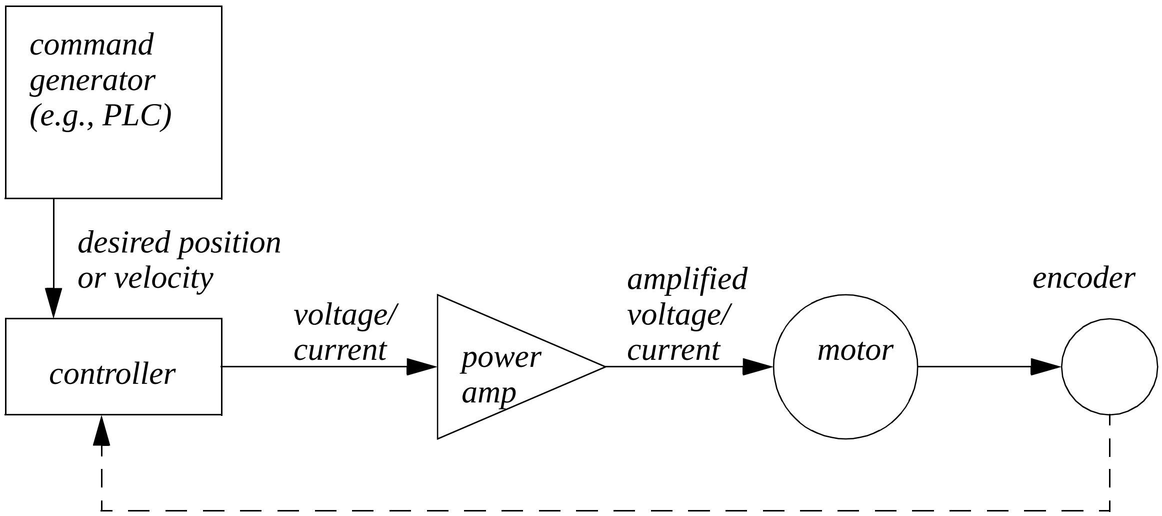


Figure 15.1 A Typical Feedback Motor Controller

15.2.1 Basic Brushed DC Motors

In a DC motor there is normally a set of coils on the rotor that turn inside a stator populated with permanent magnets. Figure 15.2 shows a simplified model of a motor. The magnetics provide a permanent magnetic field for the rotor to push against. When current is run through the wire loop it creates a magnetic field.

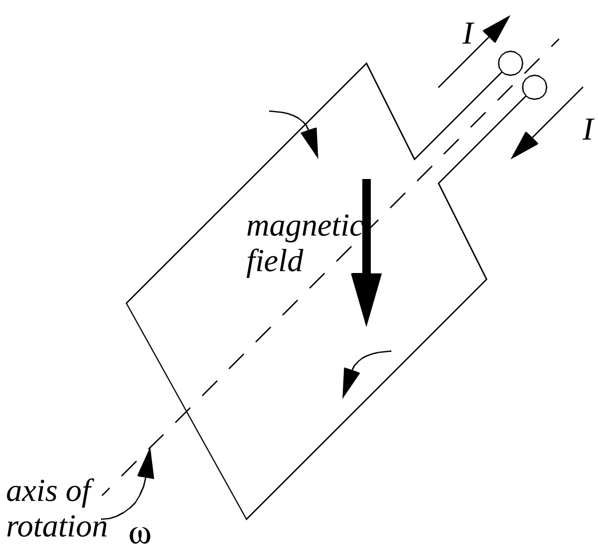


Figure 15.2 A Simplified Rotor

The power is delivered to the rotor using a commutator and brushes, as shown in Figure 15.3. In the figure the power is supplied to the rotor through graphite brushes rubbing against the commutator. The commutator is split so that every half revolution the polarity of the voltage on the rotor, and the induced magnetic field reverses to push against the permanent magnets.

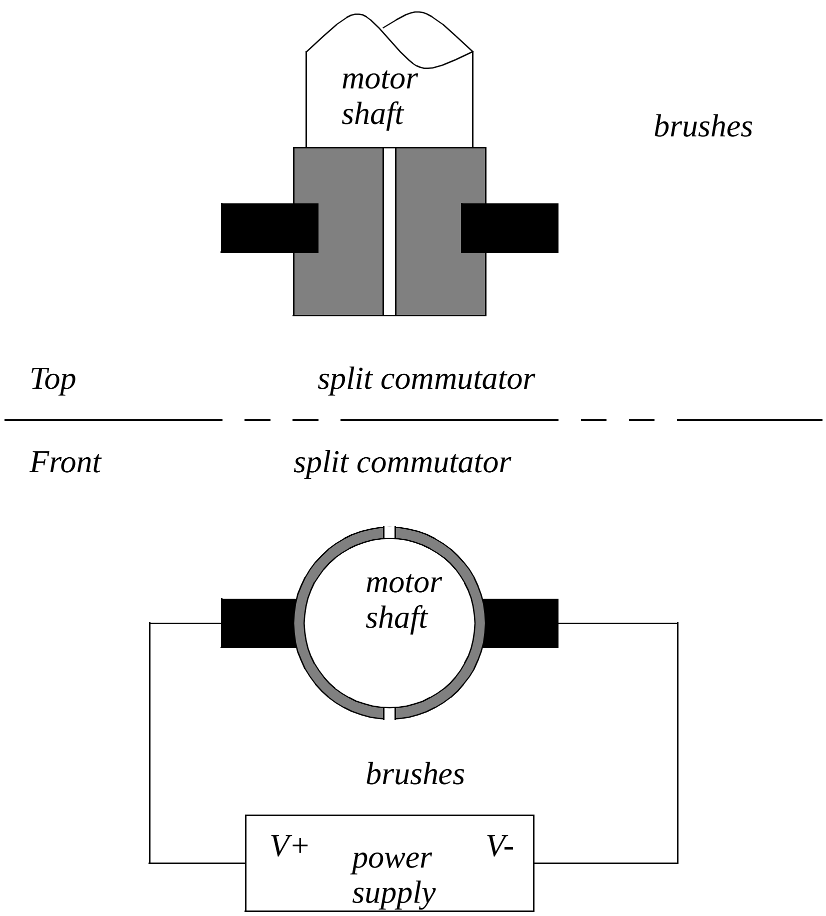


Figure 15.3 A Split Ring Commutator

The direction of rotation will be determined by the polarity of the applied voltage, and the speed is proportional to the voltage. A feedback controller is used with these motors to provide motor positioning and velocity control.

These motors are losing popularity to brushless motors. The brushes are subject to wear, which increases maintenance costs. In addition, the use of brushes increases resistance, and lowers the motors efficiency.

ASIDE: The controller to drive a servo motor normally uses a Pulse Width Modulated (PWM) signal. As shown below the signal produces an effective voltage that is relative to the time that the signal is on. The percentage of time that the signal is on is called the duty cycle. When the voltage is on all the time the effective voltage delivered is the maximum voltage. So, if the voltage is only on half the time, the effective voltage is half the maximum voltage. This method is popular because it can produce a variable effective voltage efficiently. The frequency of these waves is normally above 20KHz, above the range of human hearing.

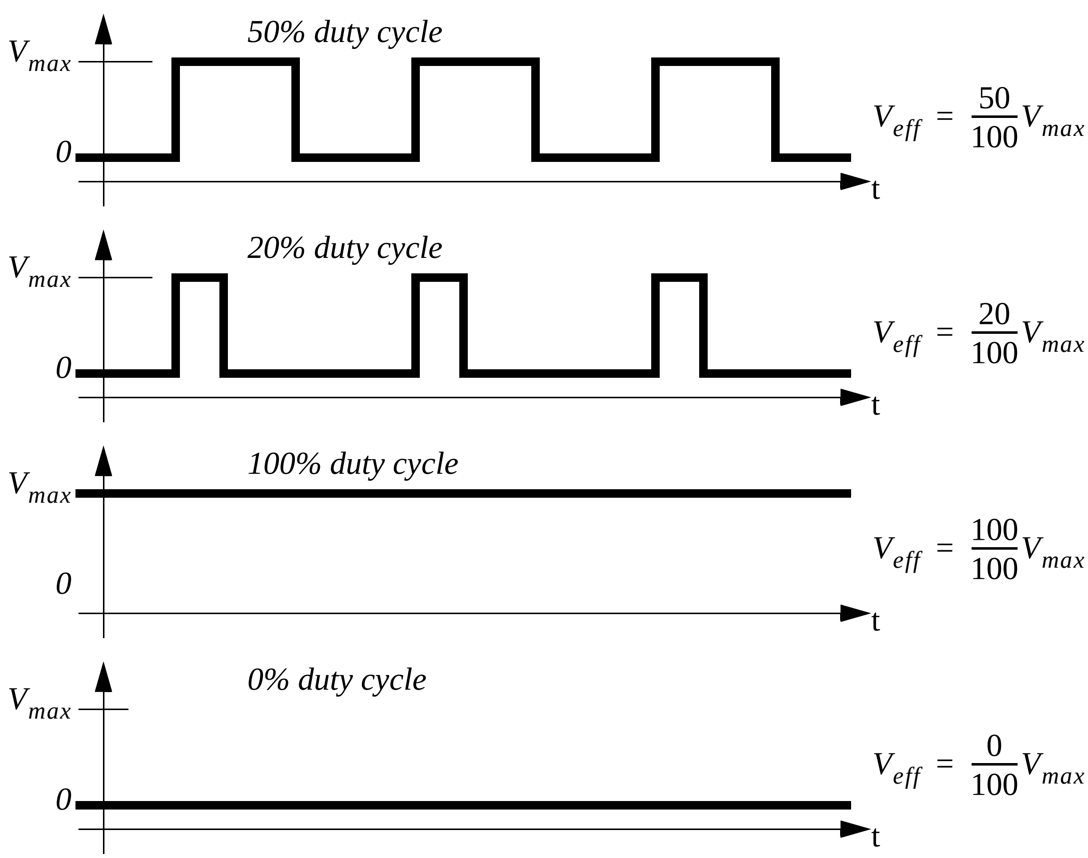


Figure 15.4 Pulse Width Modulation (PWM) For Control

ASIDE: A PWM signal can be used to drive a motor with the circuit shown below. The PWM signal switches the NPN transistor, thus switching power to the motor. In this case the voltage polarity on the motor will always be the same direction, so the motor may only turn in one direction.

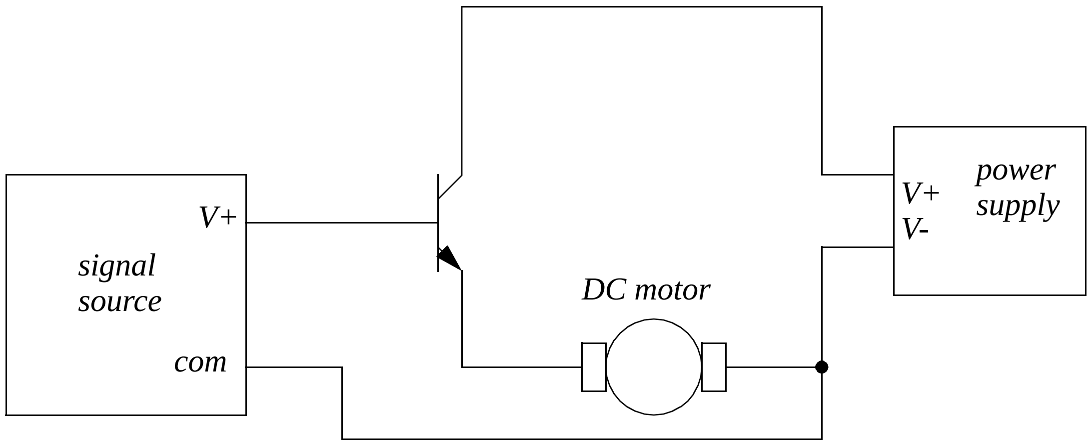


Figure 15.5 PWM Unidirectional Motor Control Circuit

ASIDE: When a motor is to be controlled with PWM in two directions the H-bridge circuit (shown below) is a popular choice. These can be built with individual components, or purchased as integrated circuits for smaller motors. To turn the motor in one direction the PWM signal is applied to the Va inputs, while the Vb inputs are held low. In this arrangement the positive voltage is at the left side of the motor. To reverse the direction the PWM signal is applied to the Vb inputs, while the Va inputs are held low. This applies the positive voltage to the right side of the motor.

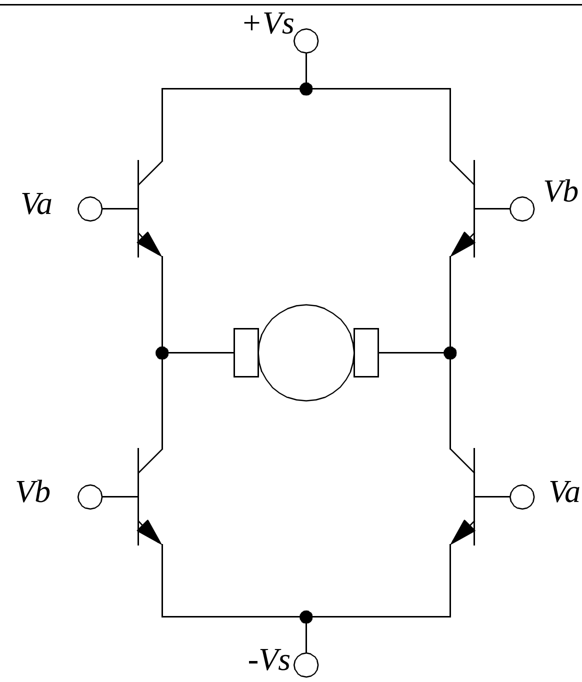


Figure 15.6 PWM Bidirectional Motor Control Circuit

15.2.2 AC Motors

• Power is normally generated as 3-phase AC, so using this increases the efficiency of electrical drives.

• In AC motors the AC current is used to create changing fields in the motor.

• Typically AC motors have windings on the stator with multiple poles. Each pole is a pair of windings. As the AC current reverses, the magnetic field in the rotor appears to rotate.

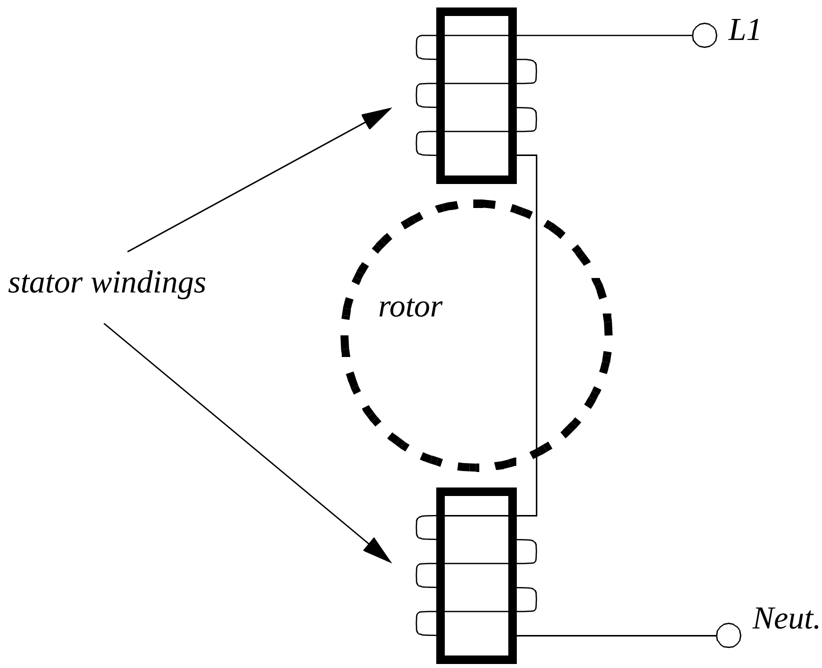


Figure 15.7 A 2 Pole Single Phase AC Motor

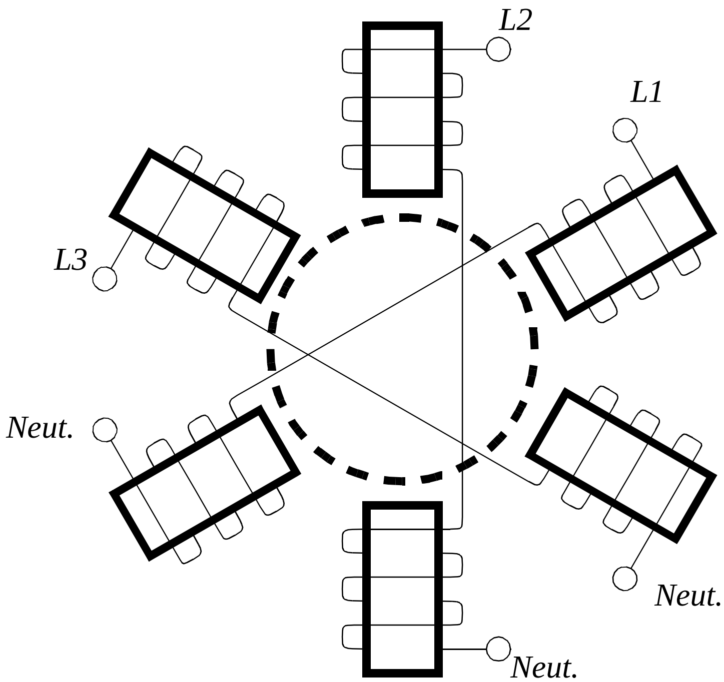


Figure 15.8 A 6 Pole 3-Phase AC Motor

• The number of windings (poles) can be an integer multiple of the number of phases of power. More poles results in a lower rotation of the motor.

• Rotor types for induction motors are listed below. Their function is to intersect changing magnetic fields from the stator. The changing field induces currents in the rotor. These currents in turn set up magnetic fields that oppose fields from the stator, generating a torque.

Squirrel cage - has the shape of a wheel with end caps and bars
Wound Rotor - the rotor has coils wound. These may be connected to external contacts via commutator

• Induction motors require slip. If the motor turns at the precise speed of the stator field, it will not see a changing magnetic field. The result would be a collapse of the rotor magnetic field. As a result an induction motor always turns slightly slower than the stator field. The difference is called the slip. This is typically a few percent. As the motor is loaded the slip will increase until the motor stalls.

An induction motor has the windings on the stator. The rotor is normally a squirrel cage design. The squirrel cage is a cast aluminum core that when exposed to a changing magnetic field will set up an opposing field. When an AC voltage is applied to the stator coils an AC magnetic field is created, the squirrel cage sets up an opposing magnetic field and the resulting torque causes the motor to turn.

The motor will turn at a frequency close to that of the applied voltage, but there is always some slip. It is possible to control the speed of the motor by controlling the frequency of the AC voltage. Synchronous motor drives control the speed of the motors by synthesizing a variable frequency AC waveform, as shown in Figure 15.9.

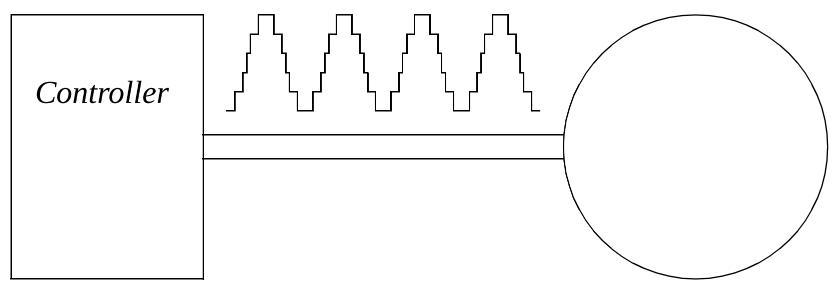


Figure 15.9 AC Motor Speed Control

These drives should be used for applications that only require a single rotational direction. The torque speed curve for a typical induction motor is shown in Figure 15.10. When the motor is used with a fixed frequency AC source the synchronous speed of the motor will be the frequency of AC voltage divided by the number of poles in the motor. The motor actually has the maximum torque below the synchronous speed. For example a motor 2 pole motor might have a synchronous speed of (2*60*60/2) 3600 RPM, but be rated for 3520 RPM. When a feedback controller is used the issue of slip becomes insignificant.

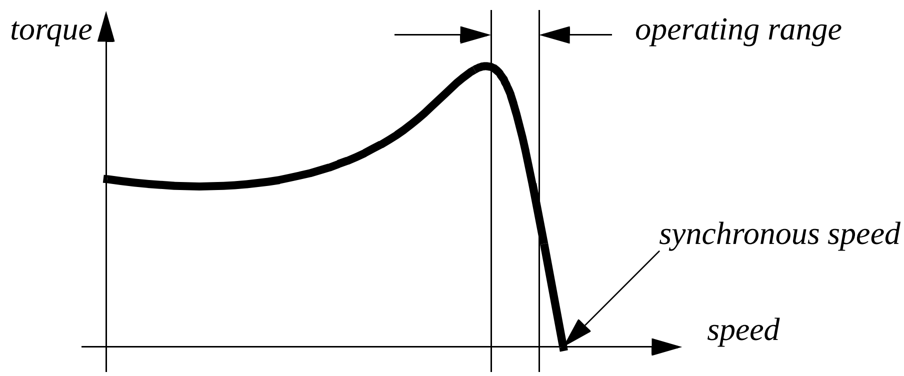


Figure 15.10 Torque Speed Curve for an Induction Motor

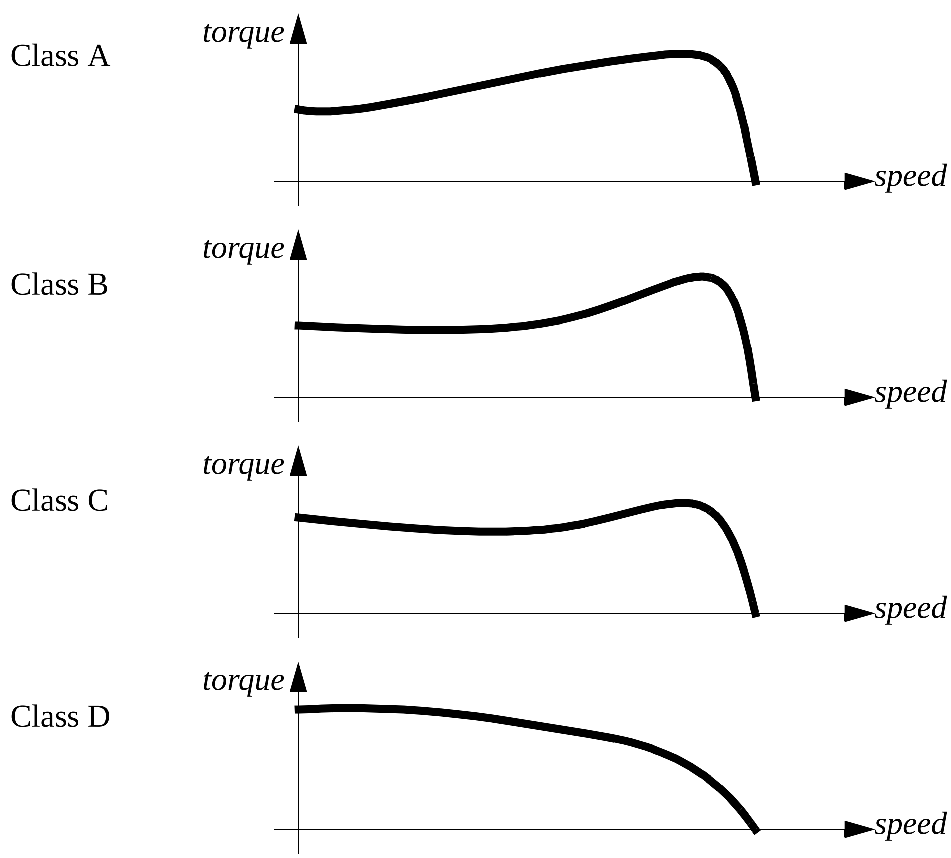


Figure 15.11 NEMA Squirrel Cage Torque Speed Curves

• Wound rotor induction motors use external resistors. varying the resistance allows the motors torque speed curve to vary. As the resistance value is increased the motor torque speed curve shifts from the Class A to Class D shapes.

• The figure below shows the relationship between the motor speed and applied power, slip, and number of poles. An ideal motor with no load would have a slip of 0%.

$$RPM = \frac{f120}{p}\left(1 - \frac{S}{100\%}\right)$$

where,

f = *power frequency (60Hz typ.)*

p = *number of poles (2, 4, 6, etc...)*

RPM = *motor speed in rotations per minute*

S = *motor slip*

• Single phase AC motors can run in either direction. To compensate for this a shading pole is used on the stator windings. It basically acts as an inductor to one side of the field which slows the filed buildup and collapse. The result is that the field strength seems to naturally rotate.

• Thermal protection is normally used in motors to prevent overheating.

• Universal motors were presented earlier for DC applications, but they can also be used for AC power sources. This is because the field polarity in the rotor and stator both reverse as the AC current reverses.

• Synchronous motors are different from induction motors in that they are designed to rotate at the frequency of the fields, in other words there is no slip.

• Synchronous motors use generated fields in the rotor to oppose the stators field.

• Starting AC motors can be hard because of the low torque at low speeds. To deal with this a switching arrangement is often used. At low speeds other coils or capacitors are connected into the circuits. At higher speeds centrifugal switches disconnect these and the motor behavior switches.

• Single phase induction motors are typically used for loads under 1HP. Various types (based upon their starting and running modes) are,

- split phase - there are two windings on the motor. A starting winding is used to provide torque at lower speeds.
- capacitor run -
- capacitor start
- capacitor start and run
- shaded pole - these motors use a small offset coil (such as a single copper winding) to encourage the field buildup to occur asymmetrically. These motors are for low torque applications much less than 1HP.
- universal motors (also used with DC) have a wound rotor and stator that are connected in series.

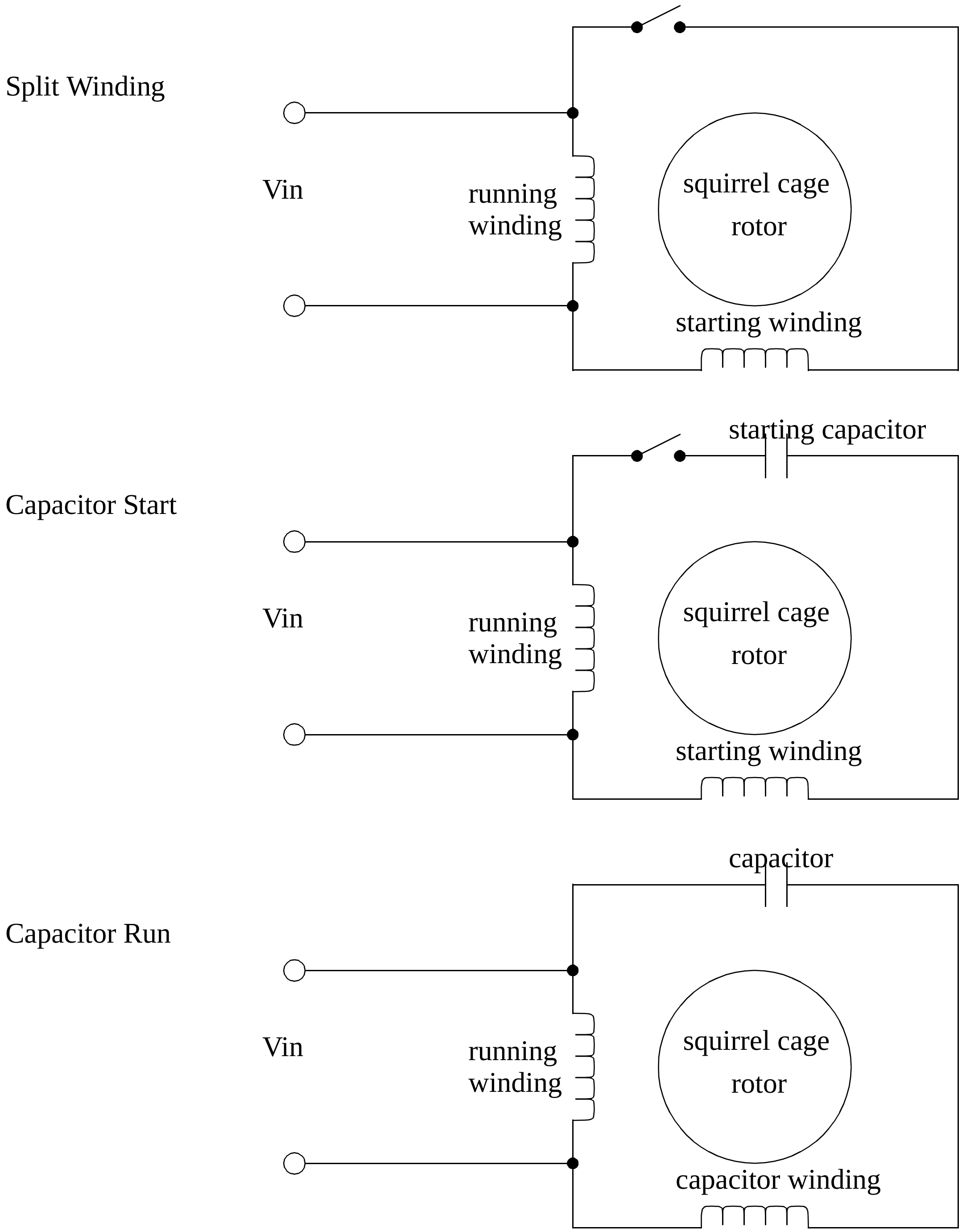


Figure 15.12 Single Phase Motor Configurations

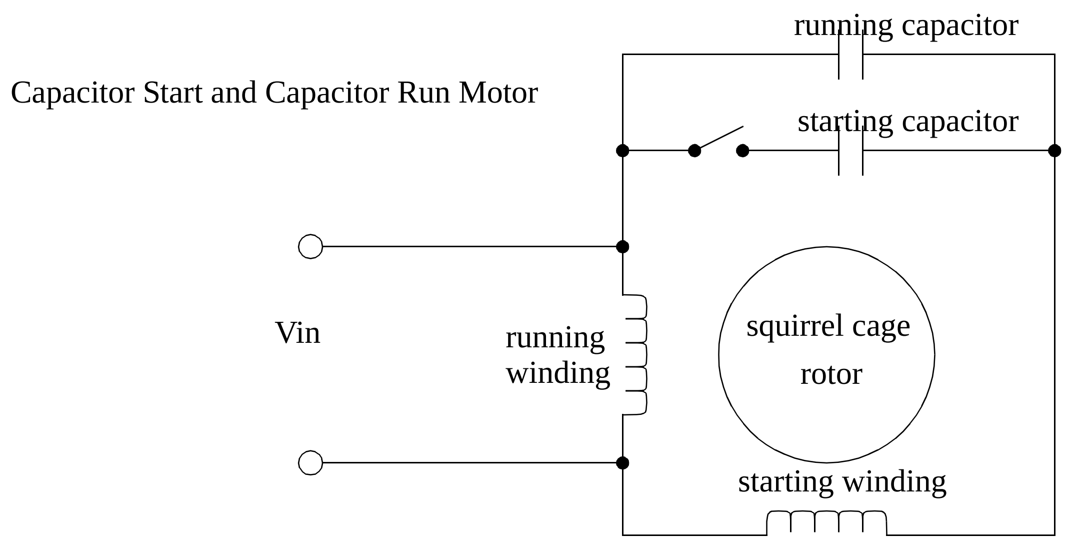


Figure 15.13 Single Phase Motor Configurations

15.2.3 Brushless DC Motors

Brushless motors use a permanent magnet on the rotor, and use windings on the stator. Therefore there is no need to use brushes and a commutator to switch the polarity of the voltage on the coil. The lack of brushes means that these motors require less maintenance than the brushed DC motors.

A typical Brushless DC motor could have three poles, each corresponding to one power input, as shown in Figure 15.14. Each of coils is separately controlled. The coils are switched on to attract or repel the permanent magnet rotor.

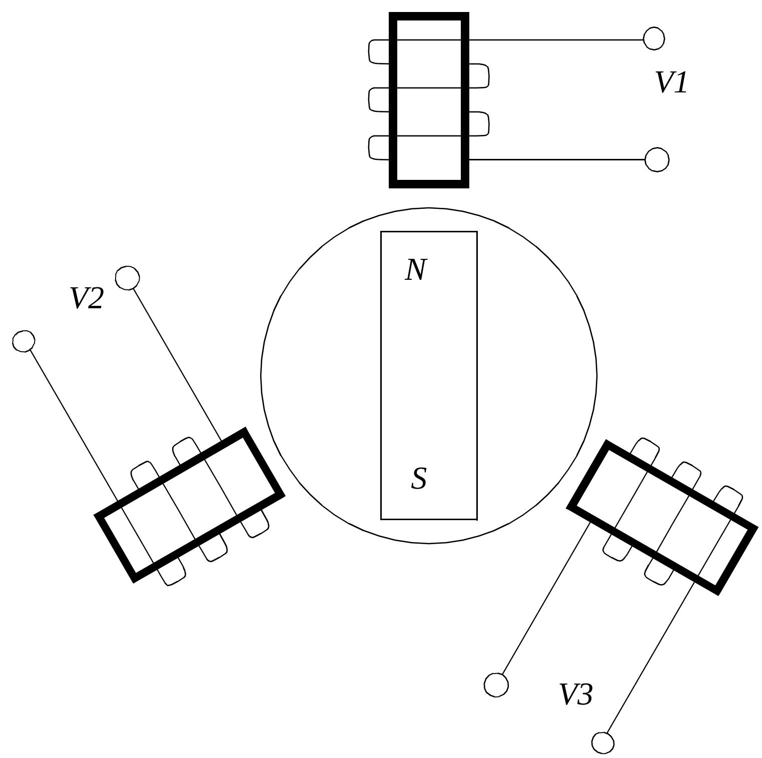


Figure 15.14 A Brushless DC Motor

To continuously rotate these motors the current in the stator coils must alternate continuously. If the power supplied to the coils was a 3-phase AC sinusoidal waveform, the motor will rotate continuously. The applied voltage can also be trapezoidal, which will give a similar effect. The changing waveforms are controller using position feedback from the motor to select switching times. The speed of the motor is proportional to the frequency of the signal.

A typical torque speed curve for a brushless motor is shown in Figure 15.15.

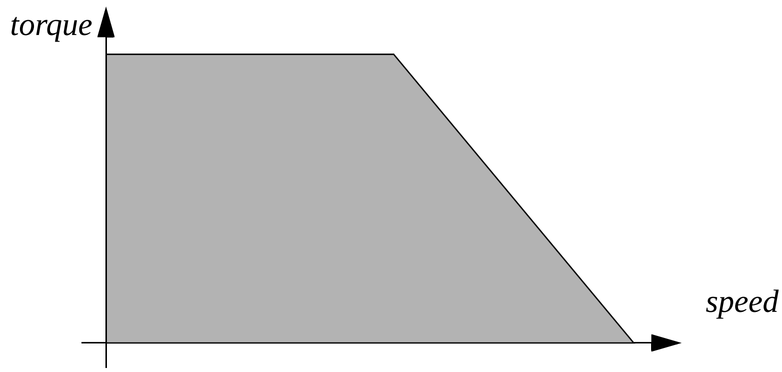


Figure 15.15 Torque Speed Curve for a Brushless DC Motor

15.2.4 Stepper Motors

Stepper motors are designed for positioning. They move one step at a time with a typical step size of 1.8 degrees giving 200 steps per revolution. Other motors are designed for step sizes of 1.8, 2.0, 2.5, 5, 15 and 30 degrees.

There are two basic types of stepper motors, unipolar and bipolar, as shown in Figure 15.16. The unipolar uses center tapped windings and can use a single power supply. The bipolar motor is simpler but requires a positive and negative supply and more complex switching circuitry.

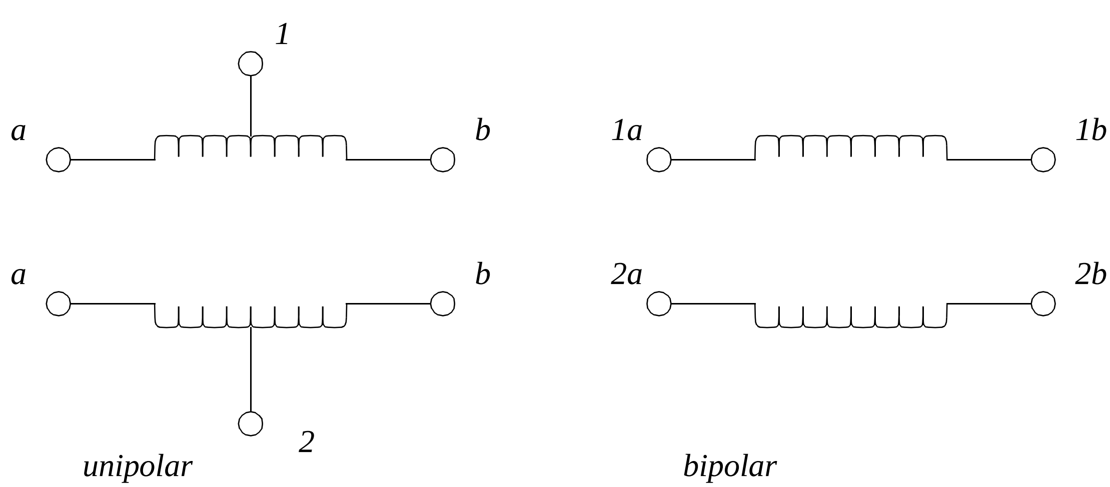
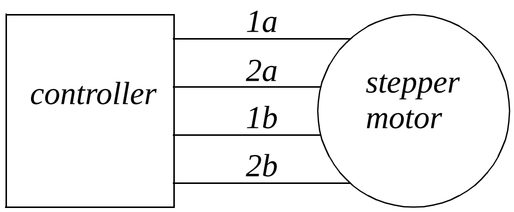


Figure 15.16 Unipolar and Bipolar Stepper Motor Windings

The motors are turned by applying different voltages at the motor terminals. The voltage change patterns for a unipolar motor are shown in Figure 15.17. For example, when the motor is turned on we might apply the voltages as shown in line 1. To rotate the motor we would then output the voltages on line 2, then 3, then 4, then 1, etc. Reversing the sequence causes the motor to turn in the opposite direction. The dynamics of the motor and load limit the maximum speed of switching, this is normally a few thousand steps per second. When not turning the output voltages are held to keep the motor in position.



Step	1a	2a	1b	2b
1	1	0	1	0
2	0	1	1	0
3	0	1	0	1
4	1	0	0	1

To turn the motor the phases are stepped through 1, 2, 3, 4, and then back to 1. To reverse the direction of the motor the sequence of steps can be reversed, eg. 4, 3, 2, 1, 4, ... If a set of outputs is kept on constantly the motor will be held in position.

Figure 15.17 Stepper Motor Control Sequence for a Unipolar Motor

Stepper motors do not require feedback except when used in high reliability applications and when the dynamic conditions could lead to slip. A stepper motor slips when the holding torque is overcome, or it is accelerated too fast. When the motor slips it will move a number of degrees from the current position. The slip cannot be detected without position feedback.

Stepper motors are relatively weak compared to other motor types. The torque speed curve for the motors is shown in Figure 15.18. In addition they have different static and dynamic holding torques. These motors are also prone to resonant conditions because of the stepped motion control.

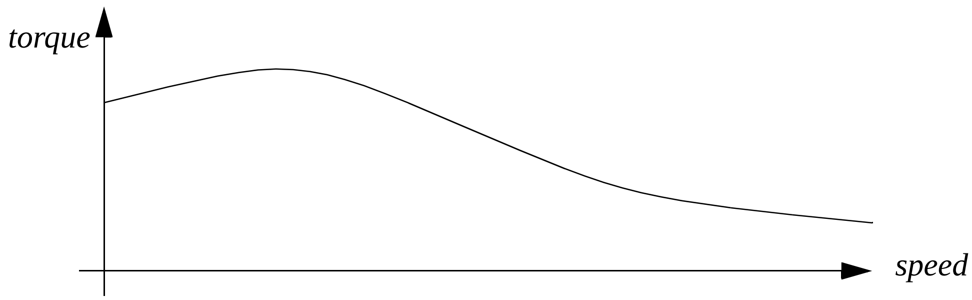


Figure 15.18 Stepper Motor Torque Speed Curve

The motors are used with controllers that perform many of the basic control functions. At the minimum a *translator* controller will take care of switching the coil voltages. A more sophisticated *indexing* controller will accept motion parameters, such as distance, and convert them to individual steps. Other types of controllers also provide finer step resolutions with a process known as *microstepping*. This effectively divides the logical steps described in Figure 15.17 and converts them to sinusoidal steps.

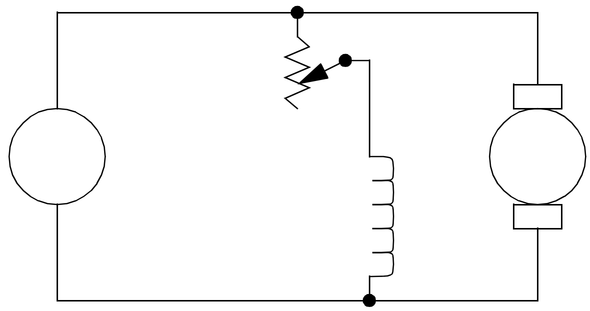
translators - the user indicates maximum velocity and acceleration and a distance to move
indexer - the user indicates direction and number of steps to take
microstepping - each step is subdivided into smaller steps to give more resolution

15.2.5 Wound Field Motors

• Uses DC power on the rotor and stator to generate the magnetic field (i.e., no permanent magnets)

• Shunt motors

- have the rotor and stator coils connected in parallel.
- when the load on these motors is reduced the current flow increases slightly, increasing the field, and slowing the motor.
- these motors have a relatively small variation in speed as they are varied, and are considered to have a relatively constant speed.
- the speed of the motor can be controlled by changing the supply voltage, or by putting a rheostat/resistor in series with the stator windings.



$$I_a = \frac{V_a}{R_a}$$

$$T = K_t I_a \phi$$

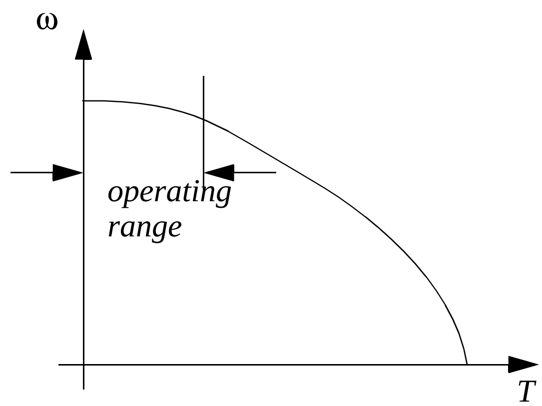
where,

I_a, V_a, R_a = *Armature current, voltage and resistance*

T = *Torque on motor shaft*

K_t = *Motor speed constant*

ϕ = *motor field flux*

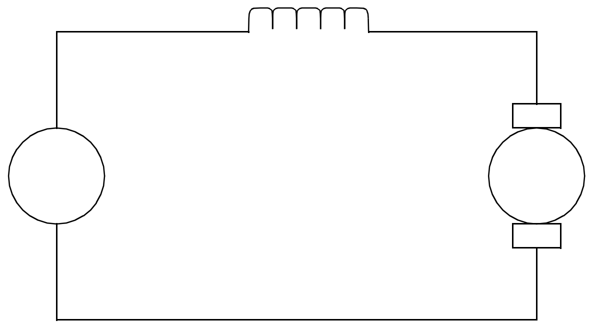


• Series motors\

- have the rotor and stator coils connected in series.
- as the motor speed increases the current increases, the motor can theoreti-

cally accelerate to infinite speeds if unloaded. This makes the dangerous when used in applications where they are potentially unloaded.

- these motors typically have greater starting torques that shunt motors



$$I_a = \frac{V_a}{R_a + R_f}$$

$$T = K_t I_a \phi = K_t I_a^2$$

where,

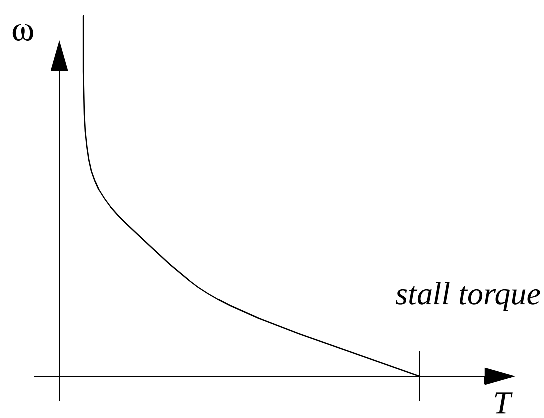
I_a, V_a = *Armature current, voltage*

R_a, R_f = *Armature and field coil resistance*

T = *Torque on motor shaft*

K_t = *Motor speed constant*

ϕ = *motor field flux*



The XXXXXXX

$$e_f = r_a i_a + D l_a i_a + e_m$$

$$e_m = K_e \theta D$$

$$T = K_T i_a$$

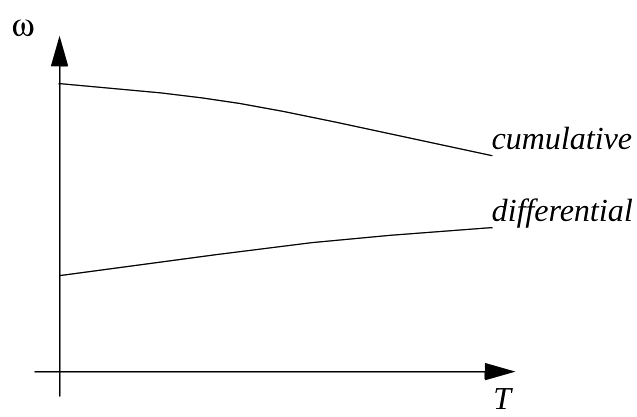
$$e_a = (r_a + l_a D) i_a + K_e D\theta$$

$$e_a = (r_a + l_a D)\left(\frac{T}{K_T}\right) + K_e D\theta$$

Figure 15.19 Equations for an armature controlled DC motor

• Compound motors\

- have the rotor and stator coils connected in series.
- differential compound motors have the shunt and series winding field aligned so that they oppose each other.
- cumulative compound motors have the shunt and series winding fields aligned so that they add



$$e_f = r_f i_f + l_f i_f D$$

$$T = K_T i_f$$

$$\frac{T}{\theta} = JD^2 + BD$$

$$\frac{\theta}{T} = \frac{1}{JD^2 + BD}$$

$$\frac{\theta}{i_f} = \frac{\theta}{T}\frac{T}{i_f} = \frac{K_T}{JD^2 + BD}$$

$$\frac{\theta}{e_f} = \frac{\theta}{i_f}\frac{i_f}{e_f} = \left(\frac{K_T}{JD^2 + BD}\right)\left(\frac{1}{r_f + l_f D}\right)$$

$$\frac{T}{e_f} = \frac{T}{i_f}\frac{i_f}{e_f} = K_T\left(\frac{1}{r_f + l_f D}\right)$$

Figure 15.20 Equations for a controlled field motor

15.3 HYDRAULICS

Hydraulic systems are used in applications requiring a large amount of force and slow speeds. When used for continuous actuation they are mainly used with position feedback. An example system is shown in Figure 15.21. The controller examines the position of the hydraulic system, and drivers a servo valve. This controls the flow of fluid to the actuator. The remainder of the provides the hydraulic power to drive the system.

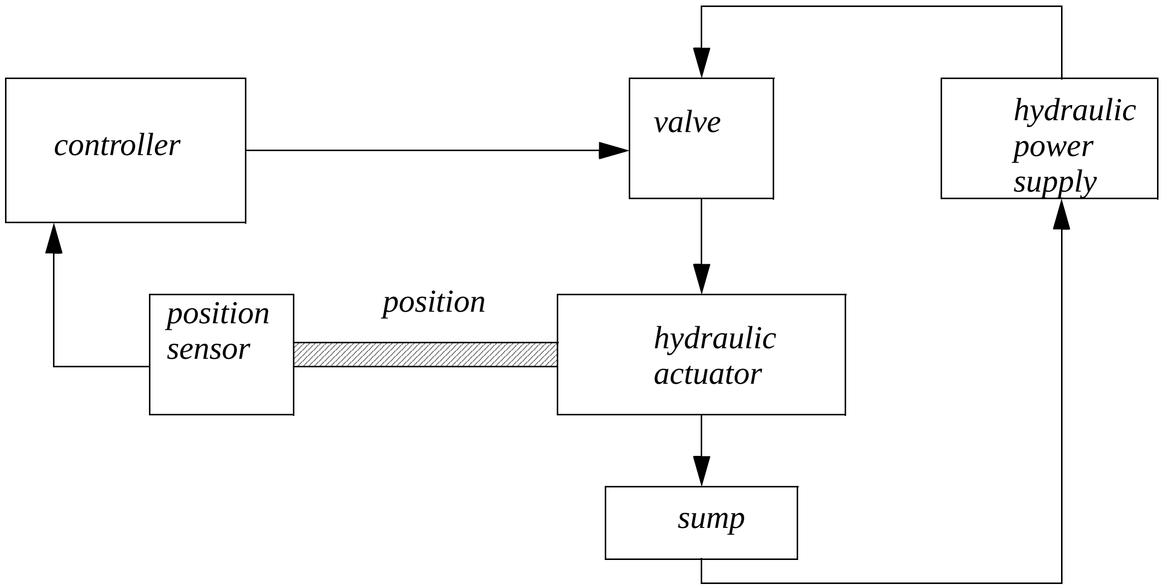


Figure 15.21 Hydraulic Servo System

The valve used in a hydraulic system is typically a solenoid controlled valve that is simply opened or closed. Newer, more expensive, valve designs use a scheme like pulse with modulation (PWM) which open/close the valve quickly to adjust the flow rate.

15.4 OTHER SYSTEMS

The continuous actuators discussed earlier in the chapter are the more common types. For the purposes of completeness additional actuators are listed and described briefly below.

Heaters - to control a heater with a continuous temperature a PWM scheme can be used to limit a DC voltage, or an SCR can be used to supply part of an AC waveform.
Pneumatics - air controlled systems can be used for positioning with suitable feedback. Velocities can also be controlled using fast acting valves.
Linear Motors - a linear motor works on the same principles as a normal rotary motor. The primary difference is that they have a limited travel and their cost is typically much higher than other linear actuators.
Ball Screws - rotation is converted to linear motion using balls screws. These are low friction screws that drive nuts filled with ball bearings. These are normally used with slides to bear mechanical loads.

15.5 SUMMARY

- AC motors work at higher speeds
- DC motors work over a range of speeds
- Motion control introduces velocity and acceleration limits to servo control
- Hydraulics make positioning easy

15.6 PRACTICE PROBLEMS

1. A stepping motor is to be used to drive each of the three linear axes of a cartesian coordinate robot. The motor output shaft will be connected to a screw thread with a screw pitch of 0.125”. It is desired that the control resolution of each of the axes be 0.025”
   a) to achieve this control resolution how many step angles are required on the stepper motor?
   b) What is the corresponding step angle?
   c) Determine the pulse rate that will be required to drive a given joint at a velocity of 3.0”/sec.

2. For the stepper motor in the previous question, a pulse train is to be generated by the robot controller.
   a) How many pulses are required to rotate the motor through three complete revolutions?
   b) If it is desired to rotate the motor at a speed of 25 rev/min, what pulse rate must be generated by the robot controller?

3. Explain the differences between stepper motors, variable frequency induction motors and DC motors using tables.

15.7 PRACTICE PROBLEM SOLUTIONS

1.

a) $P = 0.125\left(\frac{in}{rot}\right) \qquad R = 0.025\frac{in}{step}$

$$\theta = \frac{R}{P} = \frac{0.025\frac{in}{step}}{0.125\left(\frac{in}{rot}\right)} = 0.2\frac{rot}{step} \qquad \text{Thus} \qquad \frac{1}{0.2\frac{rot}{step}} = 5\frac{step}{rot}$$

b) $\theta = 0.2\frac{rot}{step} = 72\frac{deg}{step}$

c) $PPS = \frac{3\frac{in}{s}}{0.025\frac{in}{step}} = 120\frac{steps}{s}$

2.

a) $pulses = (3rot)\left(5\frac{step}{rot}\right) = 15steps$

b) $\frac{pulses}{s} = \left(25\frac{rot}{min}\right)\left(5\frac{step}{rot}\right) = 125\frac{steps}{min} = 125\left(\frac{1min}{60s}\right)\frac{steps}{min} = 2.08\frac{step}{s}$

3.

	speed	torque
stepper motor	very low speeds	low torque
vfd	limited speed range	good at rated speed
dc motor	wide range	decreases at higher speeds

15.8 ASSIGNMENT PROBLEMS

1. A stepper motor is to be used to actuate one joint of a robot arm in a light duty pick and place application. The step angle of the motor is 10 degrees. For each pulse received from the pulse train source the motor rotates through a distance of one step angle.
   - a) What is the resolution of the stepper motor?
   - b) Relate this value to the definitions of control resolution, spatial resolution, and accuracy, as discussed in class.
   - c) For the stepper motor, a pulse train is to be generated by a motion controller.

How many pulses are required to rotate the motor through three complete revolutions? If it is desired to rotate the motor at a speed of 25 rev/min, what pulse rate must be generated by the robot controller?

2. Describe the voltage ripple that would occur when using a permanent magnet DC motor as a tachometer. Hint: consider the use of the commutator to switch the polarity of the coil.

3. Compare the advantages/disadvantages of DC permanent magnet motors and AC induction motors.