Electric Motors

This lecture describes the principles of operation of various types of solenoids and various electric motors: synchronous, squirrel-cage, universal, shunt DC, series DC, permanent-magnet DC and stepper.
After this lecture you should be able to compute the important specifications and select the appropriate type(s) of motor for a given application.

Linear Actuators

For many applications the actuator need only physically move some mechanism into one of two positions. This can be done with a solenoid, which is simply an electromagnet used to attract a magnetic or steel core. A typical example of a solenoid is an electrically-controlled door latch. The solenoid can be driven from AC, DC or rectified AC.

Exercise: What type of core can be used with an AC-powered solenoid?

Important specifications for a solenoid include stroke length, force versus position, voltage, pull-in current and hold current.

Solenoids can also operate valves to control pneumatic or hydraulic power sources (for example, from a central compressor) which then control a hydraulic/pneumatic actuator or device. For example, a hydraulic press or a paint sprayer.

Solenoids can be controlled using switching transistors.

Electric Motor Selection

There are hundreds of types of electric motors. The most common type of motor is a rotating machine that consists of a rotor (the part that rotates) and a stator (fixed). The motor turns because of the interaction between the magnetic field set up by field coil windings and current flowing in an armature coil winding. Either the field or armature windings can be replaced by permanent magnets. Electrical connection to the rotor, when necessary, is made using sliding electrical contacts (slip rings or a commutator).

Among the specifications that need to be considered when selecting a motor are:

- speed range (rpm), fixed or variable
- torque (maximum, starting, pull-out),
- torque versus speed characteristics
- output power (kW or hp) ($P = T\omega$, 1hp = 746 W)
- type of power supply (AC or DC, voltage, current) (e.g. 12VDC 5A, or 240VAC, 3phase, 25A)
- efficiency (%)
- armature inertia (for control motors)
- armature inductance and resistance (for control motors)
- physical characteristics (motor and shaft dimensions, weight, ventilation requirements, etc.)

Exercise: An electric motor for a garage door opener lifts a door weighing 50 kg through a distance of 1 m in 10s while turning at 600 rpm. Ignore all friction loses in the system. What are the approximate power and torque requirements for this motor? If the motor is 80% efficient and is supplied by 120VAC, how much current will it draw?

AC Motors

AC (alternating current) motors are widely used since most electric power is supplied in the form of AC.

Synchronous AC motors run at an integer fraction of the power line frequency (e.g. for a 60 Hz power line frequency the possible speeds would be 3600 rpm, 1800 rpm, etc.). Synchronous motors are often used when a constant speed speed is required or when various motors must operate in synchronism (e.g. electric clocks, different parts of an assembly line). The field windings (on the rotor) are normally supplied with DC and the armature windings are supplied with AC.

Induction motors run at a few percent less than some integer fraction of the power line frequency (e.g. 1800 - 5% rpm) and this fraction increases with the load. The stator windings are supplied with AC. The current in the rotor windings is produced (induced) by the difference in frequency between the AC frequency and the motor speed. This means an electrical connection to the rotor (and the resulting brushes) are not required. Induction motors are therefore simple, inexpensive, reliable and quite widely used. Typical applications are those where precise speed control is not essential such as refrigerator compressors, furnace blowers, washing machines, lawn mowers, etc. They are available in ratings from hundreds of kW to a few hundred watts.

In applications where it is desired to use an induction motor and still be able to vary its speed, a variable-frequency AC power supply can be used. This power supply converts the AC power to DC and then back to AC at the desired frequency. This conversion can be done quite efficiently.

The direction of rotation is set when the motor starts up, either by using additional start-up circuitry or by having some asymmetry in the construction of the motor. AC generators (typically constructed as synchronous motors and sometimes called alternators) work in the same way as AC motors but a power source is used to drive the rotor with the opposite torque than when the device operates as a motor.

Some AC motors (e.g. the small "universal" motors used in many household appliances) use a commutator and operate on a principle similar to series DC motors described below. The speed of these motors can be controlled over a wide range. The speed control is achieved by varying the motor current either by using an external variable resistor or by reducing the supply voltage with one of the SCR or triac circuits described earlier.

DC Motors

The main advantage of DC motors is that their speed and torque can be easily varied over a wide range.

For DC machines the field winding is on the stator and the armature winding on the rotor.

A commutator is a device that is used to reverse the direction of rotor current flow (an thus the direction of the magnetic field) as the rotor turns. The commutator consists of two or more fixed contacts ("brushes") that slide over various rotating contacts on the rotor. These contacts are connected to the armature windings.

Current must be supplied to both the field windings and the armature (through the commutator) for the motor to operate. Usually the field and armature windings are connected together and connected to the same power supply. A DC motor can be designed for the two windings to be connected in series or parallel (shunt) or a combination.

When the two windings are in parallel the field current is independent of the armature current. The series motor thus has limited starting torque. Typical applications therefore include blower motors, lathes, etc.

When the two windings are in series the field current is the same as the armature current. This current will be higher at low speeds (high torque) and the motor will have a high starting torque. Series motors are therefore used for applications such as trains, cars, hoists, etc.

The DC motor speed can be reduced by reducing the armature current or increasing the field current. For small DC motors the armature current can be varied by using switching transistors to convert a DC supply into a pulse-width-modulated (PWM) signal. Large DC motors use AC power that is rectified to a varying DC voltage and whose average value is controlled using SCRs as described earlier.

The direction of rotation of a DC motor can be easily reversed by reversing the direction of the current in either the armature or field windings (usually in the field since it has lower current).

Permanent magnets (PM) are often used in small motors to replace either the field or armature windings. This improves the efficiency of the motor since no field current is required. The speed-torque characteristics of a PM motor are the same as for a DC motor using a parallel field winding.

Some DC motors use sensors, logic circuits and transistors to switch the current flow in the stator windings. These electronics replace the commutator and eliminate the need for sliding contacts and brushes.

Most control applications involving DC motors require some type of additional sensor to provide torque, position, or speed information (“feedback”) to the controller. These sensors can be in the form of tachometers, pulse counters, rotary shaft encoders or various other devices. These types of motors are called *servo motors*.

Exercise: What are some motor applications where position and/or speed need to be closely controller? Which of these would use servo motors?

In some control applications the DC motor must respond quickly to changes in the control voltage. In these cases the moment of inertia of the rotor and the inductance and resistance of the windings become important specifications because they can limit the speed with which the motor current can be changed and the rate at which the rotor can be accelerated.

Exercise: Identify some DC motors found in a car. What types of motors are they? What is the smallest DC motor you can think of? The largest?

Stepper Motors

A type of motor that is widely used with electronic controls is the stepper motor. This type of DC motor, as its name indicates, rotates in discrete “steps.” Stepper motors can be designed for different step sizes. Typical steps per revolution vary from 200 (1.8 degrees) to 12 (15 degrees).

The main advantage of stepper motors is that they allow precise position control without requiring a feedback sensor and using only on/off outputs.

The most common type of stepper motor consists of a permanent magnet rotor with a number of poles and a number of stator windings. The stator windings are arranged so that they can pull the rotor into number of stable orientations that differ by the stepping angle.

By varying the order in which the stator windings are turned on and off the rotor can be rotated in either direction. By controlling the number of steps the shaft can be moved to a known angle.

A microprocessor or a special-purpose peripheral IC generates the logic control signals that turn each of the windings on and off in the correct sequence to move the rotor the desired number of steps. Switching transistors are used to switch the current to each of the windings.

The control program or the stepper-motor control IC must move the rotor sufficiently slowly that the “pull-out” torque is not exceeded. If this happens the stepper rotor will miss a pulse and get out of sync with the controller.

The applied torque depends not only on the load but also on the acceleration of the motor. To achieve the best performance it is thus necessary to vary the stepping speed to maintain the acceleration within specified tolerances.

Exercise: Identify a motor application that can be done most easily by a stepper motor.