A motor is a form of actuator that converts electrical energy to kinetic energy, i.e. mechanical motion. Although most motors produce rotational motion, some include an output stage using a worm gear or “rack and pinion” principle that produces linear motion.

Motors are used in numerous devices such as household appliances, automotive electronics, consumer electronics, audio/video recording/playback equipment, computing devices, robots, and toys. Even cell phones use a miniature motor with an eccentric cam to implement “vibration mode”.

Motors are broadly categorized as being either alternating current (AC) or direct current (DC) and each of these categories have a number of subtypes. Figure 1 shows circuit symbols for some common motor types. The type of motor is important when considering both the intended application of the motor and its interface or drive circuit.

Motors are rated according to output power in terms of the SI unit watt, which is the product of voltage and amperage. For example, a motor operating on 100V at 2A consumes 200W. Note that this motor would not be able to produce 200W of power to its load due to the fact that no motor is perfect and 100% efficiency is not attainable. If this motor is 80% efficient, 20% of the 200W or 40W is lost in the form of heat while only 160W is delivered to the load as useful power. Obviously, high efficiency ratings are desired; however, this does increase the cost of the motor. Also, while most countries use the SI unit watt, some industries and regions such as the US prefer rating motors in horsepower (hp), named for historical reasons. One horsepower equals 746 watts.

1. **AC Motors**

Types: synchronous, induction

AC motors include synchronous and induction subtypes wherein the input power to the motor is an alternating current source such as the main electrical grid. Such motors are popular in industrial settings where AC power is readily available. They are also popular in home appliances. AC motors feature relatively high power output and low cost, both in terms of manufacturing and operation. On/off control of a small, i.e. appliance, AC motor is as simple as controlling a relay or Triac between the motor and the AC power source. Variable control of an AC motor is possible when using Triac by delaying the trigger pulse to the gate within each half-wave by a prescribed phase angle; this is known as the “phase control” technique.

High-power industrial AC motors are controlled with a contactor. A contactor operates much like a relay; however they are rated for switching high-current loads typically exceeding 15 amperes and ranging into the thousand amp range. Contactors also usually include arc suppression to prolong internal contact life against the damage from interrupting high load currents.

2. **DC Motors**

DC motors operate from a steady DC voltage source and are popular in battery operated devices or where DC voltage from a power supply is available. A number of DC motor variations and of their control techniques exist. The major differences are in cost, efficiency, application and drive circuit complexity.
2.1 Brushed

A brushed DC motor is the simplest and lowest cost motor. It uses a set of permanent field magnets and a wire-wound armature with an output shaft. Its two DC inputs connect internally to the armature coil via a set of carbon brushes pressed against the commutator plates via springs. When energized, the commutator effectively reverses the coil polarity twice for each rotation which perpetuates continuous rotation. The polarity of the DC inputs sets the motor rotation direction and the input voltage controls the motor RPM.

Brushed motors are also great devices for pulse-width modulation (PWM) control. In this technique, the motor operating voltage remains constant and the amount of time the voltage is applied to the motor is modulated at a high enough frequency so as to make the motor on and off times unnoticeable. Shown in figure 2, the control circuit is the same as with simple on/off control. A logic high on the output port turns the motor on while a low turns it off.

![Fig. 2: Brushed DC motor control circuit](image)

Repeatedly turning MOSFET transistor Q1 on 5 ms then off 5 ms results in a 50% duty cycle at 100 Hz. Overall, the motor receives power 50% of the time and runs at the correspondingly smaller ratio of its maximum RPM. This scenario along with 25% and 75% scenarios is shown in figure 3. By varying the duty cycle on the output port, any power level from 0 to 100% may be delivered to the motor. PWM control is very popular with microprocessor systems due to the simple interface circuit and exploitation of a strictly digital output. This method works just as well with many other devices such as lamps, LEDs, heating elements, and automobile anti-lock brake systems (ABS).

![Fig. 3: PWM effective power](image)

Disadvantages of brushed motors include brush wear, shorter lifespan, and lower efficiency due to the friction of the brushes against the commutator. These drawbacks are where brushless motors take the lead.

2.2 Brushless

In nearly perfect opposition to brushed motors, brushless motors feature higher efficiency, minimal wear, and longer life but are higher in cost and require more complex controllers. This type of motor is popular in computer cooling fans, CD/DVD drives, and modern electric R/C models. Whereas brushed motors use a moving rotor (the armature) and fixed stators (the magnets), a brushless motor reverses these roles. The
armature remains fixed and magnets rotate about the armature. This has lead to brushless inrunner and brushless outrunner variants. Because brushless motors do not have brushes and commutators, they require multiphase DC with precise timing and phasing requirements. This function is usually performed by a dedicated microcontroller in an external electronic speed control (ESC) unit.

[need pic of BLDC motor and ESC here]

2.3 Steppers

Stepper motors are a specialized form of brushless motors that rotate on the basis of small, discrete steps. They feature highly precise positioning, high holding torque, and accurate slow speed operation. Steppers are heavily used in robotic applications, laser and inkjet printers, and numerous manufacturing processes. They are available both with and without encoders to provide direct feedback to the controller.

Stepper motors are designed and operated in either unipolar or bipolar mode. The simpler unipolar mode applies current in a single direction in each coil but requires more connections. The unipolar stepper shown in figure 4 requires six connections: a separate coil ground for each of A, A', B, and B' and two common connections for the shared V+ supply inputs. The ULN2003A is a seven channel Darlington driver with internal clamping diodes via the ‘C’ pin. Logic high inputs from the four output ports cause the respective output channel to switch on providing a ground connection of up to 500 mA.

![ULN2003A diagram](image)

**Fig. 4: Unipolar stepper motor interface**

Bipolar steppers do not have the coil center tap available. Thus, the control interface must be able to alternate polarity of the A/A' and B/B' coils to achieve proper rotational control. This is typically achieved with a separate H-bridge for each coil.

Specifications for a given stepper motor include the number of magnetic poles it has for a complete rotation. A 40 pole stepper would rotate $360° \div 40$ steps per revolution or $9°$ per step. For coherent movement, the coils must be fired in a specific sequence. For the design in figure 4, the sequence is A, B, A', B' then repeat. This sequence is shown in timing diagram form in figure 5a. For the output port wiring given, the numeric output values would be 8, 4, 2 and 1. This single phase excitation sequence works; however it is rarely used because it only generates half-power. The more common dual phase sequence shown in figure 5b positions the motor shaft halfway between the single phase step positions but it does so with full power due to always having a pair of coils energized at any point in time. The coil sequence is AB, BA', A'B' and B'A or numerically C₁₀, 6, 3 and 9. This produces double the output torque of the single phase sequence.
When increased precision is desired, it is possible to combine both single- and dual-phase excitation into what is called **half stepping** or 1-2 phase excitation. This strategy alternates between a half power and a full power output pattern as shown in figure 6.

Of special note is the step delay of each output pattern as shown in figure 5. This delay ultimately determines the RPM speed of the motor. For the 40 pole stepper above, a step delay of 1 sec. ÷ 40 steps or 25ms per step would result in 1 rotation per second (60 RPM). Varying the step delay from long to short creates a “soft start” effect while the converse creates a “soft stop” effect. This is important in robotic arm positioning, for example, to maintain accuracy and to decrease wear and tear on mechanical components. Finally, producing the step sequence in reverse will result in opposite rotation of the motor. All of these step sequence characteristics are easy to produce from a microprocessor.

### 2.4 Servos

Shown in the figure 7, a **servo motor** is self-contained device that combines a motor with a control system to precisely control the position or speed of the motor. An input command sets the desired motor position/speed while an internal **feedback** signal senses the current motor status. The feedback comes from a sensor which is mechanically linked to the motor output. In many cases, a precision potentiometer is used as the feedback sensor. The difference between the input command and the negative feedback represents the **error** and is determined by a summer. The motor drive component then uses the error to determine whether to drive the motor clockwise, counterclockwise, or leave it in its current position.
Although servos can use a variable DC voltage as the input command, it is more common to use a form of pulse-width modulation as described earlier in this chapter. This application of PWM, using the width of an input pulse to set the desired servo position, is used by servos in the radio control industry. R/C cars, boats, airplanes, etc., use an on-board receiver to receive, interpret, and demultiplex transmissions from the operator's transmitter and forward individual servo channels to separate servos. The various servos are used for steering, motor speed, and attitude control in the case of aircraft. R/C servos typically rotate ±90° from a center position based on the width of the input pulse, which is repeated at 20 Hz to upwards of 300 Hz in high-speed digital servos. Standard servos require an input pulse between 1 and 2 ms with 1500 µs being "neutral" or center. Pulse waveforms for center, full counter-clockwise and full clockwise situations are shown in figure 8. The polarity of the deviation from 1500 µs determines the direction to rotate the motor while the magnitude of the deviation determines how far from center to move. In a special version of "continuous servo", the magnitude of deviation from center pulse width determines the speed at which the motor is driven and therefore the output shaft.

R/C servos generally operate at a nominal 4.8VDC as provided by a typical 4-cell NiCd battery and feature a gear train to manipulate the speed and torque of the output shaft. They are available in analog and digital variants with brushed, brushless, and coreless motors in a range of sizes, output torque, speeds, and costs. The input pulse signal is logic-compatible. For robotic applications, continuous rotation servos provide an excellent power source for differential drive platforms. A differential drive system uses two separate motors for independent left and right drive. Depending on the wheel configuration, point turns, radius turns and skid steering are all possible.

References: