AN907

Stepping Motors Fundamentals

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INTRODUCTION

Stepping motors fill a unique niche in the motor control world. These motors are commonly used in measurement and control applications. Sample applications include ink jet printers, CNC machines and volumetric pumps. Several features common to all stepper motors make them ideally suited for these types of applications. These features are as follows:

1. **Brushless** – Stepper motors are brushless. The commutator and brushes of conventional motors are some of the most failure-prone components, and they create electrical arcs that are undesirable or dangerous in some environments.
2. **Load Independent** – Stepper motors will turn at a set speed regardless of load as long as the load does not exceed the torque rating for the motor.
3. **Open Loop Positioning** – Stepper motors move in quantified increments or steps. As long as the motor runs within its torque specification, the position of the shaft is known at all times without the need for a feedback mechanism.
4. **Holding Torque** – Stepper motors are able to hold the shaft stationary.
5. **Excellent response** to start-up, stopping and reverse.

The following sections discuss the most common types of stepper motors, what circuitry is needed to drive these motors, and how to control stepping motors with a microcontroller.

TYPES OF STEPPING MOTORS

There are three basic types of stepping motors: permanent magnet, variable reluctance and hybrid. This application note covers all three types. Permanent magnet motors have a magnetized rotor, while variable reluctance motors have toothed soft-iron rotors. Hybrid stepping motors combine aspects of both permanent magnet and variable reluctance technology.

The stator, or stationary part of the stepping motor holds multiple windings. The arrangement of these windings is the primary factor that distinguishes different types of stepping motors from an electrical point of view. From the electrical and control system perspective, variable reluctance motors are distant from the other types. Both permanent magnet and hybrid motors may be wound using either unipolar windings, bipolar windings or bifilar windings. Each of these is described in the sections below.

Variable Reluctance Motors

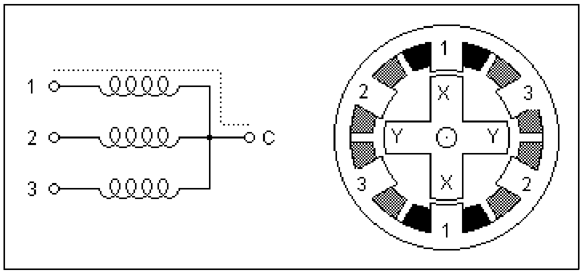
Variable Reluctance Motors (also called variable switched reluctance motors) have three to five windings connected to a common terminal. Figure 1 shows the cross section of a three winding, 30 degree per step variable reluctance motor. The rotor in this motor has four teeth and the stator has six poles, with each winding wrapped around opposing poles. The rotor teeth marked X are attracted to winding 1 when it is energized. This attraction is caused by the magnetic flux path generated around the coil and the rotor. The rotor experiences a torque and moves the rotor in line with the energized coils, minimizing the flux path. The motor moves clockwise when winding 1 is turned off and winding 2 in energized. The rotor teeth marked Y are attracted to winding 2. This results in 30 degrees of clockwise motion as Y lines up with winding 2. Continuous clockwise motion is achieved by sequentially energizing and de-energizing windings around the stator. The following control sequence will spin the motor depicted in Figure 1 clockwise for 12 steps or one revolution.

EXAMPLE 1:

Winding 1: `1001001001001`
Winding 2: `0100100100100`
Winding 3: `0010010010010`
time ⟶

Figure 1 illustrates the most basic variable reluctance stepping motor. In practice, these motors typically have more winding poles and teeth for smaller step angles. The number of poles can be made greater by adding windings, for example, moving to 4 or 5 windings, but for small step angles, the usual solution is to use toothed pole pieces working against a toothed rotor. Variable reluctance motors using this approach are available with step angles close to one degree.

FIGURE 1: VARIABLE RELUCTANCE STEPPER MOTOR



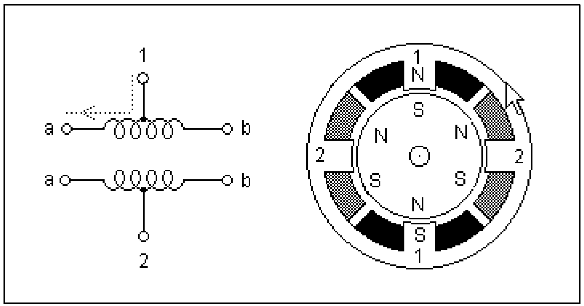
Unipolar Motors

Unipolar stepping motors are composed of two windings, each with a center tap. The center taps are either brought outside the motor as two separate wires (as shown in Figure 2) or connected to each other internally and brought outside the motor as one wire. As a result, unipolar motors have 5 or 6 wires. Regardless of the number of wires, unipolar motors are driven in the same way. The center tap wire(s) is tied to a power supply and the ends of the coils are alternately grounded.

Unipolar stepping motors, like all permanent magnet and hybrid motors, operate differently from variable reluctance motors. Rather than operating by minimizing the length of the flux path between the stator poles and the rotor teeth, where the direction of current flow through the stator windings is irrelevant, these motors operate by attracting the north or south poles of the permanently magnetized rotor to the stator poles. Thus, in these motors, the direction of the current through the stator windings determines which rotor poles will be attracted to which stator poles. Current direction in unipolar motors is dependent on which half of a winding is energized. Physically, the halves of the windings are wound parallel to one another. Therefore, one winding acts as either a north or south pole depending on which half is powered.

Figure 2 shows the cross section of a 30 degree per step unipolar motor. Motor winding number 1 is distributed between the top and bottom stator poles, while motor winding number 2 is distributed between the left and right motor poles. The rotor is a permanent magnet with six poles, three north and three south, as shown in Figure 2.

FIGURE 2: UNIPOLAR STEPPER MOTOR



The difference between a permanent magnet stepping motor and a hybrid stepping motor lies in how the multi-pole rotor and multi-pole stator are constructed. These differences will be discussed later.

EXAMPLE 2:

Winding 1a: `100010001000`
Winding 1b: `001000100010`
Winding 2a: `010001000100`
Winding 2b: `000100010001`
time ⟶

Note: Only half of each winding is energized at a time in the above sequence. As above, the following sequence will spin the motor clockwise 12 steps or one revolution.

EXAMPLE 3:

Winding 1a: `110011001100`
Winding 1b: `001100110011`
Winding 2a: `011001100110`
Winding 2b: `100110011001`
time ⟶

Unlike in the first sequence described, two winding halves are energized at one time in the second sequence. This gives the motor more torque, but also increases the power usage by the motor. Each of the above sequences describes single stepping or stepping the motor in its rated step size (in this case 30 degrees). Combining these two sequences allows for half stepping the motor. The combined sequence is shown in Example 4 (24 steps per revolution).

EXAMPLE 4:

```
Winding 1a:  11000001110000011100000111
Winding 1b:  00011100000111000001110000
Winding 2a:  01110000011100000111000001
Winding 2b:  00000111000001110000011100
                 time  ⟶
```

This method moves the motor in steps that are half its rated step size. It is important to note that the torque generated by the motor during this sequence is not constant, as alternating steps have one and two halves of a winding energized respectively.

Figure 2 illustrates the most basic unipolar motor. For higher angular resolutions, the rotor must have more poles. Permanent magnet rotors with 100 poles have been made, and this pole count is commonly achieved for hybrid rotors, using toothed end-caps on a simple bipolar permanent magnet. When the rotor has a high pole count, the stator poles are always toothed so that each stator winding works against a large number of rotor poles.

Bipolar Motors

Bipolar stepping motors are composed of two windings and have four wires. Unlike unipolar motors, bipolar motors have no center taps. The advantage to not having center taps is that current runs through an entire winding at a time instead of just half of the winding. As a result, bipolar motors produce more torque than unipolar motors of the same size. The draw back of bipolar motors, compared to unipolar motors, is that more complex control circuitry is required by bipolar motors.

Current flow in the winding of a bipolar motor is bidirectional. This requires changing the polarity of each end of the windings. As shown in Figure 3, current will flow from left to right in winding 1 when 1a is positive and 1b is negative. Current will flow in the opposite direction when the polarity on each end is swapped. A control circuit, known as an H-bridge, is used to change the polarity on the ends of one winding. Every bipolar motor has two windings, therefore, two H-bridge control circuits are needed for each motor. The H-bridge is discussed in more detail in the **“Basic Control Circuits”** section.

FIGURE 3: BIPOLAR STEPPER MOTOR

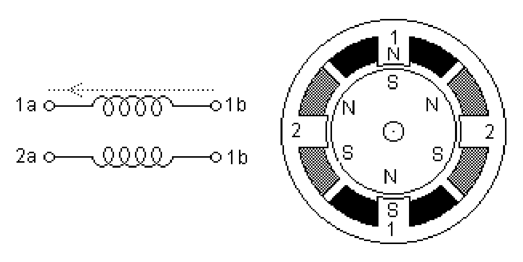


Figure 3 illustrates a 30 degree per step bipolar motor. Motor winding 1 is distributed between the top and bottom stator poles, while motor winding 2 is distributed between the left and right stator poles. The rotor is a permanent magnet with 6 poles, 3 south and 3 north arranged around its circumference.

Like a unipolar motor, bipolar motors can be single stepped with two different control sequences. Using + and - to indicate the polarity of the power applied to each motor terminal and 0 to indicate no power is applied, these sequences are shown in Example 5 for one revolutions or 12 steps. The first sequence minimizes power consumption by energizing only one winding at a time, while the second sequence maximizes torque by energizing both windings at a time.

EXAMPLE 5:

Terminal 1a:	+	0	-	0	+	0	-	0	+	0	-	0
Terminal 1b:	-	0	+	0	-	0	+	0	-	0	+	0
Terminal 2a:	0	+	0	-	0	+	0	-	0	+	0	-
Terminal 2b:	0	-	0	+	0	-	0	+	0	-	0	+
				time —>								
Terminal 1a:	+	+	-	-	+	+	-	-	+	+	-	-
Terminal 1b:	-	-	+	+	-	-	+	+	-	-	+	+
Terminal 2a:	-	+	+	-	-	+	+	-	-	+	+	-
Terminal 2b:	+	-	-	+	+	-	-	+	+	-	-	+
				time —>								

Combining these two sequences into one sequence will half step the motor so that it moves in 15 degree increments. The sequence for half stepping the motor is shown in Example 6 for one revolution or 24 steps.

EXAMPLE 6:

Terminal 1a:	+ + 0 - - - 0 + + + 0 - - - 0 + + + 0 - - - 0 +
Terminal 1b:	- - 0 + + + 0 - - - 0 + + + 0 - - - 0 + + + 0 -
Terminal 2a:	0 + + + 0 - - - 0 + + + 0 - - - 0 + + + 0 - - -
Terminal 2b:	0 - - - 0 + + + 0 - - - 0 + + + 0 - - - 0 + + +
	time —>

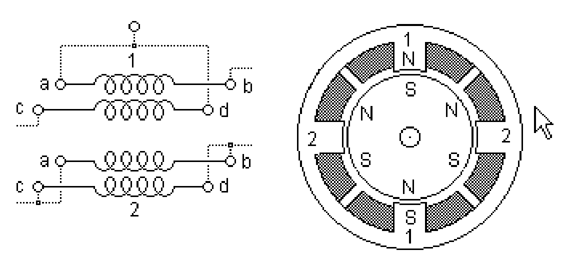
Note: The torque generated by the motor during this sequence is not constant as alternating steps have one and two windings energized respectively.

Bifilar Motors

The term bifilar literally means “two threaded.” Motors with bifilar windings are identical in rotor and stator to bipolar motors with one exception – each winding is made up of two wires wound parallel to each other. As a result, common bifilar motors have eight wires instead of the four wires of a comparable bipolar motor.

Bifilar motors are driven as either bipolar or unipolar motors. To use a bifilar motor as a unipolar motor, the two wires of each winding are connected in series and the point of connection is used as a center-tap. Winding 1 in Figure 4 shows the unipolar winding connection configuration. To use a bifilar motor as a bipolar motor, the two wires of each winding are connected in either parallel or series. Winding 2 in Figure 4 shows the parallel connection configuration. A parallel connection allows for high current operation, while a series connection allows for high voltage operation.

FIGURE 4: BIFILAR STEPPER MOTOR



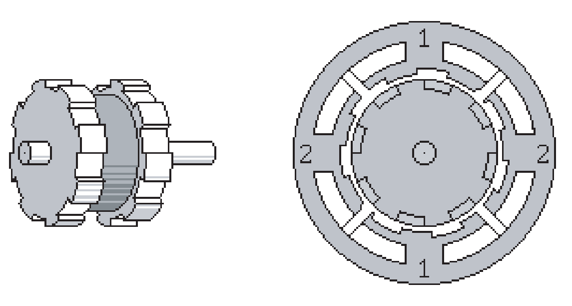
Interestingly, unipolar motors are wound using bifilar windings so that the external connection, which serves as a center tap, is actually connected as shown for winding 1 in Figure 4. As a result, unipolar motors may be used as a bipolar motor at the rated voltage and half the rated current specified for the motor. This statement is based on the temperature and power constraints of a motor.

Hybrid Motors

Hybrid motors share the operating principles of both permanent magnet and variable reluctance stepping motors. The rotor for a hybrid stepping motor is multi-toothed, like the variable reluctance motor, and contains an axially magnetized concentric magnet around its shaft (see Figure 5). The teeth on the rotor provide a path which helps guide the magnetic flux to preferred locations in the air gap. The magnetic concentric magnet increases the detent, holding and dynamic torque characteristics of the motor when compared with both the variable reluctance and permanent magnet types.

In terms of stepping the motor, hybrid motors are driven like unipolar and bipolar motors. Refer to the previous sections **“Unipolar Motors”** and **“Bipolar Motors”** for a description of how to make a hybrid motor turn.

FIGURE 5: HYBRID STEPPING MOTOR



CHOOSING A MOTOR

There are several factors to take into consideration when choosing a stepping motor for an application. Some of these factors are what type of motor to use, the torque requirements of the system, the complexity of the controller, as well as the physical characteristics of the motor. The following paragraphs discuss these considerations.

Variable Reluctance Versus Permanent Magnet or Hybrid

Variable Reluctance Motors (VRM) benefit from the simplicity of their design. These motors do not require complex permanent magnet rotors, so are generally more robust than permanent magnet motors.

With all motors, torque falls with increased motor speed, but the drop in torque with speed is less pronounced with variable reluctance motors. With appropriate motor design, speeds in excess of 10,000 steps per second are feasible with variable reluctance motors, while few permanent magnet and hybrid motors offer useful torque at 5000 steps per second and most are confined to speeds below 1000 steps per second.

The low torque drop-off with speed of variable reluctance motors allows use of these motors, without gearboxes, in applications where other motors require gearing. For example, some newer washing machines use variable reluctance motors to drive the drum, thus allowing direct drive for both the slow oscillating wash cycle and the fast spin cycle.

Variable reluctance motors do have a drawback. With sinusoidal exciting currents, permanent magnet and hybrid motors are very quiet. In contrast, variable reluctance motors are generally noisy, no matter what drive waveform is used. As a result, permanent magnet or hybrid motors are generally preferred where noise or vibration are issues.

Unlike variable reluctance motors, permanent magnet and hybrid motors cog when they are turned by hand while not powered. This is because the permanent magnets in these motors attract the stator poles even when there is no power. This magnetic detent or residual holding torque is desirable in some applications, but if smooth coasting is required, it can be a source of problems.

With appropriate control systems, both permanent magnet and hybrid motors can be microstepped, allowing positioning to a fraction of a step, and allowing smooth, jerk-free moves from one step to the next. Microstepping is not generally applicable to variable reluctance motors. These motors are typically run in full-step increments. Complex current limiting control is required to achieve high speeds with variable reluctance motors.

Unipolar Versus Bipolar

Permanent magnet and hybrid stepping motors are available with either unipolar, bipolar or bifilar windings; the latter can be used in either unipolar or bipolar configurations. The choice between using a unipolar or bipolar drive system rests on issues of drive simplicity and power to weight ratio.

Bipolar motors have approximately 30% more torque than an equivalent unipolar motor of the same volume. The reason for this is that only one half of a winding is energized at any given time in a unipolar motor. A bipolar motor utilizes the whole of a winding when energized.

The higher torque generated by a bipolar motor does not come without a price. Bipolar motors require more complex control circuitry than unipolar motors (see **"Basic Control Circuits"**). This will have an impact on the cost of an application.

If in doubt, a unipolar motor or bifilar motor are good choices. These motors can be configured as a unipolar or bipolar motor and the application tested with the motors operating in either mode.

Hybrid Versus Permanent Magnet

In selecting between hybrid and permanent magnet motors, the two primary issues are cost and resolution. The same drive electronics and wiring options generally apply to both motor types.

Permanent magnet motors are, without question, some of the least expensive motors made. They are sometimes described as can-stack motors because the stator is constructed as a stack of two windings enclosed in metal stampings that resemble tin cans and are almost as inexpensive to manufacture. In comparison, hybrid and variable reluctance motors are made using stacked laminations with motor windings that are significantly more difficult to wind.

Permanent magnet motors are generally made with step sizes from 30 degrees to 3.6 degrees. The challenge of magnetizing a permanent magnet rotor with more than 50 poles is such that smaller step sizes are rare! In contrast, it is easy to cut finely spaced teeth on the end caps of a permanent magnet motor rotor, so permanent magnet motors with step sizes of 1.8 degrees are very common, and smaller step sizes are widely available. It is noteworthy that, while most variable reluctance motors have fairly coarse step sizes, such motors can also be made with very small step sizes.

Hybrid motors suffer some of the vibration problems of variable reluctance motors, but they are not as severe. They generally can step at rates higher than permanent magnet motors, although very few of them offer useful torque above 5000 steps per second.

Functional Characteristics

Even when the type of motor is determined, there are still several decisions to be made before selecting one particular motor. Torque, operating environment, longevity, physical size, step size, maximum RPM – these are some of the factors that will influence which motor is chosen.

STEP SIZE

One of the most crucial decisions to make is the step size of the motor. This will be determined by the resolution necessary for a particular application. The most common step sizes for PM motors are 7.5 and 3.6 degrees. This corresponds to 48 and 100 steps per revolution respectively. Hybrid motors typically have step sizes ranging from 3.6 degrees (100 steps per revolution) to 0.9 degrees (400 steps per revolution).

Some stepping motors are sold with gear reductions which provide smaller step angles than are possible with even the finest stepping motors. Gear reductions also increase the available torque, but because torque falls with stepping rate, they decrease the maximum rotational speed.

For linear movement, many stepper motors are coupled to a lead screw by a nut (these motors are also known as linear actuators). Even coarse steps with this arrangement translate to very fine movements of the lead screw because of the gear reduction inherent to this mechanism.

TORQUE

Torque is a critical consideration when choosing a stepping motor. Stepper motors have different types of rated torque. These are:

- Holding torque – The torque required to rotate the motor's shaft while the windings are energized.
- Pull-in torque – The torque against which a motor can accelerate from a standing start without missing any steps, when driven at a constant stepping rate.
- Pull-out torque – The load a motor can move when at operating speed.
- Detent torque – The torque required to rotate the motor's shaft while the windings are not energized.

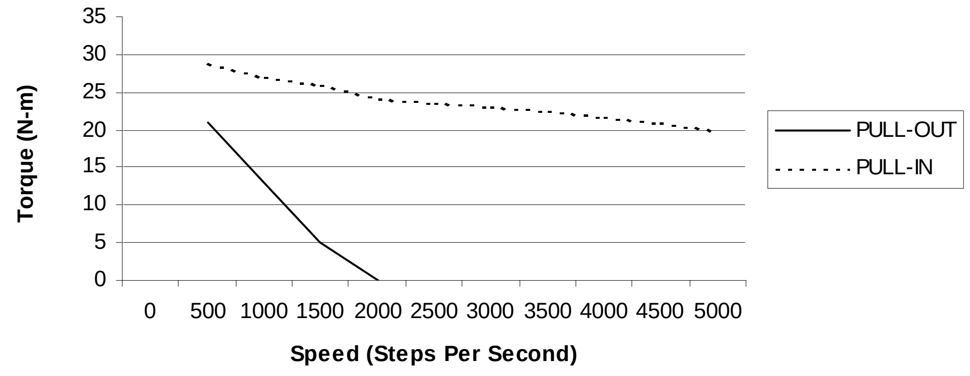
Stepping motor manufacturers will specify several or all of these torques in their data sheets for their motors.

The dynamic torques, pull-in and pull-out, are a function of step rate. These torques are important for determining whether or not a stepping motor will "slip" when operating in a particular application. A "slip" refers to the motor not moving when it should or moving when it should not (overrunning a stop). In either case, the result is the controller will no longer know the position of the motor. Open loop positioning fails in this case. The motor must be adequately sized to prevent this from happening or a closed loop feedback system employed.

The pull-in torque offered by a stepping motor depends strongly on the moment of inertia of any load rigidly attached to the motor. This makes this torque figure somewhat problematic because the moment of inertia of the rig used to measure this torque is rarely stated in manufacturers data sheets and is rarely equal to the moment of inertia of the load actually driven in the application.

Most manufacturers provide torque curves in their data sheets. Figure 6 shows an example of a torque curve for a stepping motor.

FIGURE 6: TORQUE VS. SPEED



LONGEVITY

Another factor to consider when choosing a motor is the longevity of the motor. Some of the questions asked should be:

- How long does the motor need to work properly?
- What environmental hazards will the motor be subjected to?
- What heat will the motor operate at?
- Is the motor's operation continuous or intermittent?

Stepper motors by their very nature are more robust than other types of motors because they do not have brushes that will wear out over time. Typically, other components in a particular system will wear out long before the motor ever will. However, all stepper motors are not created equal and even the best motors will fail if the proper considerations are not made. The following are some design guidelines that influence motor longevity:

- Ball bearings vs bronze bushings – Ball bearings last longer than bronze bushings and do not generate as much heat, but they cost more.
- Motors that run near their rated torque will not last as long as those that do not. Motors should be chosen so that they will run at 40-60% of their torque rating.
- Protect the motor from harsh environments. Exposure, humidity, harsh chemicals, dirt and debris will all take their toll on a motor.
- Ensure adequate cooling. Motors generate heat and this must be dissipated. For motors that include an integral heat sink, ensure adequate circulation of cooling air. Other motors are designed to be cooled by conduction to the chassis on which the motor is mounted. Hybrid motors that sue rare-earth magnets are particularly heat sensitive.
- Finally, motors should be driven properly. This means special care should be taken to ensure the current rating of the windings are not exceeded. This will be discussed in depth in the **"Current Limiting"** section.

BASIC CONTROL CIRCUITS

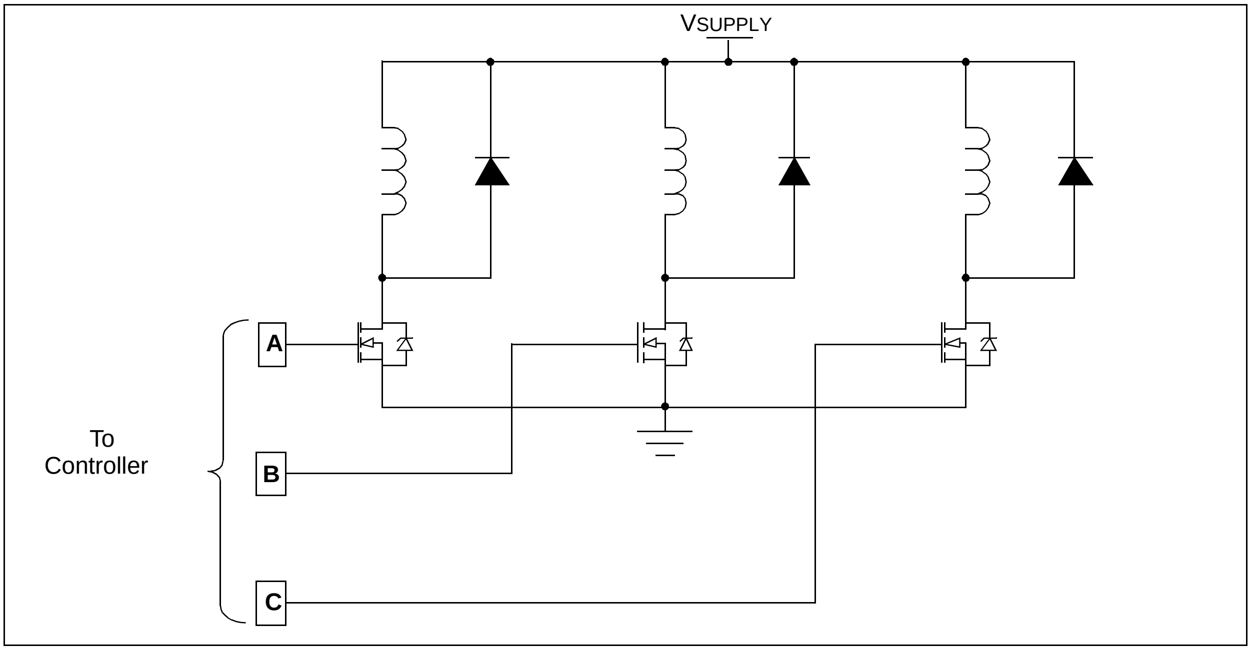
This section will show the basic circuits needed to drive the various types of stepping motors. These circuits will be expanded on later in the **"Current Limiting"** section to include current limiting considerations.

Variable Reluctance

Variable reluctance motors have multiple windings, typically three to five, which are all tied together at one end. The windings are turned on one at a time in a particular sequence to turn the motor.

Figure 7 shows the basic circuit for driving a variable reluctance motor. Note the diodes across the windings. As with all inductive loads, as voltage is switched on across a winding, the current in the winding begins ramping up. When the switching MOSFET for the winding is turned off a voltage spike is produced that can damage the transistor. The diode protects the MOSFET from the voltage spike assuming the diode is adequately sized.

FIGURE 7: VARIABLE RELUCTANCE MOTOR CONTROL CIRCUIT.

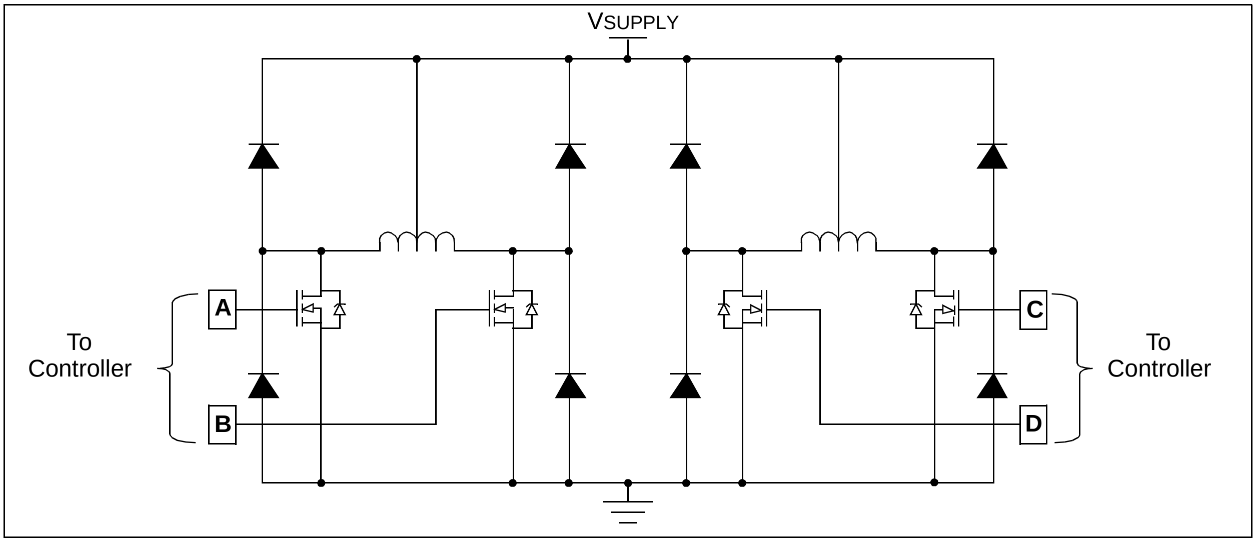


Unipolar

The basic control circuit for a unipolar motor, shown in Figure 8, is similar to that for a variable reluctance motor. Note the extra diodes across each of the MOSFETs. These are necessary because the inductor is center tapped in unipolar motors. When one end of the motor winding is pulled down, the other end will rise and visa versa. These diodes prevent the voltage from falling below ground across the MOSFETs.

Some MOSFETs have integral diodes that allow reverse current to flow unimpeded, regardless of the gate voltage. If such transistors are used, and if these integral diodes have sufficient current carrying capacity to carry the full motor current, the lower diodes shown in Figure 8 can be omitted. All of the diodes must have switching speeds comparable to the speed of the transistors.

FIGURE 8: UNIPOLAR MOTOR CONTROL CIRCUIT



Bipolar

The basic circuit for driving the windings of a bipolar motor is the H-bridge, shown in Figure 9. An H-bridge can be configured to allow current to flow in either direction across a winding. Referring to Figure 9, current will flow from left to right in Winding 1 when MOSFETs Q1 and Q4 are turned on while Q2 and Q3 are off. Current will flow from right to left when Q2 and Q3 are on while Q1 and Q4 are off.

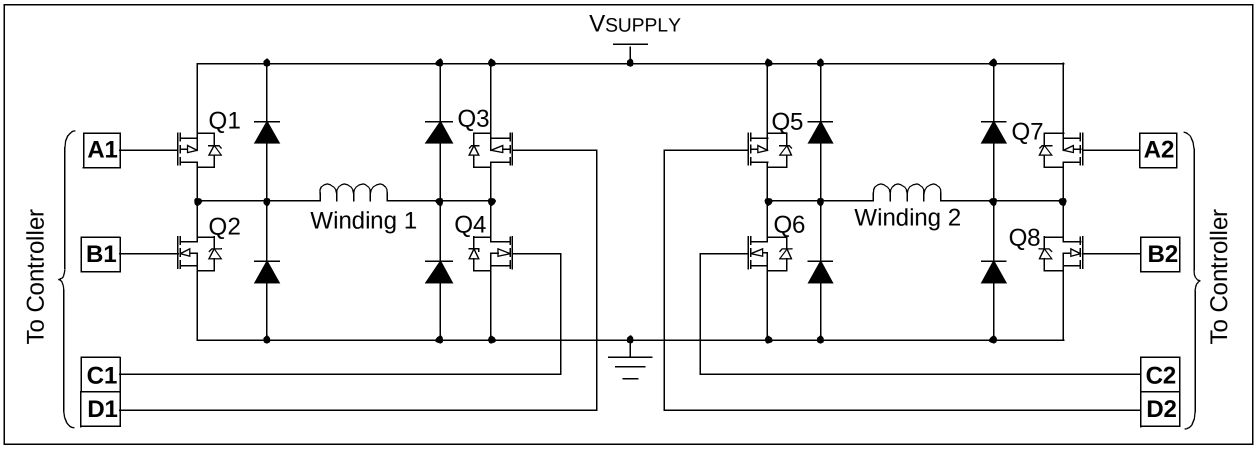
Note: Transistors Q2 and Q4 are N-channel MOSFETs and therefore require a positive bias on turn-on. Q1 and Q3 are P-channel MOSFETs, requiring a negative bias to turn-on. An alternate H-bridge design uses identical MOSFETs for all 4 transistors, and uses charge-pump and level shifting circuitry to drive the gates of the upper transistors shown in Figure 9.

H-bridges have one inherent danger that should be mentioned. Under no circumstances should the transistors on the same side of the bridge be switched on at the same time. This will cause a short which will damage the control circuit. Special care should be made to switch all MOSFETs off before turning the next set of MOSFETs on.

The diodes in parallel with each of the MOSFETs protect the MOSFETs from voltage spikes caused by switching the inductor. These diodes must be adequately sized in order to prevent damage to the MOSFET or diode itself.

As pointed out for unipolar motors, some MOSFETs have integral diodes; in fact, these are shown in the schematic representation for MOSFETs used in Figure 9; if these are able to conduct the full motor current, the additional diodes shown in the figure can be omitted.

FIGURE 9: BIPOLAR MOTOR CONTROL CIRCUIT



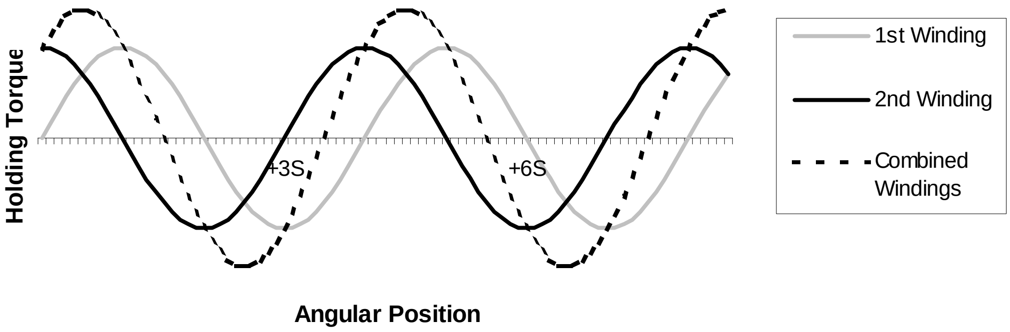
MICROSTEPPING

Single stepping a motor results in jerky movements of the motor, especially at lower speeds. Microstepping is used to achieve increased step resolution and smoother transitions between steps. In most applications, microstepping increases system performance while limiting noise and resonance problems.

Microstepping works on the principle of gradually transferring current from one winding to another. This is achieved by pulse-width modulating the voltage across the windings of a motor. The duty cycle of the signal charging one winding is decreased as the duty cycle of the signal charging the next winding is increased.

In order to understand the fundamentals of microstepping, it's necessary to look at the torque exerted by a stepper motor as it turns. Figure 10 shows a graph of torque verses rotor position for an ideal two-winding stepper motor. Note the sinusoidal shape of the waveforms; in real motors, these waveforms will only be approximately sinusoidal, and the sum of the torques from the two windings will not be the perfect arithmetic sum of the torques with just one or the other winding powered.

FIGURE 10: TORQUE VS. ANGULAR POSITION FOR AN IDEAL TWO WINDING MOTOR



The desired motion of a stepper motor is linear. This means the steps should be equal in size with no noticeable acceleration or deceleration of the shaft as the motor turns. Good microstepping implementations strive to get as near to this linear motion as possible.

The torque curve for one winding of the ideal two winding stepping motor in Figure 10 can be expressed mathematically by the following equation:

EQUATION 1:

$$T_1 = H\sin(((\pi/2)/S)\theta)$$

where T_1 = torque of the first winding

H = holding torque

S = step angle, in radians

θ = shaft angle, in radians

The torque of the second winding is expressed by the following equation.

EQUATION 2:

$$T_2 = H\cos(((\pi/2)/S)\theta)$$

A technique referred to as sine-cosine microstepping adjusts the current in each winding so the net torque is constant. In an ideal motor, the torque produced by each winding is proportional to the current in that winding, and the torques add linearly. Saturation and fringe-field effects make real motors non-ideal, but in practice, they are close enough that we can ignore these nonlinearities. As a result, if we want to hold the motor rotor at the angle θ, we can do so by setting the currents through the motor windings to the values given in Equation 3 and Equation 4.

EQUATION 3:

$$I_1 = I\text{MAX}\ cos(((\pi/2)/S)/\theta)$$

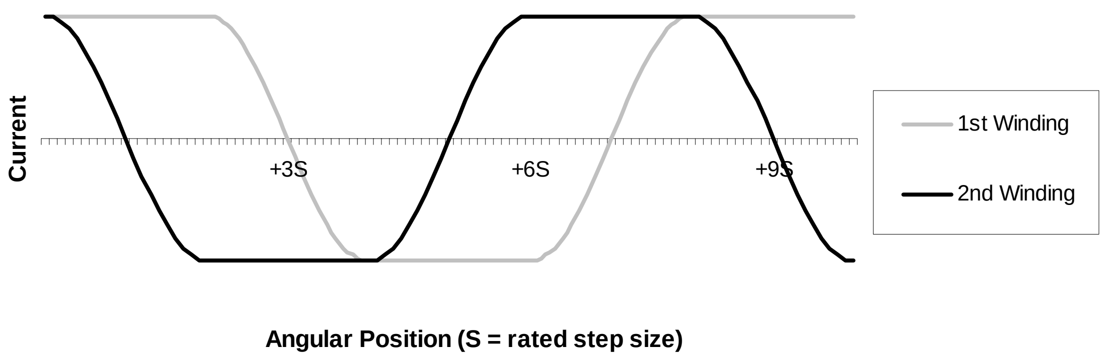
EQUATION 4:

$$I_2 = I\text{MAX}\ sin(((\pi/2)/S)/\theta)$$

These equations assume that the current in the windings will not exceed IMAX. The next section will talk about current limiting considerations.

A second way to implement microstepping maximizes torque in a bipolar stepping motor, though the torque is not constant while the motor turns. In this method, one winding is energized while the current flow in the other winding is ramped down, reversed and then ramped up again. The second winding then remains energized while the first winding undergoes the polarity reversal. Like the sine-cosine microstepping method, smooth movement of the motor is achieved with this method by changing the current in the windings in a sinusoidal fashion. Figure 11 shows the way the current in each winding is altered as the shaft turns.

FIGURE 11: BIPOLAR MICROSTEPPING FROM MAXIMUM TORQUE



In an ideal motor, microstepping can be used to achieve arbitrarily fine angular resolution, but in practice friction and departures from the ideal sinusoidal torque versus shaft angle curve make this impractical. In practice, it is rarely worthwhile to subdivide each motor step into more than 32 microsteps, and even this is generous!

Using 32 microsteps per step, we can step in increments of 0.23 degrees using an inexpensive permanent magnet motor with 7.5 degrees per step. We could achieve the same resolution using 1:32 reduction gearing, but this introduces backlash and it reduces the maximum speed. Compared to microstepping, gearing has the benefit of increasing the torque and position-holding stiffness of the motor.

It is impractical to calculate the sine or cosine of the duty cycle for the PWM signal supplying a winding because the time to process the calculation and code space needed. It's more practical to have a sine look-up table with the values for the duty cycle. In practice, only one look-up table is needed because cosine is just an offset of sine. The look-up table pointers corresponding to each winding just need to be offset by 90 degrees.

Microstepping Limitations

The previous discussion assumed an ideal two winding stepping motor. There are several factors that affect the linearity of microstepping in real motors. The first limitation is static friction in the system. Figure 10 shows a graph of torque verses position of the motor shaft. Figure 12 shows this same graph (for one winding) with the dotted lines representing the effect static friction has on the system. Redrawing the graph in Figure 12 to show only the available torque for a single winding results in the graph shown in Figure 13. Note the resulting dead zone between the zones of available torque. Also note that the magnitude of torque overall is less than the ideal case.

FIGURE 12: STATIC FRICTION IMPOSED ON TORQUE VS ANGULAR POSITION

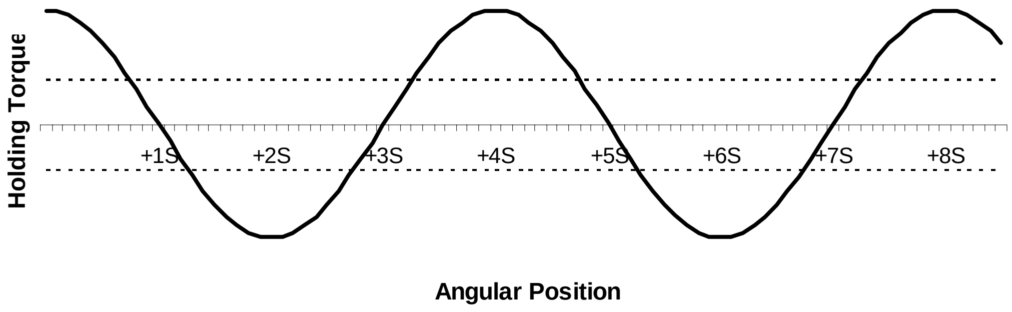
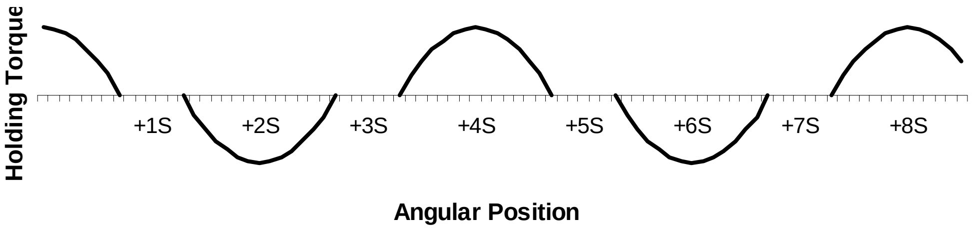


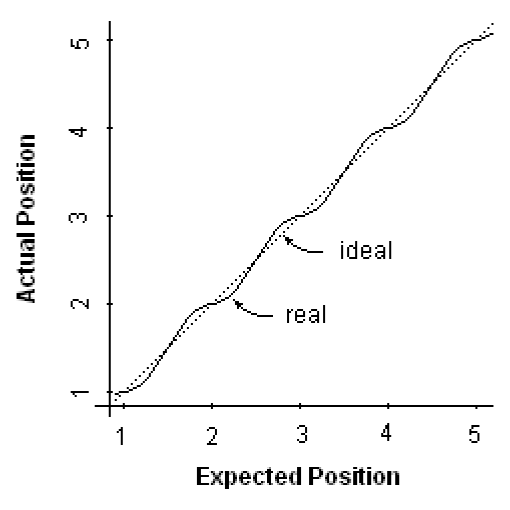
FIGURE 13: MOTOR TORQUE MINUS STATIC FRICTION



The dead zone has an impact on microstepping because it limits the angular resolution of the stepping motor. It also makes it impossible to produce perfectly smooth transitions between steps.

Another limitation to microstepping is the fact that the torque verses position curve is not perfectly sinusoidal for real motors. The toothed shape of the rotor and other physical characteristics of the motor contribute to this. Figure 14 shows a plot of actual position vs. expected position for a typical motor.

FIGURE 14: REAL VS ACTUAL ROTOR POSITION



The digital nature of the motor drive circuitry poses two additional limits on the accuracy of microstepping. If current levels through the motor windings are produced from digital data, either by using analog-to-digital converters or by measuring the current using digital-to-analog converters, the precision of these conversions introduces problems. In addition, if the currents through the motor windings are set by pulse-width modulation, once the stepping rate comes anywhere near the pulse rate used for current control, the precision of the current control system becomes almost meaningless.

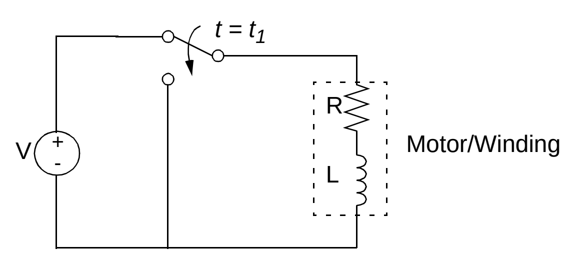
CURRENT LIMITING

Stepping motors are often run at voltages higher than their rated voltage. Although this is not necessarily the case for very small stepper motors, high torque stepper motors need to run at higher voltages in order for the motor to reach its full potential. Increasing the voltage supplied to a motor increases the rate at which current rises in the windings of the motor. The more responsive current in the windings, the greater the torque and speed characteristics of the motor. This section will explain why performance is boosted and what role current limiting plays in this process.

Stepper Motor Winding Model

In order to understand why running stepper motors at high voltage is beneficial to motor performance, it is necessary to look at the behavior of current in the windings of a stepping motor. A winding can be modeled as the inductive-resistive circuit shown in Figure 15.

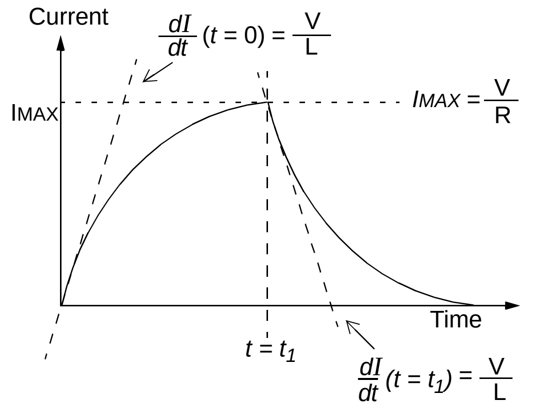
FIGURE 15: RESISTIVE-INDUCTIVE WINDING MODEL



There are three components to this model: the supply voltage, the resistance of the winding (R) and the inductance of the winding (L).

Figure 16 shows how current behaves over time when the supply voltage is applied.

FIGURE 16: WINDING CURRENT VS TIME



The current rises exponentially until IMAX is reached. Current as a function of time is given by:

EQUATION 5:

$$I(t) = (V/R) \times (1 - e^{-t \times R/L})$$

The instantaneous rate that current rises when voltage is first applied is given by:

EQUATION 6:

$$dI/dt(t = 0) = V/L$$

Ohms law governs the maximum current level.

EQUATION 7:

$$\mathit{IMAX} = V/R$$

The current in the winding will remain at IMAX until the supply voltage is switched off. Referring to Figure 16, the current drops exponentially when the voltage supply is removed. Current, as a function of time, drops according to:

EQUATION 8:

$$I(T) = (V/R) \times E^{-(T-T1) \times R/L}$$

The instantaneous rate that the current drops when voltage is removed is given by:

EQUATION 9:

$$dI/dt = -V/L$$

These equations show that current rises and falls for a given winding as a function of the supply voltage and the internal resistance of the winding. It is important to understand this relation when applying a higher than specified voltage to a stepping motor. The reason it is important is that ***the current in the windings of a stepping motor must never exceed the maximum specified current (IMAX)[1].*** Running a motor at high voltage but not taking into consideration current limitations can be very detrimental to motor life, the driver circuitry, and the well being of people who come in contact with the motor (the motor gets really hot!).

Note 1: IMAX is a specification found in the stepper motor manufacturer's data sheet.

Referring to Equation 5 and Equation 6, the rate that current rises in a winding is increased by using a higher supply voltage. Equation 7, however, shows that IMAX is also affected by increasing the supply voltage. So how can the rise time be improved without the current exceeding IMAX? The simplest way is to add resistance in series with the motor.

In-series Resistance

The first way to increase the supply voltage without exceeding IMAX is to connect a power resistor in series with each winding of the motor. Figure 17 shows this circuit. In the circuit shown, the magnitude of the supply voltage is tripled (2V). This requires that a power resistor equivalent to two times the internal resistance of the winding (R) be added. This brings the total resistance of the circuit to 2R. Notice the resistance and voltage are increased proportionally so that Equation 3 is still satisfied and IMAX is unchanged (i.e., IMAX = 2V/2R = V/R).

FIGURE 17: WINDING MODEL WITH ADDITIONAL RESISTANCE

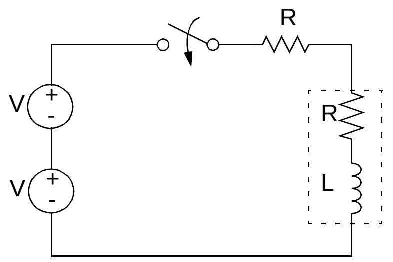
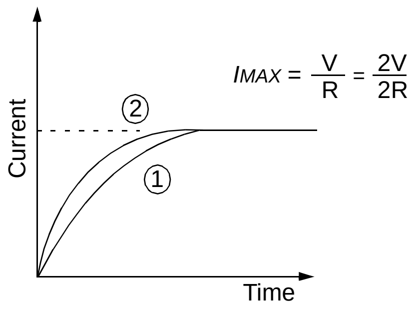


Figure 18 shows how current rise time is affected by increasing the supply voltage and resistance. The rise time is improved, therefore, the performance of motor is improved. However, in order to achieve this performance boost, the efficiency of the system has dropped significantly with the introduction of a power resistor. The power resistor limits current in a less than efficient manner by burning it off as heat. Depending on the magnitude of the voltage supply increase, the power resistor may be extremely large and expensive. For battery controlled operation, the run time of the system is significantly reduced by the power wasted in the power resistor.

FIGURE 18: CURRENT VS TIME

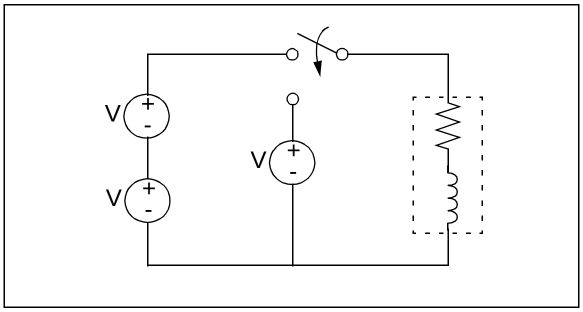


Another drawback of using a power resistor is that it does not optimize the rise time of the current in a winding. Referring to Equation 5 again, increasing resistance has an adverse affect on the rise time. Though increasing the voltage supply and resistance proportionally produces a better rise time than not increasing either, it would be ideal to increase the supply voltage without adding resistance in series with the winding. So how can the supply voltage be increased without the addition of resistance and the current still not rise above the motors rated IMAX? The answer is to use two supply voltages.

Two Power Supplies

Applying a high voltage to the winding until IMAX is reached and then dropping the voltage to a level that will maintain IMAX is the most efficient way to improve the performance of a stepping motor. One way to do this involves the use of two power supplies. Figure 19 shows what this circuit might look like.

FIGURE 19: TWO SUPPLY VOLTAGES

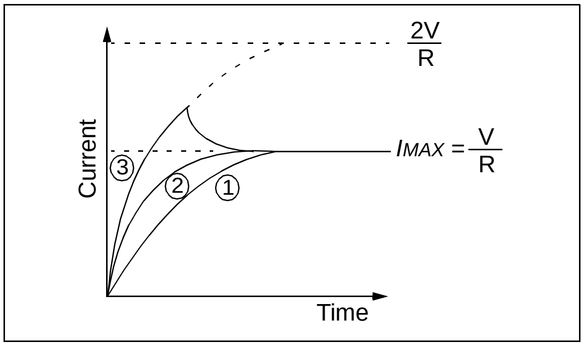


The circuit requires a way to switch from one power supply to the other. The time at which power is switched from one supply to the other can be controlled by either a closed loop or an open loop system. In the case of an open loop system, Equation 5 is used to calculate the length of time that the high voltage is applied to the winding before switching to the low voltage supply. For closed loop control, a small current sensing resistor provides feedback to the controller and the voltage is switched when IMAX is reached. This will be talked about more in the next section (chopping circuits) and is applicable to using two power supplies.

Figure 20 shows how the current behaves for the three situations discussed thus far:

1. Using the rated voltage
2. Using high voltage with a power resistor
3. Using high voltage during the rise time of the current to IMAX and then switching to the rated voltage

FIGURE 20: CURRENT VS TIME



Note that using two voltage supplies yields the best results. The current rises rapidly and then remains at IMAX when supply voltage is switched. This method also has the added benefit of being power efficient compared to adding a in-series resistor. One drawback to the two voltage supply method, however, is that using two separate supplies is often impractical in most applications. Rarely are two voltage supplies available for a given application and using two supplies is far less cost effective than using just one. So how can one voltage supply be used to accomplish this task? The solution is the use of chopper control.

Chopper Control

Chopper control is a way to limit the current in the winding of a stepping motor when using a high voltage supply (a voltage higher than a motors rated voltage). This method is very suitable when using a microcontroller for stepping motor control because limited additional microcontroller resources are required. The basic idea behind chopper control is to use a high voltage source to bring the current in the winding of a stepping motor up to IMAX very quickly. When IMAX is reached the voltage is chopped or switched off. A pulse-width modulated waveform is used to create an average voltage and an average current equal to the nominal voltage and current for the winding. The duty cycle of this PWM waveform is shown in the following relation:

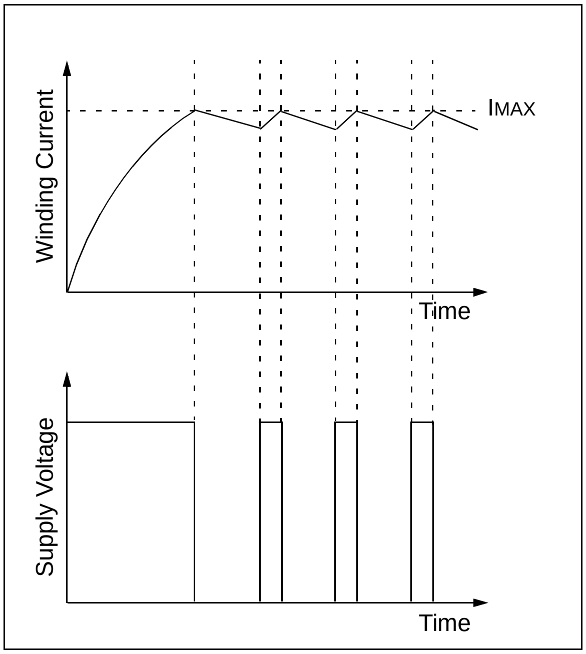
EQUATION 10:

$$D = V_{NOMINAL}/V_{SUPPLY}$$

$$\text{Where } V_{NOMINAL} = I_{MAX}/r$$

A comparison of current and the voltage applied to the winding over time is shown Figure 21.

FIGURE 21: CURRENT AND SUPPLY VOLTAGE COMPARISON FOR CHOPPER CONTROL



As Figure 21 indicates, the voltage supply is switched on until I_{MAX} is reached. Thereafter, the voltage is modulated to limit the current in the winding to I_{MAX}.

There are many different ways to implement chopper control using a microcontroller. The following circuit illustrates a hardware-based design. More discussion about chopper control as it relates to microcontrollers will be covered in the next section (Microcontroller Control of a Stepping Motor.)

Figure 22 shows what one possible chopper circuit looks for in a bipolar motor. The way this circuit works is that the voltage across the current sense resistor (R_{SENSE}) is compared to a control voltage ($V_{CONTROL}$) which is predetermined according to:

EQUATION 11:

$$V_{CONTROL} = R_{SENSE} \times I_{MAX}$$

In practice, the sense resistor should be as small as possible while still allowing $V_{CONTROL}$ to be easily measurable. Values of $V_{CONTROL}$ between 0.6 volts (one silicon diode drop) and 5 volts are common, and sense resistances on the other of 1/2 or 1 ohm are common. Generally, the voltage across R_{SENSE} should not exceed 10% of the supply voltage! For very high current motors, current sensing using Hall-effect sensors and other advanced technologies can greatly reduce losses from current sensing.

When V_{SENSE} rises above $V_{CONTROL}$, the voltage across the winding is switched off. The passive components connected to the comparator provide hysteresis so that the voltage is not reapplied until:

$V_{SENSE} = V_{CONTROL} - V_X$, where V_X is a small voltage.

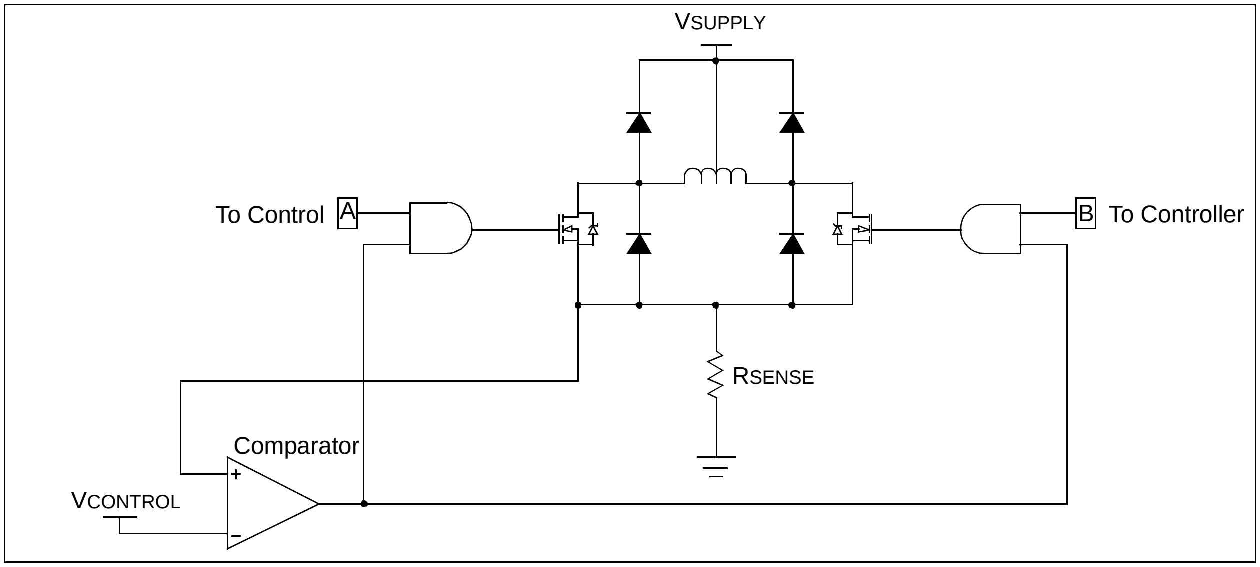
Hysteresis is necessary to prevent limiting the frequency with which the comparator and MOSFETs chop the supply voltage. Both thermal switching losses in the MOSFETs and radio frequency dissipation from the entire circuit rise with chopping frequency, so this frequency should generally be held in the audio range but well above the maximum expected stepping rate.

Current Limiting For Microstepping

Current limiting is an integral part of microstepping. Microstepping varies the current sinusoidually between 0 and I_{MAX}, rather than bringing the current up to I_{MAX} as quickly as possible. Microstepping can be combined with the high voltage supply current limiting techniques talked about in this section in order to improve the responsiveness of a motor when microstepping. When microstepping at a high voltage, the duty cycle of waveforms modulating each of the windings must be limited so that the current in the windings never exceeds I_{MAX}. For instance, if a 5V stepping motor is being driven by a 10V peak-to-peak waveform, the duty cycle of the waveform should never exceed 50%.

With reference to Figure 22, microstepping could be implemented by deriving $V_{CONTROL}$ from the output of a digital-to-analog converter in the controller; some motor driver chips even include 3-bit internal DACs along with the comparator and final-stage drive circuitry.

FIGURE 22: CHOPPER CIRCUIT



Understanding Motor Specifications

Low performance stepper motors are purposefully built with a high internal resistance so that they can be run on a typical voltage source, usually 5V to 12V. These motors do not produce much torque for their size, nor do they spin very fast. They can be run without current limiting considerations as long as they are driven at their rated voltage. However, higher motor performance (speed and torque) can be achieved by running these motors at higher voltages.

High torque stepping motors are a different story all together. These motors have very small internal resistances and run at high currents. An example of a high performance motor would be a motor with the specifications shown in Table 1. The statement of holding torque in Table 1 is typical of many motor manufacturers, using kilograms as a measure of force. This must be converted to dyne-centimeters or newton-meters before doing any physical calculations.

TABLE 1: HIGH PERFORMANCE STEPPING MOTOR SPECIFICATION

Step Angle	Voltage	Current	Resistance	Inductance	Holding Torque	Rotor Inertia	Number of Leads	Weight
Deg	V	A/Phase	Ohm/Phase	mH/Phase	kg-cm	g-cm^2	LEAD	kg
1.8	1.8	4.5	0.4	0.96	16	570	6	1.4

Notice the voltage specification 1.8V. Running the motor at this voltage will yield terrible performance in terms of speed and torque. ***High performance stepping motors are intended to be driven at higher voltages with current limiting considerations*.**

As discussed earlier, motor windings have some internal resistance (R). This resistance is a function of wire diameter, the number of turns and the resistivity of the winding material. This resistance is ultimately what determines the maximum current that a winding should be subjected to. The power loss of a winding is given by:

EQUATION 12:

$$P_{LOSS} = R \times I_{MAX}^2$$

The maximum current allowed in a motor winding must not overheat the motor, it must not drive the magnetic circuits into saturation and it must not produce motor fields that are sufficient to demagnetize the motor rotor. In a well designed permanent magnet motor, when both motor windings are run at IMAX and the motor is properly mounted and ventilated, it will be very close to both its thermal and magnetic limits. This is why it is so critical that the drive circuitry should never permit currents exceeding IMAX.

The voltage specification given on motor data sheets is simply the maximum voltage across a motor winding that will produce a current equal to IMAX given the internal resistance of the winding. As stated earlier, IMAX is the critical specification for a motor that should not be exceeded. The voltage specification for a motor is simply the voltage that will produce a current equal to IMAX given the internal resistance of the winding. Equation 7 shows this relation. Referring to Table 1, multiplying current per phase by the ohms per phase results in the rated voltage.

BASIC MICROCONTROLLER STEPPING MOTOR CONTROL

This section discusses using PIC® microcontrollers for stepper motor control. There are several peripherals available on Microchip parts that make controlling a stepping motor more precise. Any PIC microcontroller can be used to control a stepper motor. However, depending on the complexity of the control desired (i.e., microstepping and current limiting), it can be very advantageous to choose a microcontroller with select peripherals that will take care of most of the stepper motor overhead.

Capture Compare PWM module

The Capture Compare PWM (CCP) module is available on many PIC microcontrollers. This peripheral is useful in stepping motor applications for its pulse-width modulation capabilities. In PWM mode, the CCP module will provide a PWM waveform on the CCP1 pin. The 10-bit duty cycle of the waveform is set by the CCPR1L and CCP1CON registers. Frequency is determined by the Timer2 prescaler value, the PR2 register and the clock speed of the device.

The CCP module is very useful when microstepping. Figure 23 shows a circuit in which the PIC16F73 is interfaced to a unipolar motor. The PIC16F73 has two CCP modules. This implementation allows for sine-cosine microstepping in which two windings are modulated simultaneously (refer to the microstepping section for a definition).

In this example, CCP1 modulates the voltage across alternating sides of winding 1 based on the input from pin RB1. Winding 2 is configured in the same manner using CCP2 and pin RB2.

Note: The PWM waveform is inverted from one side of the winding to the other.

If the circuit in Figure 23 is used with VSUPPLY equal to VNOMINAL for the motor, duty cycles for the choppers can be run from 0 to 100% for microstepping. If the VSUPPLY is above VNOMINAL, the maximum duty cycle for each chopper must be reduced proportionally.

ENHANCED CCP PWM MODULE

The Enhanced Capture Compare module available on many PIC microcontrollers offers the same functionality as the CCP module, plus several additional features. The enhanced PWM mode has full-bridge and half-bridge support, programmable dead band delay and auto shutdown. Full-bridge mode is useful for implementing microstepping control for a bipolar motor.

Figure 24 shows how the output pins of one ECCP module can be multiplexed to the windings of a bipolar motor using added external AND-invert logic gates. The microstepping technique used here is high-torque microstepping in which the voltage applied to only one winding is modulated at any given time (see the Microstepping Section for a definition of high-torque microstepping).

The TC4469 dual H-bridge shown in Figure 24 is a logic-input CMOS quad driver developed by Microchip. This IC is a MOSFET driver but can be used to drive small stepper motors that require very little current (under 200 mA). The output stage of each gate on the TC4469 is a half-bridge.

FIGURE 23: UNIPOLAR MICRO STEPPING

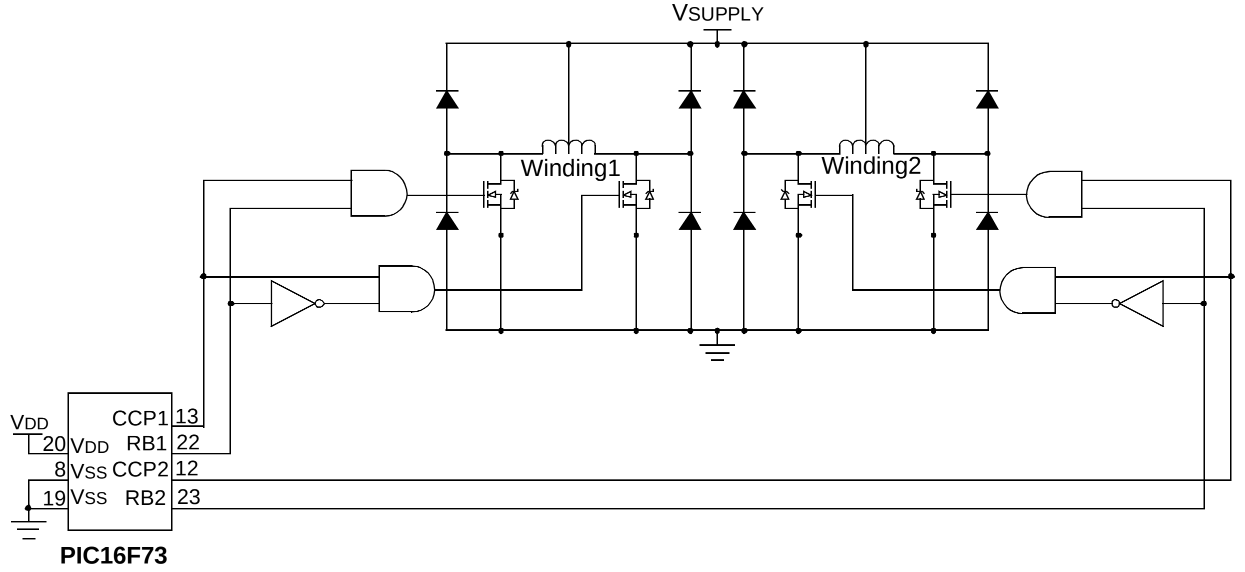
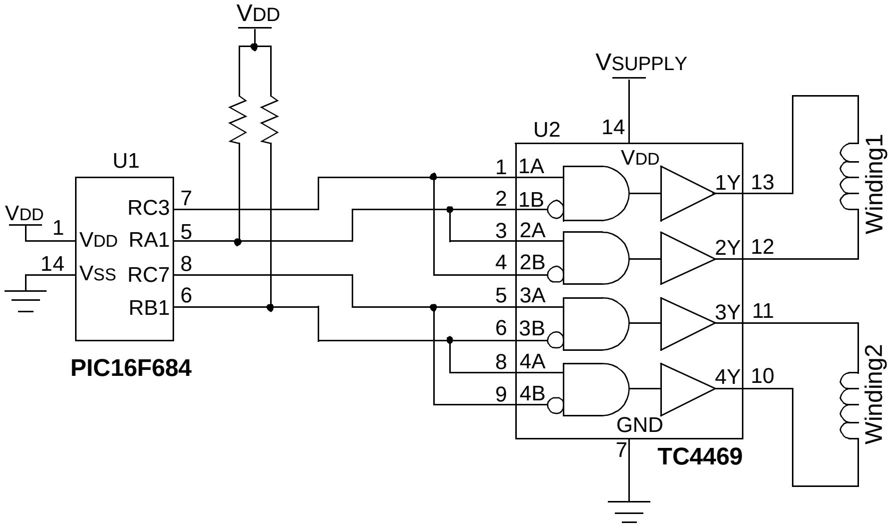


FIGURE 24: BIPOLAR MICROSTEPPING USING THE ECCP MODULE



COMPARATORS

The current limiting section discussed how comparators can be used in chopper circuits. Several PIC microcontrollers have on-chip comparators that can be used to accomplish this task. The comparators can be used to chop the input directly in hardware or can generate a software interrupt in the microcontroller indicating IMAX has been reached. When an interrupt is generated, the PIC microcontroller can modulate the voltage across the winding so that the average voltage equals the nominal voltage for the phases of the stepping motor. This functionality can be accomplished by a CCP or ECCP module.

A/D CONVERTERS

The same functionality just discussed can also be accomplished by feeding the output of the sense resistor into a PIC A/D converter by way of an operational amplifier. The way this works is the A/D converter is read continually by the microcontroller. When the value generated by the A/D converter indicates IMAX is reached, the microcontroller will modulate the voltage across the winding so that Vnominal is maintained.

Note:	In practice, the comparator implementation uses less processor resources than the ADC implementation. The comparator implementation also yields a faster response.

CONCLUSION

Stepper motors are ideally suited for measurement and control applications. The step resolution and performance of these motors can be improved through a technique called microstepping. Stepping motor performance can also be improved by driving these motors at a voltage greater than what they are rated for. If higher voltage is used to boost performance, then current limiting considerations must be taken into account.

PIC® microcontrollers are able to drive all the different types of stepping motors: variable reluctance, permanent magnet and hybrid. Single-stepping, half-stepping, microstepping and current limiting are all stepper motor drive techniques that are well within the utility of PIC microcontrollers. The CCP, ECCP and comparator modules available in Microchip's microcontroller line allow for the implementation of the more advanced stepping motor control techniques, namely microsteppng and current limiting. In summary, PIC microcontrollers are an ideal choice for stepping motor control.

REFERENCES

Stepping Motor Tutorial by Dr. Douglas W. Jones (http://www.cs.uiowa.edu/~jones/step/#introduction), Copyright 1995

Stepper Motor Tutorial by Rustie Laidman (http://209.41.165.153/stepper/), Copyright 2000

Article: *The Rise of VSR Motor*, Greg Paula, Mechanical Engineering Magazine; Copyright 1998 by The American Society of Mechanical Engineers

Drive Circuit Basics, Industrial Circuits Application Notes, (http://library.solarbotics.net/pdflib/pdf/drive.pdf)

AN822, *Stepper Motor Microstepping with PIC18C452*, Microchip Technology Inc.

The Handbook of Small Electric Motors, Yeadon and Yeadon, Eds, McGraw Hill, 2001

HTTP://www.cs.uiowa.edu/~jones/step/

Shinano Kenshi Corporation, (http://www.shinano.com/stepper.htm)

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01/26/04