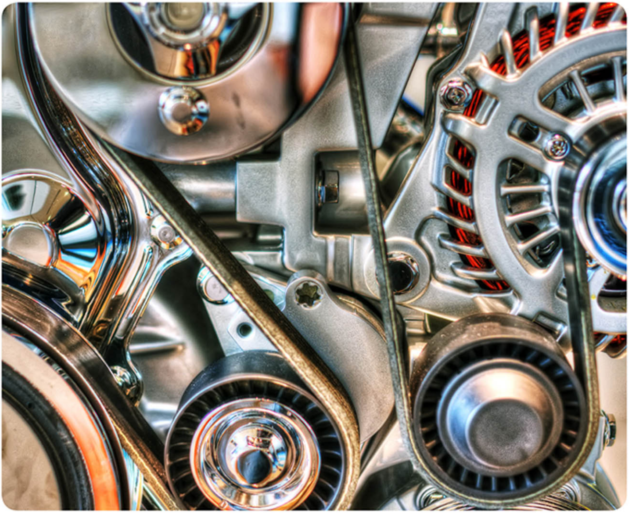
MOTORS for MAKERS

A Guide to Steppers, Servos, and Other Electrical Machines



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Matthew Scarpino

MOTORS for MAKERS

A Guide to Steppers, Servos, and Other Electrical Machines

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MOTORS FOR MAKERS: A GUIDE TO STEPPERS, SERVOS, AND OTHER ELECTRICAL MACHINES

ISBN-13: 978-0-13-403283-2
ISBN-10: 0-13-403283-7

Library of Congress Control Number: 2015951266

Printed in the United States of America

First Printing: December 2015

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Matthew Scarpino is an engineer with more than 12 years of experience designing hardware and software. He has a master's degree in electrical engineering and is an Advanced Certified Interconnect Designer (CID+). He is the author of *Designing Circuit Boards with EAGLE: Make High-Quality PCBS at Low Cost*.

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INTRODUCTION

When I received my master's degree in electrical engineering in 2002, I couldn't help but feel a little disappointed. I knew all about analog circuit theory, but I knew next to nothing about practical circuit boards. I could compute the Lorentz force in an electric motor, but I had no idea how motor controllers worked in the real world. Put simply, I could write programs and solve equations, but I couldn't *make* anything.

Shortly after I received my degree, the first Arduino boards appeared in the marketplace. Their simplicity and low cost sparked a worldwide interest in electronics, and within a few years, the Maker Movement was born. Makers aren't interested in heavy mathematics and physics. Makers are concerned with what they can build. Whether it involves 3D printers or the Raspberry Pi, makers care about cool hardware, especially if it involves electronics.

But makers get nervous when it comes to motors. Pre-built quadcopters are growing in popularity, but I don't see many makers designing their own electronic speed controls (ESCs) or programming their own robotic arms. This is perfectly understandable. Motors are more complicated than other circuit elements. With motors, you don't just have to be concerned with electrical quantities such as voltage and current; you have to think about mechanical quantities such as torque and angular speed.

The topic of electric motors isn't easy, but the goal of this book is to make the concepts approachable to non-engineers. I assume a minimal background in mathematics and physics, and throughout the book, the emphasis is always on *making*. Instead of discussing the Lorentz force and electromagnetic flux, this book focuses on practical knowledge. Instead of bombarding you with equations, I'll show you the different types of motors available and the ways they can be controlled.

It takes time and patience to become comfortable with motors, but once you've ascended the learning curve, you'll be able to work on new and fascinating types of projects. Robots and remote-controlled vehicles will all fall within your grasp. The road is long, but I assure you that the destination is worth the journey.

Who This Book Is For

As the title should make clear, this is a book for makers. If you're looking for a textbook on phasor diagrams and Maxwell's equations, this isn't the book for you. If you're looking for practical information related to motor operation and control, you've come to the right place. If you want to know about the different types of motors and what they're good for, this is the book to have.

I've done my best to make motors comprehensible to non-engineers, but this book is not for beginners. In writing this book, I assume that you already know about volts, amps, and ohms. Further, I assume that you can look at a simple circuit diagram and get a sense for how the system works.

How This Book Is Organized

To present the topic of electric motors as clearly as possible, I've split the content into four parts:

- Part I, "Introduction," provides an overview of what motors are and how they work. Chapter 1, "Introduction to Electric Motors," introduces the history of electric motors and explains the two building blocks that make motor operation possible. Chapter 2, "Preliminary Concepts," expands on this, and explains how motors convert voltage and current into torque and angular speed.
- Part II, "Exploring Electric Motors," examines the many different types of motors available for makers. Specifically, the chapters in this part focus on DC motors, stepper motors, and servomotors. Later chapters investigate AC motors, linear motors, and gears. For each type of motor, the chapter explains how it operates and how it can be controlled.
- Part III, "Electrical Motors in Practice," presents three real-world applications of electric motors. Chapters 9 through 11 show how motors can be controlled with the popular circuit boards Arduino Mega, Raspberry Pi, and BeagleBone Black, respectively. Chapter 12, "Designing an Arduino-Based Electronic Speed Control (ESC)," explains how to build an electric speed control (ESC), and Chapter 13, "Designing a Quadcopter," explains how to build a quadcopter. The final chapter focuses on the important topic of electric vehicles.
- Part IV, "Appendixes," provides supplemental information that I hope will be helpful. Appendix A, "Electric Generators," discusses the topic of electric generators and the different types of machines that convert motion into electricity. Following that, the glossary in Appendix B provides definitions for many of the terms discussed throughout the book.

A handful of chapters present source code and circuit designs related to the content. These source code files and design files can be downloaded from http://motorsformakers.com.

Let Me Know What You Think

Feel free to email me at mattscar@gmail.com. I'm usually pretty good about responding promptly, though I won't promise a response to every concern.

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4

STEPPER MOTORS

In this and the following chapter, the primary concern is *motion control*—making sure the motor turns with a specific angle and/or speed. This book discusses two types of motors intended for motion control: stepper motors and servomotors. I'll refer to them as *steppers* and *servos*, respectively, and this chapter focuses on steppers.

A stepper's purpose is to rotate through a precise angle and halt. The speed and torque of the rotation are secondary concerns. As long as the stepper rotates through the exact angle and stops, its mission is accomplished. Each turn is called a *step*, and common step angles include 30°, 15°, 7.5°, 5°, 2.5°, and 1.8°.

Due to their simplicity and precision, steppers are popular in electrical devices. Analog clocks, manufacturing robots, and printers (2D and 3D) rely on steppers for motion control. An important advantage is that the controller doesn't have to read the stepper's position to determine its orientation. If the stepper is rated for 2.5°, each control signal will turn the rotor through an angle of 2.5°.

For many applications, we want the step angle to be as small as possible. The smaller the motor's step angle, the greater its *angular resolution*. Another important figure of merit is torque, particularly *holding torque*. A stepper is expected to hold its position when it comes to a halt, and holding torque identifies the maximum torque it can exert to maintain its position.

Modern steppers can be divided into three categories:

- **Permanent motor (PM)**—High torque, poor angular resolution
- **Variable reluctance (VR)**—Excellent angular resolution, low torque
- **Hybrid (HY)**—Combines structure of PM and VR steppers, provides good torque and angular resolution

The first part of this chapter examines these categories in detail. In each case, I'll discuss the motor's fundamental operation and present its advantages and disadvantages. The last part of the chapter explains how steppers can be controlled with electrical circuits.

4.1 Permanent Magnet (PM) Steppers

Small and reliable, permanent magnet (PM) steppers are popular in embedded devices such as disk drives and computer printers. Figure 4.1 depicts the ST-PM35 stepper from Mercury Motor.

Figure 4.1
A permanent magnet (PM) stepper motor

PM steppers have a lot in common with the brushless DC (BLDC) motors discussed in the preceding chapter. In fact, you can think of a PM stepper as a BLDC whose windings are energized to provide discrete rotation instead of continuous rotation.

4.1.1 Structure

The preceding chapter introduced the brushless DC motor and its two subcategories: inrunners and outrunners. PM steppers are similar to inrunners in many respects, and a good way to introduce them is to compare and contrast them with inrunner BLDCs. Figure 4.2 illustrates the internal structure of a simple PM stepper.

There are five important similarities between PM steppers and inrunner BLDCs:

- Neither motor has a brush or a mechanical commutator (all steppers discussed in this book are brushless).
- The rotor is on the inside, with permanent magnets mounted on its perimeter.
- The stator is on the outside, with electromagnets (called windings) inside slots.
- The controller energizes the windings with pulses of DC current.
- Many of the windings are connected together. Each group of connected windings forms a phase.

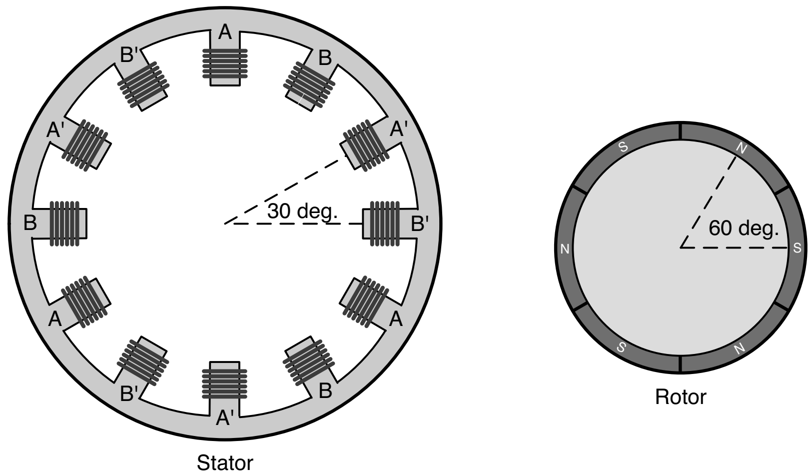


Figure 4.2 Internal structure of a permanent magnet (PM) stepper motor

PM steppers are brushless and receive DC pulses from the controller. For this reason, they could be classified as BLDCs. But in this book, as in other literature, we'll only employ the term BLDC for motors that aren't specifically intended for motion control.

Let's look at the differences between the two types of motors. Table 4.1 contrasts the characteristics of PM steppers with those of inrunner BLDCs.

Table 4.1 Contrasting Characteristics of PM Steppers and Inrunner BLDCs

PM Stepper	Inrunner BLDC
Intended for discrete rotation.	Intended for continuous rotation.
Almost always has two phases.	Almost always has three phases.
Controller energizes one or two phases at a time.	Controller energizes two phases at a time and leaves third phase floating.
Many windings and rotor magnets.	Few windings and rotor magnets.

From a structural perspective, the primary difference between PM steppers and inrunners is that PM steppers have more windings and rotor magnets. As it turns out, this is necessary to make the angular resolution as small as possible. The following discussion explains why this is the case.

4.1.2 Operation

To understand how a PM stepper operates, it's crucial to see how its step angle is determined by the number of windings and rotor magnets. This discussion focuses on the motor depicted in Figure 4.2. Its stator has 12 windings and its rotor has six magnets mounted on its perimeter.

PM steppers are generally two-phase motors. In the figure, the different phases are denoted A and B. The windings labeled A' and B' receive the same current as those labeled A and B, but in the opposite direction. That is, if A behaves as a north pole, A' behaves as a south pole.

Each winding has one of three states: positive current, negative current, and zero current. For this discussion, positive current implies a north pole and negative current implies a south pole.

Now let's see how these motors operate. Figure 4.3 illustrates a single turn of a PM stepper. In the windings, a small "N" implies that the winding behaves like a north pole due to positive current. A small "S" implies that the winding behaves like a south pole due to negative current. If a winding doesn't have an N or S, it isn't receiving current.

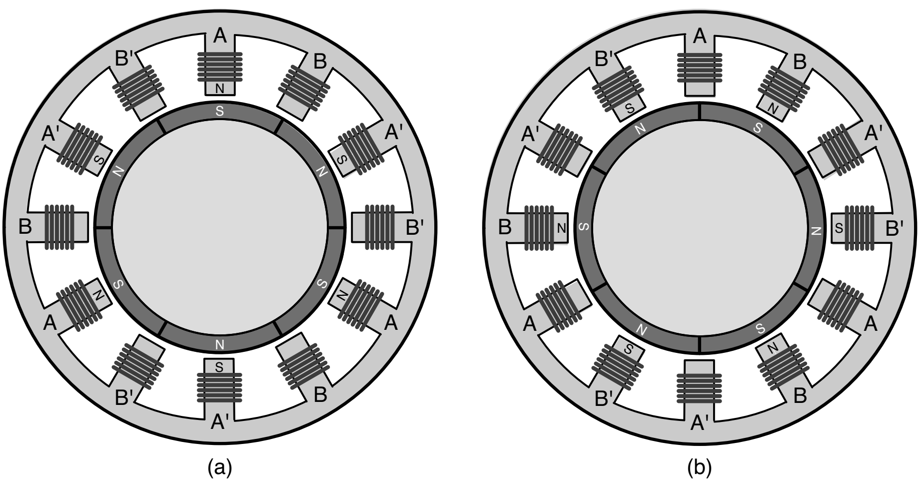


Figure 4.3
30° rotation of a PM stepper motor

In Figure 4.3a, A is positive (north pole), A' is negative (south pole), and Phase B isn't energized. The rotor aligns itself so that its south poles are attracted to the A windings and its north poles are attracted to the A' windings.

In Figure 4.3b, B is positive (north pole), B' is negative (south pole), and Phase A isn't energized. The rotor rotates so that its poles align with the B and B' windings. The rotation angle equals the angle between the A and B windings, which means the rotor turns exactly 30° in the clockwise direction. This arrangement of eight windings and six poles is common for PM stepper motors, though others turn at angles of 15° and 7.5°.

In case this isn't clear, let's look at a second movement. Figure 4.4 presents another 30° rotation of a PM stepper motor.

In Figure 4.4a, B is negative (south pole), B' is positive (north pole), and A isn't energized. The rotor is positioned so that its poles align with the B windings.

In Figure 4.4b, A is positive (north pole), A' is negative (south pole), and B isn't energized. The rotor turns exactly 30° in the clockwise direction to align itself between the A windings.

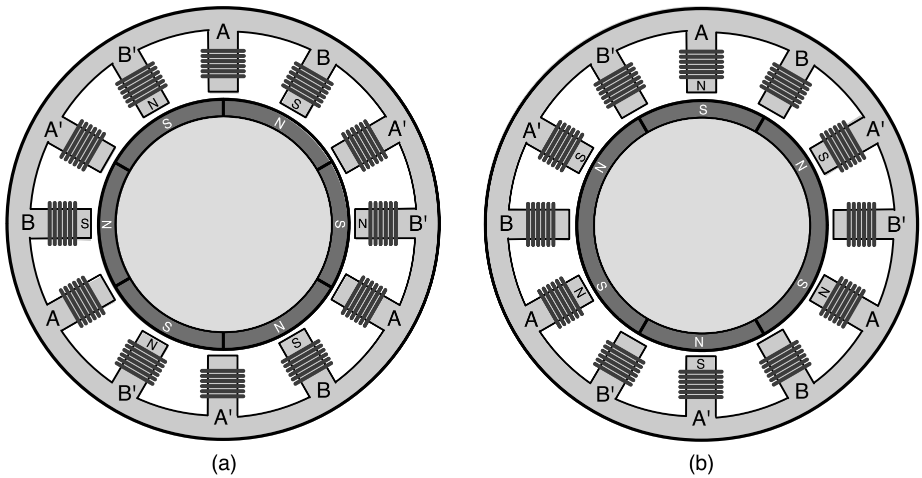


Figure 4.4 Further rotation of a PM stepper motor

The controller's job is to deliver current to the windings so the rotor continues turning in 30° increments. The difference in control signaling is a major difference between steppers and BLDCs. The last part of this chapter discusses the circuitry needed to govern a stepper's operation.

4.2 Variable Reluctance (VR) Steppers

Just as resistance determines the flow of electric current, *reluctance* determines the flow of magnetic flux. In a variable reluctance (VR) stepper, the rotor turns at a specific angle to minimize the reluctance between opposite windings in the stator.

The primary advantage of VR steppers is that they have excellent angular resolution. The primary disadvantage is low torque.

This section presents VR steppers in detail. I'll explain their internal structure first and then show how they rotate as their windings are energized.

4.2.1 Structure

Structurally speaking, variable reluctance (VR) steppers have a lot in common with PM steppers. Both have windings on their stator and opposite windings are connected to the same current source.

However, there are two primary differences between VR steppers and PM steppers:

- **Rotor**—Unlike a PM stepper, the rotor in a VR stepper doesn't have magnets. Instead, the rotor is an iron disk with small protrusions called *teeth*.
- **Phases**—In a PM stepper, the controller energizes windings in two phases. For a VR stepper, the controller energizes every pair of opposite windings independently. In other words, if the stator has N windings, it receives N/2 signals from the controller.

Figure 4.5 illustrates the rotor and stator of a VR stepper. In this motor, the stator has eight windings and the rotor has six teeth.

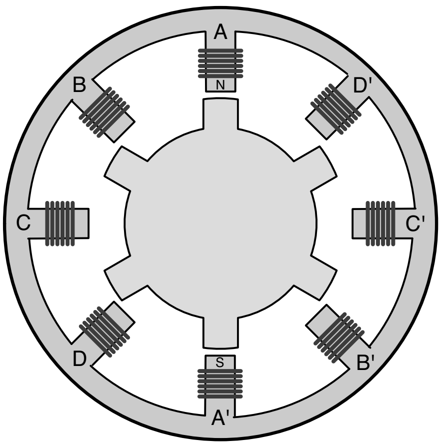


Figure 4.5
Structure of a variable reluctance (VR) stepper

The rotor doesn't have magnets, but because it's made of iron, its teeth are attracted to energized windings. In the figure, the A and A' windings are labeled N and S, which shows how they're energized by the controller. The teeth in the rotor align with these windings to provide a path for magnetic flux between A and A'.

4.2.2 Operation

As illustrated in Figure 4.5, only one pair of teeth is aligned with the windings at any time. When the controller energizes a second pair of windings, the rotor turns so that a different pair of teeth will be aligned. Because the teeth aren't magnetized, it doesn't matter whether a winding behaves as a north pole or as a south pole.

This can be confusing, so Figure 4.6 illustrates the rotation of a VR stepper. In this example, the stepper rotates 15° in a counterclockwise orientation.

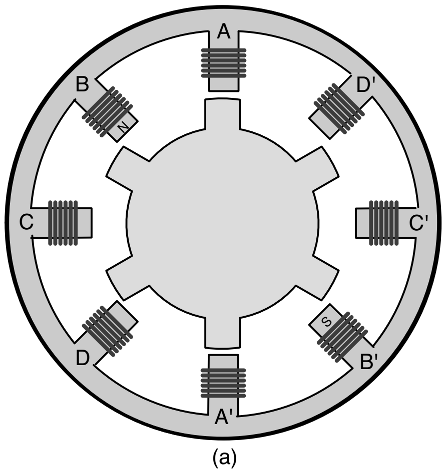
In Figure 4.6a, the controller has delivered current to the B and B' windings, and the rotor has aligned itself accordingly. In Figure 4.6b, the C and C' windings are energized. The C and C' windings attract the nearest pair of teeth, which moves the rotor 15° in the clockwise direction.

If you know the number of windings in the stator (N_w) and the number of teeth on the rotor (N_t), the step angle of a VR stepper can be computed with the following equation:

$$Step\ angle = 360° \times \frac{N_w - N_t}{N_w N_t}$$

In Figure 4.6, N_w equals 8 and N_t equals 6. Therefore, the step angle can be computed as 360(2/48) = 15°. The angular resolution can be improved by increasing the number of windings and teeth. With the right structure, the step angle can be made much less than that of a PM stepper.

Figure 4.6
15° rotation of a VR stepper



However, there's a problem. The torque of a VR stepper is so low that it can't turn a significant load. For this reason, VR steppers are not commonly found in practical systems. In fact, I've only ever seen a handful of VR motors for sale.

To make up for the shortcomings of VR steppers, engineers have designed a motor that combines the resolution of a VR motor and the torque of a PM motor. This is called a hybrid (HY) stepper.

4.3 Hybrid (HY) Steppers

A hybrid (HY) stepper provides the best of both worlds. Like a PM stepper, its rotor has magnets that provide torque. Like a VR stepper, the rotor has teeth that improve the angular resolution. As an example, Figure 4.7 depicts the JK42HW34 hybrid stepper from RioRand.

Figure 4.7
A hybrid (HY) stepper

Hybrid motors have two disadvantages. First, HY steppers can be significantly more expensive than PM steppers. Second, HY steppers are larger and heavier than PM steppers. To see why this is the case, you need to understand their structure.

4.3.1 Structure

If you followed the discussions of PM and VR steppers, HY steppers won't present any difficulty. Their rotors and stators are different from those of either stepper type, but the principle of their operation is similar.

Rotor

If you compare the HY stepper depicted in Figure 4.7 to the PM stepper in Figure 4.1, you'll see that the HY stepper is longer. The reason for this is that the HY stepper rotor has (at least) two rotating mechanisms connected to one another. These are called *rotor poles*, and Figure 4.8 gives an idea of what they look like.

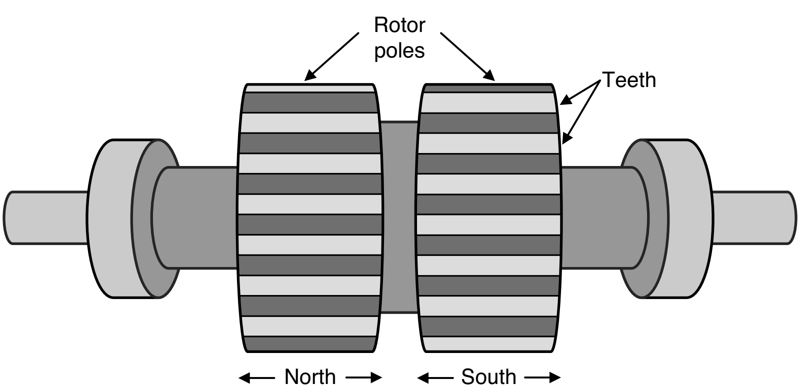


Figure 4.8
Rotor poles of an HY stepper

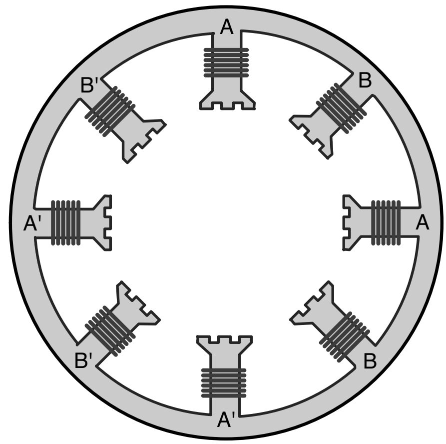
The rotor poles are magnetized so that one behaves like a north pole and one behaves like a south pole. Each pole has its own teeth, and the teeth of one rotor pole are oriented between those of the other. The angular difference between the two sets of teeth determines the step angle of the motor. The more teeth the stepper has, the better the angular resolution.

The rotor in Figure 4.8 has one pair of rotor poles, but other HY steppers may have two, three, or more pairs. Adding rotor poles increases the stepper's rotational torque and holding torque, but also increases its size and weight.

Stator

The stator windings of a PM stepper or VR stepper are too large to attract/repel the teeth of one rotor pole without repelling or attracting the teeth of the other rotor pole. For this reason, the stator of an HY stepper has teeth that are approximately the same size as the teeth on the rotor. This is shown in Figure 4.9.

Figure 4.9
Toothed stator of an HY stepper



In this figure, each winding has three teeth. In a real stepper, the windings may have many more. If a winding is energized to produce a north pole, its teeth will attract the teeth of the rotor's south pole. If a winding behaves as a south pole, its teeth will attract the teeth of the rotor's north pole.

4.3.2 Operation

Like a VR stepper, an HY stepper can have multiple phases, one for each pair of windings. But the majority of the HY steppers I've encountered are like PM motors. That is, the windings are divided into two phases: A/A' and B/B'. These are the phases labeled in Figure 4.9.

Each phase receives positive current, negative current, and zero current. When one phase is energized, its windings attract the teeth of one rotor pole. When the next phase is energized, its windings attract the teeth of the other rotor pole. Hybrid steppers commonly have 50–60 teeth on a rotor pole, which increases the angular resolution. It's common to see hybrid steppers with step angles as low as 1.8° and 0.9°.

4.4 Stepper Control

Because VR steppers are so scarce, this section focuses on controlling PM and HY steppers, which are almost always two-phase motors. Some PM and HY steppers are bipolar and have four wires. Others are unipolar and have five or six wires.

The terms *bipolar* and *unipolar* identify how the wires are connected to the motor's windings. Before you design a control circuit for a stepper, you should know whether it's unipolar or bipolar as well as the difference between the two types. For this reason, the first part of this section discusses bipolar and unipolar steppers and how to control them.

The last part of this discussion presents different methods of delivering current to a stepper's windings. These methods include half-stepping, which improves angular resolution but reduces torque, and microstepping, which improves angular resolution even further.

4.4.1 Bipolar Stepper Control

A two-phase bipolar stepper has four wires. Figure 4.10 shows how they're connected inside the stepper.

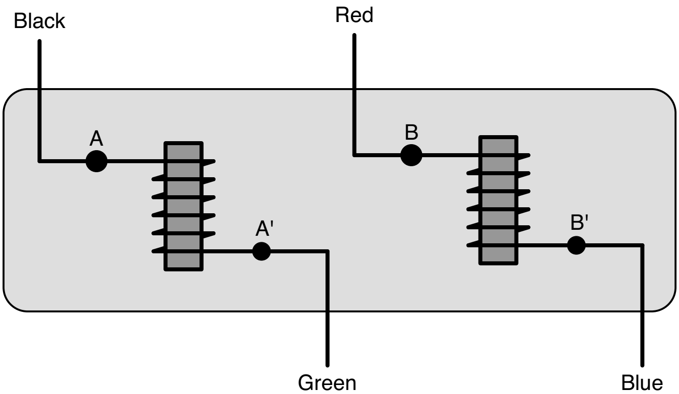


Figure 4.10
Connections of a bipolar stepper

This figure depicts electromagnets and their corresponding phases: A/A' and B/B'. As explained in Chapter 3, "DC Motors," the electromagnet's poles are determined by the nature of the current flow. If current flows from the black wire to the green wire, A will be the north pole and A' will be the south pole. If current flows from green to black, A will be the south pole and A' will be the north pole.

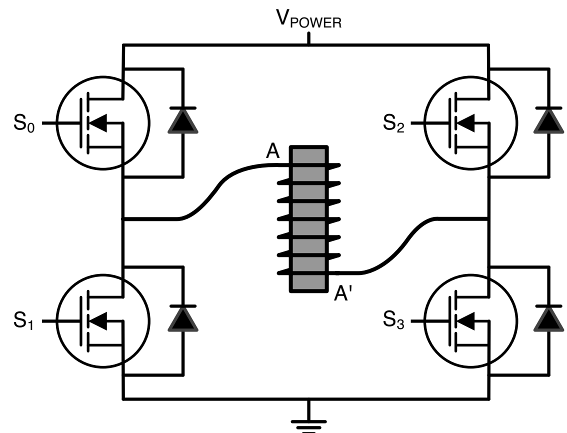
Figure 4.10 identifies the colors of the wires entering the stepper, but these aren't set by any standard. Instead, they follow a convention I've encountered in many bipolar steppers. If you find a stepper whose wires have different colors, the first place to look is the stepper's datasheet. If this doesn't help, you can test the wires with an ohmmeter—the resistance between A and A', like that between B and B', is very small. The resistance between wires in different phases is very high.

To design a circuit that drives a bipolar stepper, you need a means of reversing current in the wires. A common method of accomplishing this involves using H bridges, which were introduced in Chapter 3. An H bridge consists of four switches that, when opened and closed properly, make it possible to deliver current in the forward and reverse directions.

Figure 4.11 shows how an H bridge can be connected to control one phase (A/A') of a bipolar motor. This uses four MOSFETs to serve as the switches.

The current's direction is controlled by setting voltages on the MOSFET gates. When S_0 and S_3 are set high and S_1 and S_2 are low, current travels from A to A', making A the north pole and A' the south pole. When S_1 and S_2 are set high and S_0 and S_3 are low, current travels from A' to A, making A' the north pole and A the south pole. When S_0 and S_2 are left low, the winding is unenergized.

Figure 4.11
Controlling one phase of a bipolar stepper with an H bridge

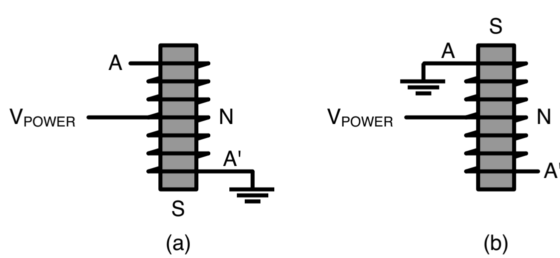


Chapter 9, "Motor Control with the Arduino Mega," and Chapter 10, "Motor Control with the Raspberry Pi," explain how stepper motors can be controlled with real-world circuitry. In both cases, the control circuit contains two H bridges capable of governing both phases of a bipolar stepper motor.

4.4.2 Unipolar Stepper Control

The wiring of a unipolar stepper motor is more complicated than that of a bipolar motor, but the goal is the same: to energize A, A', B, and B' and to set their north/south poles accordingly. To understand how this is done, consider the two circuits depicted in Figure 4.12.

Figure 4.12
Electromagnet circuits with a center tap



In both figures, V_{POWER} is connected to the center of the electromagnet's winding. This type of connection is called a *center tap*.

In Figure 4.12a, the bottom of the winding is connected to ground. Current flows from the center to ground, energizing the electromagnet and making the bottom of the winding (labeled A') the south pole. The north pole is located at the center.

Now here's the tricky part: The top of the winding isn't connected to anything, so no current flows from the top of the winding to the center. However, the entire iron core is magnetized by the current in the lower wire, which means that the top of the winding also behaves as the electromagnet's north pole. Therefore, in Figure 4.12a, A is north and A' is south.

Figure 4.12b illustrates the reverse situation. The top of the winding is connected to the ground, so current flows from the winding's center to the top. This makes the top of the winding (A) the south pole and the center of the winding the north pole. Because the entire iron core is magnetized, the bottom of the winding (A') also behaves as the north pole.

From a circuit designer's perspective, controlling a two-phase unipolar stepper requires three steps:

1. Provide V_{POWER} to the A/A' and the B/B' windings.
2. For each winding, connect one wire to ground to set the magnetic poles.
3. Leave other wires unconnected.

Figure 4.13 depicts the six wires entering the unipolar stepper: two carry power (V_{POWERA} and V_{POWERB}) and four are connected to A, A', B, or B'. Each of the latter four wires is connected to a MOSFET. When the MOSFET's gate voltage exceeds its threshold, the wire is connected to ground. Otherwise, the wire is left unconnected.

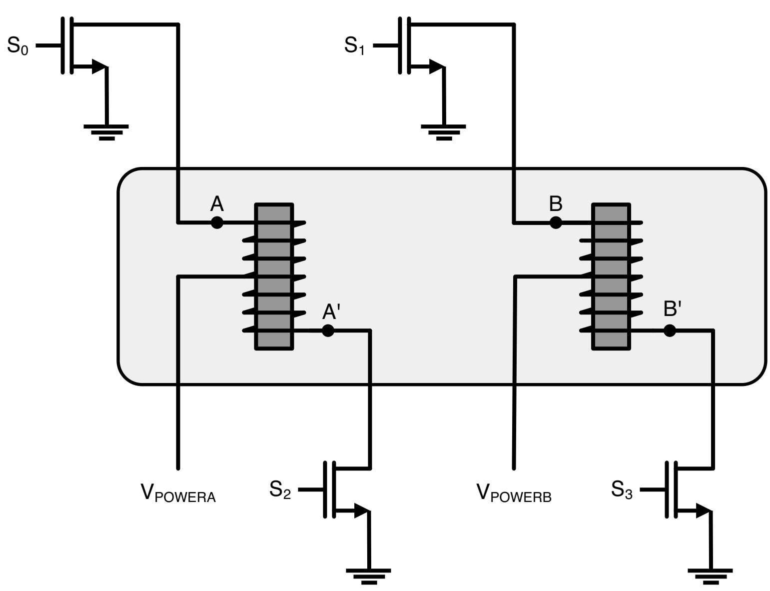


Figure 4.13 Connections of a unipolar stepper

When a MOSFET switches on, the corresponding end of the winding becomes the south pole. The opposite end of the winding becomes the north pole. For example, when voltage is applied to S_1, the resulting current makes B the south pole and B' the north pole.

> **note**
> This figure doesn't assign colors to any of the wires. This is because I've never found two unipolar steppers that use the same color convention. Check the datasheet to see how the wires should be connected.

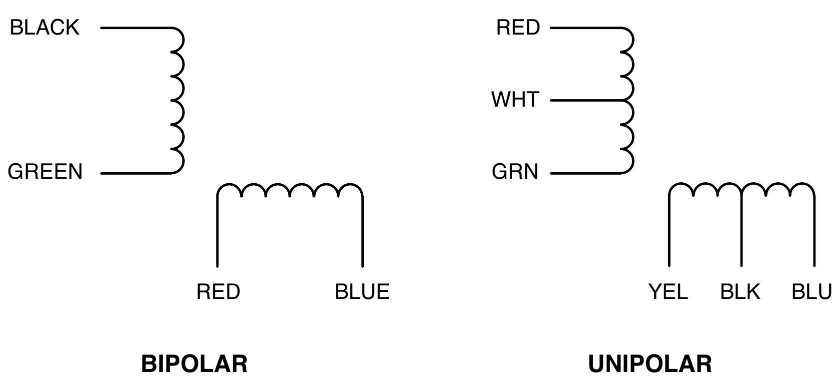
Many unipolar steppers have five wires instead of six. For these motors, the two supply wires, V_{POWERA} and V_{POWERB}, are connected together. The other four wires remain unchanged.

Unipolar steppers are easier to control than bipolar steppers because there's no need to manage the switches of two H bridges. However, when a unipolar stepper is energized, only half of the electromagnet is used. Therefore, if a unipolar stepper and a bipolar stepper have the same windings, the unipolar stepper will be half as efficient. This is why I recommend using bipolar steppers whenever possible.

If you ignore the V_{POWER} wires of a unipolar stepper, you can deliver current directly between A and A' and between B and B'. In essence, this is driving a unipolar stepper as a bipolar stepper.

I'd like to make one last point concerning unipolar and bipolar steppers. If you look at a stepper's datasheet, the wiring diagrams won't look like the diagrams presented in this chapter. They represent windings using simpler symbols, and Figure 4.14 shows a sample diagram for a bipolar stepper and a unipolar stepper.

Figure 4.14
Sample wiring diagrams in a stepper datasheet



Like many datasheets, this figure doesn't identify which winding is A/A' and which is B/B'. This isn't a significant concern. If you replace A/A' with B/B' in a control sequence, the motor's rotation won't be seriously affected.

4.4.3 Drive Modes

This chapter has explained how to operate steppers by energizing one or two winding pairs at a time, but there are a number of different ways to drive a stepper, and this discussion touches on four of them:

- **Full-step (one phase on) mode**—Each control signal energizes one winding.
- **Full-step (two phases on) mode**—Each control signal energizes two windings.
- **Half-step mode**—Each control signal alternates between energizing one and two windings.
- **Microstep mode**—The controller delivers sinusoidal signals to the stepper's windings.

Choosing between these modes requires making tradeoffs involving torque, angular resolution, and power.

Full-Step (One Phase On) Mode

The simplest way to control a stepper is to energize one winding at a time. This is the method discussed at the start of this chapter. Figure 4.15 shows what the signaling sequence looks like when controlling a stepper in this mode.

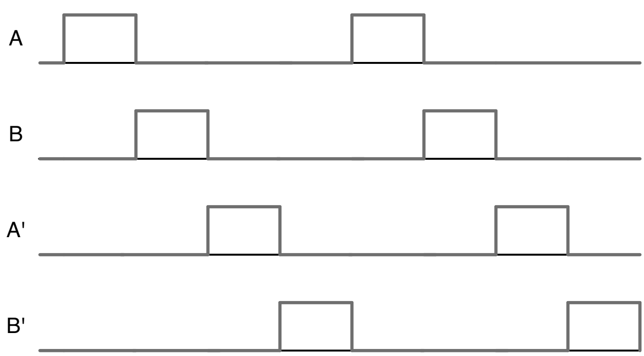


Figure 4.15
Drive sequence in full-step (one phase on) mode

With each control signal, the rotor turns to align itself with the energized winding. The rotor always turns through the stepper's rated step angle. That is, if a PM motor is rated for 7.5°, each control signal causes it to turn 7.5°.

Full-Step (Two Phases On) Mode

In the full-step (two phases on) mode, the controller energizes two windings at once. This turns the rotor through the stepper's rated angle, and the rotor always aligns itself between two windings. Figure 4.16 illustrates one rotation of a stepper motor driven in this mode.

Figure 4.17 shows what the corresponding drive sequence looks like.

The main advantage of this mode over full-step (one phase on) is that it improves the motor's torque. Because two windings are always on, torque increases by approximately 30%–40%. The disadvantage is that the power supply has to provide twice as much current to turn the stepper.

Figure 4.16
Stepper rotation in full-step (two phases on) mode

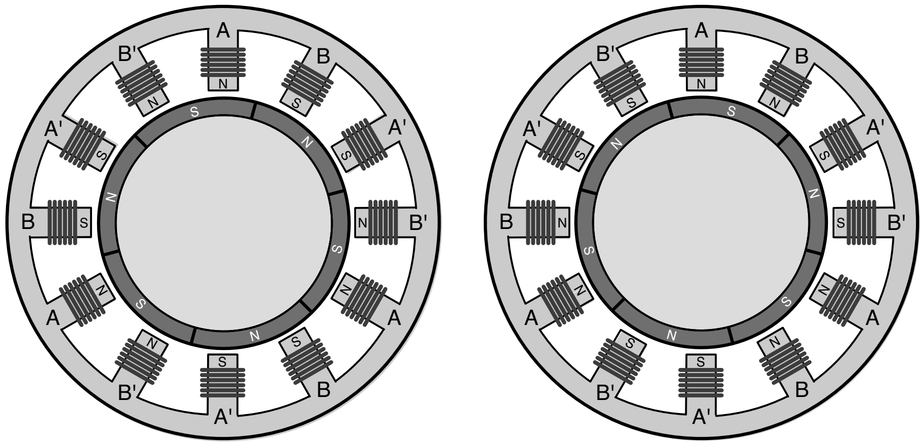
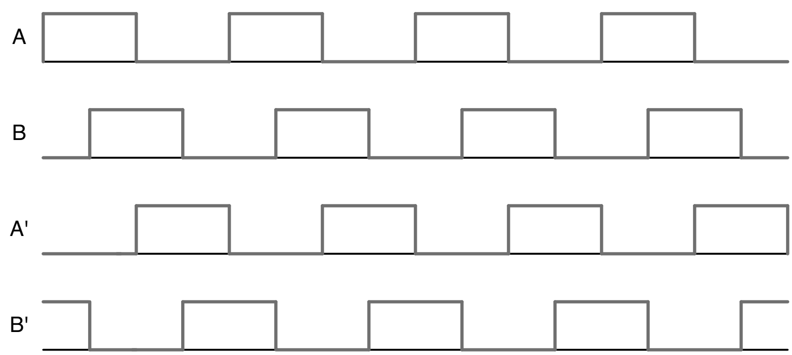


Figure 4.17
Drive sequence in full-step (two phases on) mode



Half-Step Mode

The half-step mode is like a combination of the two full-step modes. That is, the controller alternates between energizing one winding and two windings. Figure 4.18 depicts three rotations of a stepper in half-step mode.

Figure 4.19 illustrates a control signal for a stepper motor driven in half-step mode.

In this mode, the rotor aligns itself with windings (when one winding is energized) and between windings (when two windings are energized). This effectively reduces the motor's step angle by half. That is, if the stepper's step angle is 1.8°, it will turn at 0.9° in half-step mode.

The disadvantage of this mode is that, when a single winding is energized, the rotor turns with approximately 20% less torque. This can be compensated for by increasing the current.

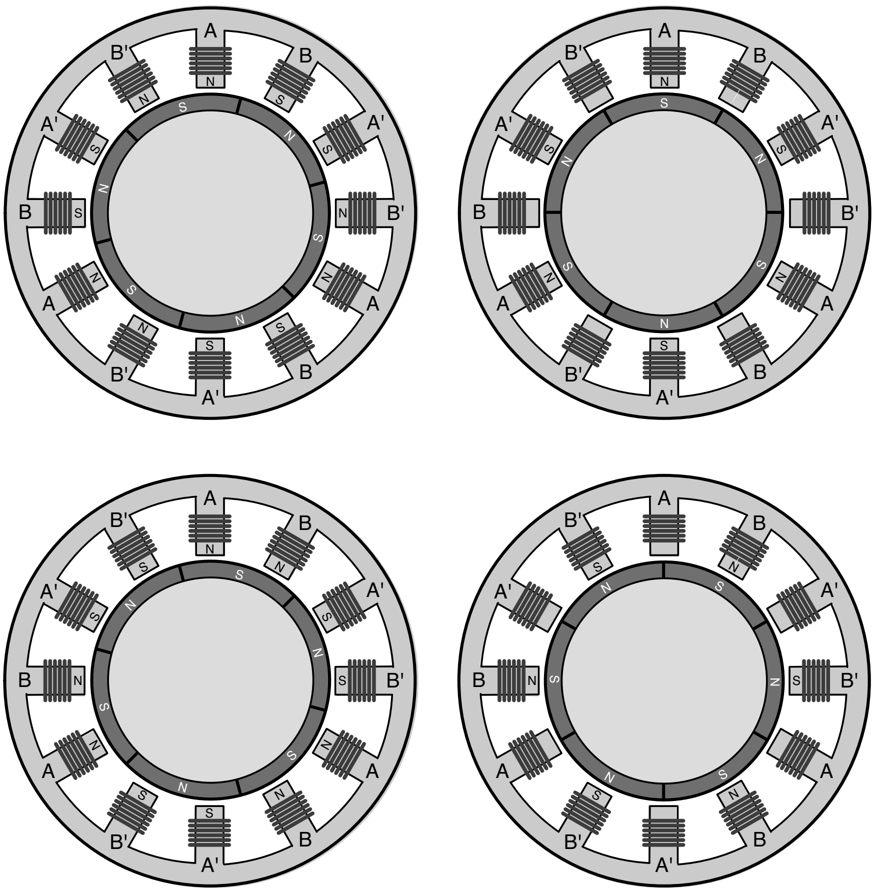


Figure 4.18
Stepper rotations in half-step mode

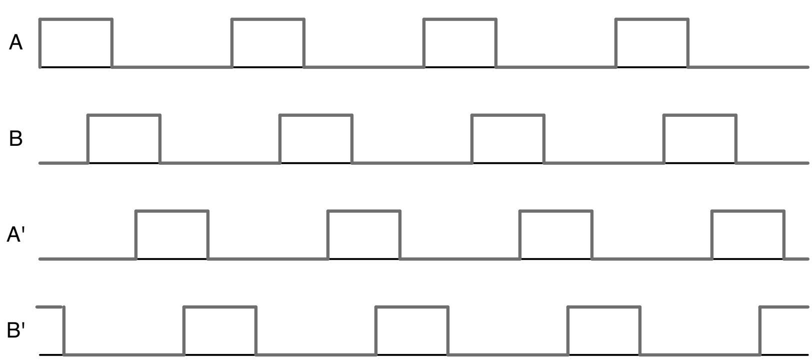


Figure 4.19
Drive sequence in half-step mode

Microstep Mode

The purpose of microstep mode is to have the stepper turn as smoothly as possible. This requires dividing the energizing pulse into potentially hundreds of control signals. Common numbers of division are 8, 64, and 256. If the energizing pulse is divided into 256 signals, a 1.8° stepper will turn at 1.8°/256 = 0.007° per control signal.

In this mode, the controller delivers current in a sinusoidal pattern. Successive windings receive a delayed version of this sinusoid. Figure 4.20 gives an idea of what this looks like.

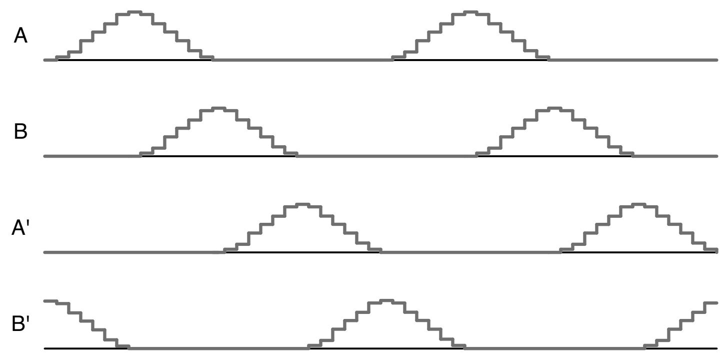


Figure 4.20 Drive sequence in microstep mode

Using this mode reduces torque by nearly 30%, but another disadvantage involves speed. As the width of a control signal decreases, the ability of the motor to respond also decreases. Therefore, if the controller delivers rapid pulses to the stepper in microstep mode, the motor may not turn in a reliable fashion.

4.5 Summary

This chapter has three goals: explain what stepper motors are, present the main types of steppers, and show how steppers can be controlled by a circuit. The first goal is straightforward. A stepper motor is a motor intended to turn at a precise angle (the step angle) and halt. Torque is usually more of a concern than speed, and the torque exerted to hold the rotor's position is called the holding torque.

The first of three types of stepper motor discussed in this chapter is the permanent magnet (PM) stepper. These motors have almost exactly the same structure as the inrunner brushless DC motors discussed in Chapter 3. One significant difference is that PM steppers have many more windings in the stator and magnets in the rotor. These additional windings and magnets make it possible for the PM stepper to turn at step angles such as 15° and 7.5°.

The second stepper type is the variable reluctance (VR) stepper. Like PM steppers, these have windings in the stator. But instead of having magnets on the rotor, the rotor of a VR stepper has teeth. A rotor can support many more teeth than magnets, so the rotor of a VR stepper turns at smaller angles than that of a PM stepper. However, because the teeth aren't magnetized, the rotor is less attracted to the stator's windings. This reduces the stepper's torque to such an extent that VR steppers are rarely encountered in practical systems.

The last stepper type combines the advantages of PM steppers and VR steppers. The rotor of a hybrid (HY) stepper is divided into two or more sections called rotor poles. Each rotor pole is magnetized to behave like a north or south pole, and each has a set of teeth around its perimeter. These teeth are attracted to similar teeth on the stator. Because of the rotor's magnetization, the HY stepper has torque similar to that of the PM stepper. Because of the rotor's teeth, the HY stepper has angular resolution similar to that of the VR stepper. Common step angles of an HY stepper are 1.8° and 0.9°.

When you're designing a control circuit for a stepper, it's important to know whether the motor is bipolar or unipolar. A bipolar stepper has four wires that correspond to the A, B, A', and B' windings. These require H bridges to deliver current in the forward and reverse directions. Unipolar steppers have additional wires that deliver power to the windings. Unipolar steppers are easier to control than bipolar steppers but are less efficient.

The drive mode identifies how the controller energizes the stepper's windings. The simplest drive mode is full-step (one phase on), in which only one winding is energized at a time. For increased torque, the full-step (two phases on) mode energizes two windings at a time. For twice the angular resolution, the half-step mode alternates between energizing one and two windings.

The fourth drive mode is microstep mode. In this mode, the controller divides its control signals into multiple signals of sinusoidal shape. This turns the rotor in tiny step angles to ensure that the rotation is as smooth as possible. Microstepping has been analyzed by many engineers and researchers, but if your system needs smooth motion control, you may want to consider a servomotor instead of a stepper motor. The next chapter presents this fascinating topic.

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