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Motor Control Fundamentals

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- Understand motor control algorithms

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Motor Control Fundamentals

Qorvo Special Edition

by David Schnaufer, David Briggs, Marc Sousa, and Jose Quinones

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Introduction

Consumers are demanding more power, smaller form factors, and higher efficiency in their home appliances, garden tools, and motor-driven products.

Like many consumer electronics products, there is also an expectation of lower cost, higher reliability, and a high ease of use. Brushless DC (BLDC) motors help address these needs.

To meet this demand, fully optimized, highly integrated system-on-chip (SOC) devices are required. Today's SOC devices are fully programmable motor controllers that enable highly efficient and compact solutions to help meet stringent green energy efficiencies required by 21st-century manufacturers. This book provides valuable details on how these SOCs work to create efficiencies and where they're used.

Foolish Assumptions

This book is written for both technical and nontechnical readers. If you're an executive, salesperson, or design engineer, this book is for you. All you need is a general curiosity about DC motor controller power management. (Okay, that's a pretty specialized interest, but we're hoping it's one of yours!)

Icons Used in This Book

Throughout this book, we occasionally use icons to call attention to important information. Here's what you can expect:

REMEMBER

The Remember icon points out important information that you'll want to recall later — the key points of the book.

TECHNICAL STUFF

Anything marked with the TechnicalStuff icon is material that the technical geeks in the room will especially enjoy. (You know who you are.)

TIP

This icon identifies practical advice that you may be able to use in your own work.

Beyond the Book

Although this book is full of good information, we could only cover so much in 24 pages! So, if you find yourself wanting more after reading this book, just go to `www.qorvo.com/products/power-management/intelligent-motor-controllers`, where you can get to more information about Qorvo's DC motor control products.

Where to Go from Here

Whether you're new to motor controls or a seasoned design engineer looking to use the latest technology in your designs, you'll find this book useful.

Each chapter in this book stands on its own, so you can skip around if you like. If you're familiar with the topics in a chapter, go ahead and skip it. We provide cross-references to information in other chapters of the book, so you can always find what you're looking for.

IN THIS CHAPTER

» Identifying the types of electric motors

» Looking at the rise of BLDC/PMSM motors

» Understanding how motor controllers work

Chapter 1
DC Motor Controller Basics

Motors play vital roles in an extraordinarily wide range of products — from cars to refrigerators and yard tools. According to IMS Research, 11 billion electric motors are added to the market each year, and they account for 45 percent of all electrical energy consumption.

Within this market, a profound shift is taking place, from traditional brushed DC motors to brushless motors. A variety of factors are at work, including the drive to greater energy efficiency across many industries. In addition, the rise of untethered applications such as portable tools require smaller, lighter motors that consume less power, so batteries last longer.

Brushless motors offer a wide range of advantages, such as greater efficiency, lighter weight, and more precise control. However, unlike traditional brushed motors, they require electronic control. Accordingly, the motor control market is growing along with the transition to brushless motors.

In this chapter, we describe the various motor types and explain how new technology is enabling DC motor usage in many different types of products. We also explain how DC brushless motors function.

Explaining the Types of Motors

Several main types of motors are available today: brushed DC motors, stepper motors, induction motors, and brushless DC (BLDC) motors/permanent magnet synchronous motors (PMSMs). Figure 1-1 summarizes them.

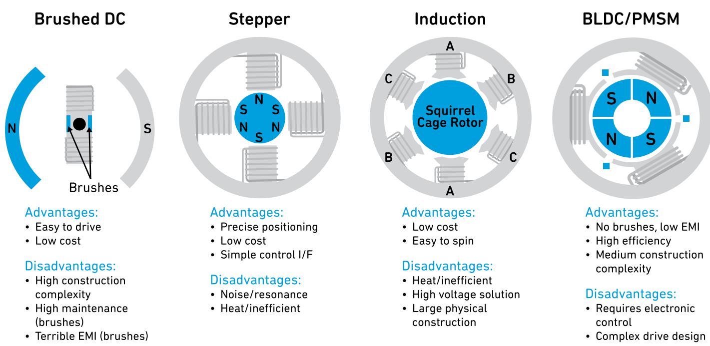


FIGURE 1-1: Types of motors.

Two closely related types of brushless motors — BLDC motors and PMSMs — have become increasingly popular for many applications. These motors eliminate the need for brushes and a commutator, which makes them much more efficient than brushed motors and effectively increases motor life.

In a brushed motor, *commutation* (the process of switching current flow in the phases in order to generate a revolving magnetic field, which produces motion) is produced by the brush/commutator interface. This interface causes friction and arcing, both of which are undesirable.

BLDC motors and PMSMs eliminate the brushes and the commutator by employing an electronically generated revolving magnetic field. This is accomplished by using external circuits to modulate the voltages and currents delivered to the phases.

REMEMBER

Although these circuits add some complexity, BLDC motors and PMSMs offer major advantages over traditional brushed motors. Their electronic commutation schemes improve energy efficiency by 20 percent to 30 percent over brushed motors running at the same speed, while being more durable, smaller, lighter, and quieter.

Understanding the Rise of BLDC Motors and PMSMs

In brushed motors, the windings are on the *rotor* (the rotating part of the motor). In brushless motors, they're on the *stator* (the stationary part of motor). Positioning the windings on the stationary portion of the electric motor and the permanent magnets on the rotor, eliminates the need for brushes. In BLDC motors or PMSMs, current to the fixed stator coils is controlled from the outside by an electronic controller.

These BLDC motors or PMSMs offer significant advantages over the other types of motors, which is why they're gradually replacing brushed DC and induction motors in many applications. In fact, BLDC motors and PMSMs have already been widely adopted in cars, power tools, and household appliances.

TIP

BLDC motors and PMSMs have several advantages over conventional brushed motors. They're energy-efficient, smaller, lighter, quieter, more reliable, and more durable. Plus, they offer precise speed control and are better for variable-speed applications. Finally, they have superior speed versus torque characteristics.

BLDC motors and PMSMs are commonly used where precise speed control is necessary. We explain more about how this works in Chapter 2, but the basic idea is shown in Figure 1-2. A Hall sensor or rotary encoder detects the position of the rotor and is used to measure speed by analyzing sensor output polarity and the rate of change. A three-phase BLDC motor or PMSM like the one in Figure 1-2 requires three Hall sensors.

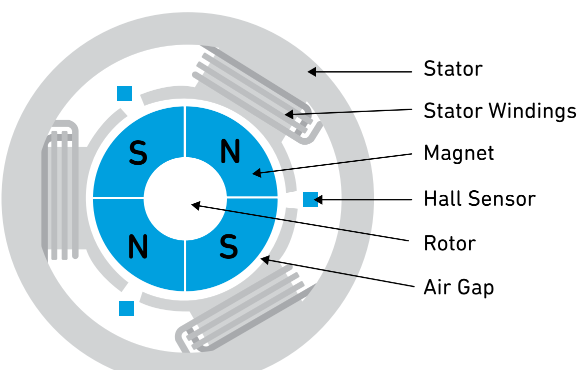


FIGURE 1-2: A three-phase BLDC motor or PMSM motor.

To deliver their advantages, these motors require additional complexity for control. Because BLDC motors or PMSMs use electronic commutation, they need supervisory circuits to ensure precise timing of coil energization for accurate speed regulation, adequate torque control, and greater efficiency. In many new motor applications that require adjustable speed and accurate position control, this drive circuitry is a must.

The good news is that all the required analog functions are integrated with a powerful microcontroller into a single motor control device that drives external (or, in some cases, internal) power metal-oxide semiconductor field-effect transistors (MOSFETs). This single device simplifies design and lowers component cost (refer to Figure 2-2).

Learning How Motor Controllers Work

The motor controller does several very important jobs. Its most basic function is to regulate the speed and direction of the electric motor by manipulating the voltage applied to its phases. But the controller also:

- Regulates motor speed, torque, or power output
- Controls startup or soft starts
- Protects against circuit faults
- Smooths motor acceleration and deceleration
- Protects against overloads

To accomplish all this, motor controllers must be much more intelligent than in the past. For example, they can increase efficiency by monitoring the load and adjusting the torque to match. The increased efficiency also reduces motor heat, noise, and vibrations.

A BLDC motor or PMSM with a conventional three-phase inverter has traditionally required multiple integrated chips (ICs) to provide the various motor controller functions (refer to Figure 2-3). These include a microcontroller, pre-driver power stages to drive power MOSFETs, differential amplifiers for amplifying sensed motor currents, comparators to extract back-electromotive force (BEMF) information, and switching and linear regulators to step down voltages.

Thanks to advances in semiconductor technology, many of those functions are now being combined into a single compact control device.

IN THIS CHAPTER

- » Looking at the brushless motor drive types
- » Choosing between sensored and sensorless motors
- » Understanding the BLDC motor control system
- » Considering the shrinking motor controller

Chapter 2 Understanding Motor Controls

In this chapter, we delve further into brushless DC (BLDC) motors, which are replacing other kinds of motors in many applications (see Chapter 1). We take a look at BLDC motors, permanent magnet synchronous motors (PMSMs), and how they're controlled.

Comparing the Brushless Motor Drive Types

There are many types of brushless motors. The single-phase and three-phase BLDC motors/PMSMs are the most widely used.

TECHNICAL STUFF

Both the BLDC motors and the PMSMs work on the principle of a synchronous motor. As commutation in the stator phases creates a revolving magnetic field, the rotor magnetic poles try to catch up to synchronize, thus starting the motor action. The rotor continues to pursue the stator at every commutation, so the motor continuously moves.

However, these two DC-type motors have a different geometry of their stator windings, so they produce a different back-electromotive force (BEMF) response.

The BLDC BEMF response is trapezoidal. This means that a different control waveform is required to control each of these motor types, because the control should match the motor type. Figure 2-1 compares the waveforms for the two types.

In contrast, in PMSMs, the coils are wound in a sinusoidal fashion, resulting in a sinusoidal BEMF signature (resembling three sinewaves phased 120 degrees apart). To maximize performance, these motors generally use sinewave commutation.

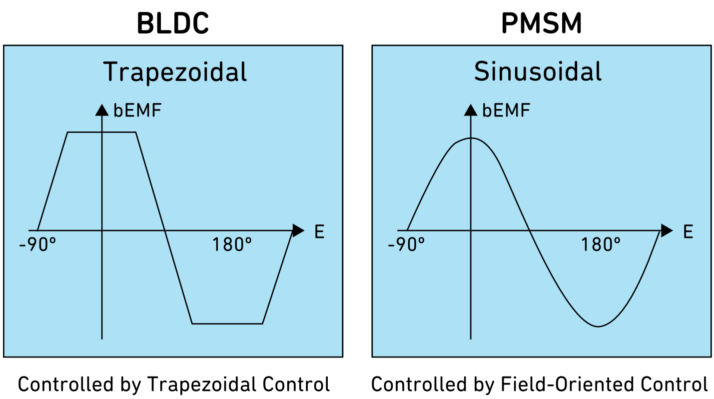


FIGURE 2-1: BEMF for BLDC and PMSM motors.

Back-electromotive force

BLDC motors/PMSMs generate BEMF by their windings when operated. When a current-carrying conductor is placed in a magnetic field, or if the conductor cuts the magnetic field, an electromotive force (EMF) is induced or produced in a conductor. If a closed path is provided, current flows through it. In any motor, as a result of motion, the EMF produced is known as *back-EMF*, because the EMF induced in the motor opposes the EMF of the generator.

Field-oriented control

Achieving the sinusoidal waveform to control the PMSM motor requires a *field-oriented control* (FOC) algorithm. FOC, or vector control, is a technique for variable frequency control of the stator in a three-phase motor using two orthogonal components. One defines the magnetic flux generated by the stator, while the other corresponds to the torque as defined by the speed of the motor determined by the rotor position.

TECHNICAL STUFF

FOC is typically used to maximize the efficiency of PMSM three-phase motors, which operate in sinusoidal mode. In sinusoidal commutation, all three wires are permanently energized with a sinusoidal current that is 120 degrees apart on each phase. This creates a north–south magnetic field that rotates inside the motor cage. The FOC algorithm requires the motor position and speed for calculation.

The sinusoidal controller for the PMSM is more complex, so it's costlier than the BLDC trapezoidal controller. This increased cost does come with some advantages, such as lower noise and less harmonics in the current waveform. However, the main advantage of the BLDC is that it's easier to control. The choice of which motor is best to use depends on the application.

TIP

It's possible to use either kind of commutation with either type of motor. However, a BLDC motor will likely perform better with a six-step trapezoidal algorithm, whereas a PMSM will perform better with sine wave commutation algorithms.

Choosing Between Sensored and Sensorless Motors

In this section, we take a closer look at two very important types of BLDC motors and PMSMs: sensored and sensorless.

Sensored motors

Sensored BLDC motors/PMSMs are used in applications that require the motor to start up under load. They use Hall sensors embedded into the motor stator. The sensor is essentially a switch with a digital output equal to the sensed magnetic field polarity (that is, HI for north and LO for south).

The motor needs a separate Hall sensor for each phase. A single-phase BLDC motor/PMSM only needs one Hall sensor; a three-phase BLDC motor/PMSM needs three. With these sensors, the controller can obtain the rotor position, determine which sector (for example, magnetic field polarity) needs to be energized, and determine when to apply the energization scheme.

TIP

Recently, Hall sensors offering absolute rotor position with an increasing number of position points have reached the market.

Sensorless motors

Hardware-based sensing adds cost for the sensors, wiring, and manufacturing, and can reduce motor manufacturing yield. For these reasons, sensorless motors have become popular in many applications.

TECHNICAL STUFF

Sensorless motors require algorithms to operate using the motor as the sensor. They rely on BEMF information. In the conventional six-step trapezoidal commutation algorithms that control BLDC motors, only two phases are energized at any given time, as shown in Figure 2-2. The other phase is floating and offers a window into the motor's BEMF. By sampling this BEMF, the rotor position can be deduced, eliminating the need for hardware-based sensors.

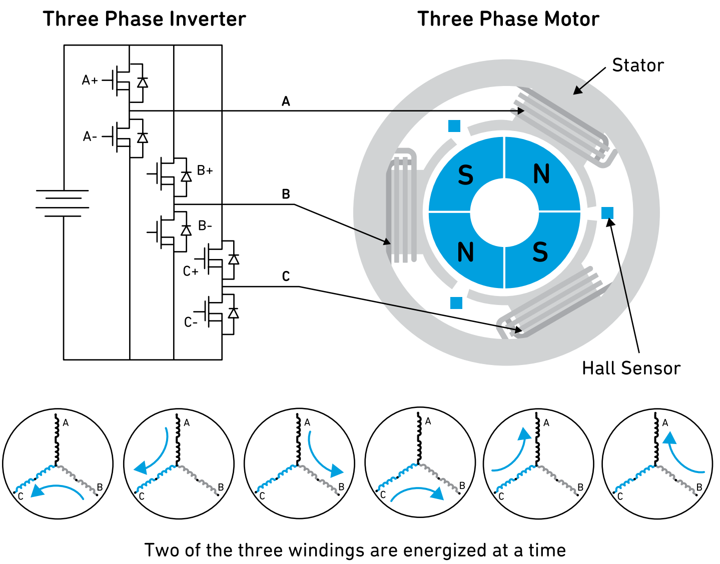


FIGURE 2-2: Three-phase BLDC motor with motor rotation.

Regardless of the motor topology, controlling these machines requires knowing the rotor position so the motor can be efficiently commutated. If the rotor's revolving magnetic field is generated in a way that fights the stator's permanent magnets, both the motion and the efficiency of the system suffer. Some motors use sensors and sensored algorithms to obtain the rotor position; others are sensorless and derive the position from mathematical models (sensorless algorithms).

The one drawback of sensorless algorithms occurs during startup, when the motor speed is zero. Because BEMF is directly proportional to motor speed, when the speed is zero, so is the BEMF. Without BEMF, the rotor position cannot be deduced. This issue is being solved by novel algorithms in which high-frequency signals are injected into the three phases to deduce rotor position.

TIP

Choosing between sensored and sensorless most commonly depends on cost. The choice of BLDC versus PMSM is generally based on performance, as well as cost and other factors.

Sensorless control reduces cost because it eliminates the need for extra hardware and brings the motor manufacturing yield very close to 100 percent. As a result, sensorless motor control is common in low-cost, variable-speed motor applications such as fans, refrigerator compressors, air conditioners, and many garden tools. However, applications that need high torque at startup — like e-bikes and many power tools — require sensored motors.

The combination of PMSMs with FOC generally provides the highest performance. However, PMSMs generally cost more than BLDC motors (although the difference is decreasing) and control is more complex. Robotics and servo applications will likely benefit from PMSMs.

Examining the Shrinking Motor Controller

Many of today's integrated motor control and drive devices are highly complex. They need analog circuitry such as differential amplifiers that sample phase currents and an analog-to-digital (ADC) converter to transfer these values to the digital domain. In parallel to those two blocks, they need comparators to sample the current and protect the system from over-current events. They use programmable digital-to-analog converters (DACs) as the reference, and employ other analog blocks, such as single-ended amplifiers, to gather phase voltages.

Instead of implementing all these functions using discrete components, it's now possible to integrate these blocks into a single device. Doing so guarantees a compact solution for all applications. Product engineers no longer have to piece together many individual components; instead, they can use a plug-and-play system-on-chip (SOC) with flexible software configurability.

As Figure 2-3 shows, the microcontroller core has an analog front-end, power drivers, power management, pulse width modulated (PWM) generators, and sequence-driven data acquisition. The power manager also handles system functions including internal reference generation, timers, hibernate mode management, and power and temperature monitoring.

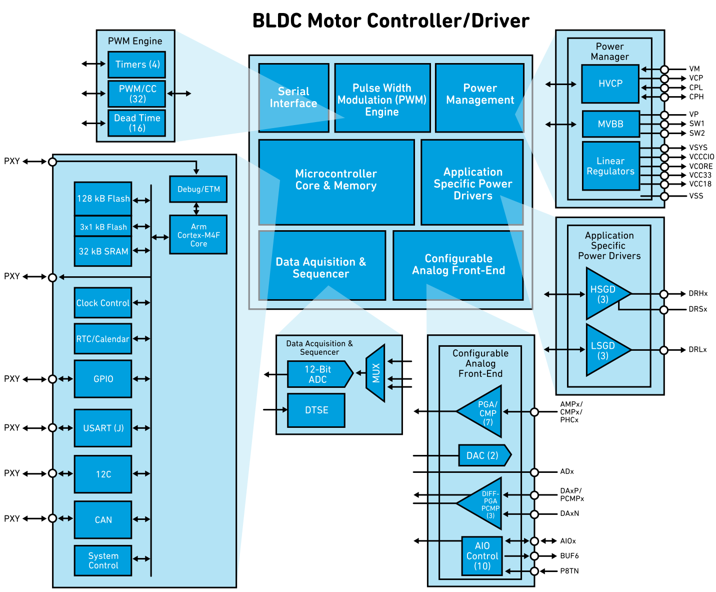


FIGURE 2-3: Basic functional blocks of today's highly integrated BLDC motor controller/driver.

IN THIS CHAPTER

» **Knowing what motor control algorithms are**

» **Seeing how controllers process sensor information**

» **Making sense of pulse width modulation**

» **Considering typical applications for BLDC motors/PMSMs**

Chapter 3 Understanding Motor Control Algorithms

In this chapter, you find out about motor control algorithms and how they work. You also read about some real-world examples in various areas.

An *algorithm* is a set of instructions designed to perform a specific task. Computer programs are essentially groups of algorithms.

In brushless DC (BLDC) motors/permanent magnet synchronous motors (PMSMs), software algorithms improve efficiency and reduce operating cost by monitoring and controlling motor operations. In sensored BLDC motors/PMSMs, some of the primary functions of the main algorithm are as follows:

- Motor initialization
- Hall sensor rotor position detection
- Switch signals checking for increasing the current reference or decreasing the current reference
- Checking for the motor rotation direction

Learning How Controllers Process Sensor Information

A BLDC motor's stator has three Hall sensors, at 120 degrees out of phase with each other (see Chapter 2). When their digital output data is combined, it produces a three-bit number that represents the rotor position.

TECHNICAL STUFF

As shown in Figure 3-1, a three-bit code can be used to represent an opcode number between 1 and 6. A three-phase BLDC motor has six states (the six possible current states derived from the three-phase outputs). The sensors are placed to provide a three-bit data output using six of the eight opcodes (1 through 6). This information is useful because the controller can determine when an illegal opcode (0 and 7) has been issued and act on the legal opcodes (1 through 6).

Here's how to read the lookup table in Figure 3-1:

- When the Hall sensor W, V, U equals opcode 1-0-1, opcode-5, sector 0 is energized.
- When the Hall sensor W, V, U equals opcode 1-0-0, opcode-4, sector 1 is energized.

And so on, for each of the other possible states.

Each Hall sensor is positioned on a rotor so that one change state occurs per rotor sector. As shown in Figure 3-1, the algorithm obtains the Hall sensor opcode and decodes it. As soon as the Hall sensor opcode changes in value, the controller must change the energization scheme to achieve commutation. The microcontroller uses the opcode to extract energization information from the lookup table. After the three-phase inverter is energized with the new sector command, the magnetic field moves to the new position, pushing the rotor along with it. This process repeats endlessly while the motor operates.

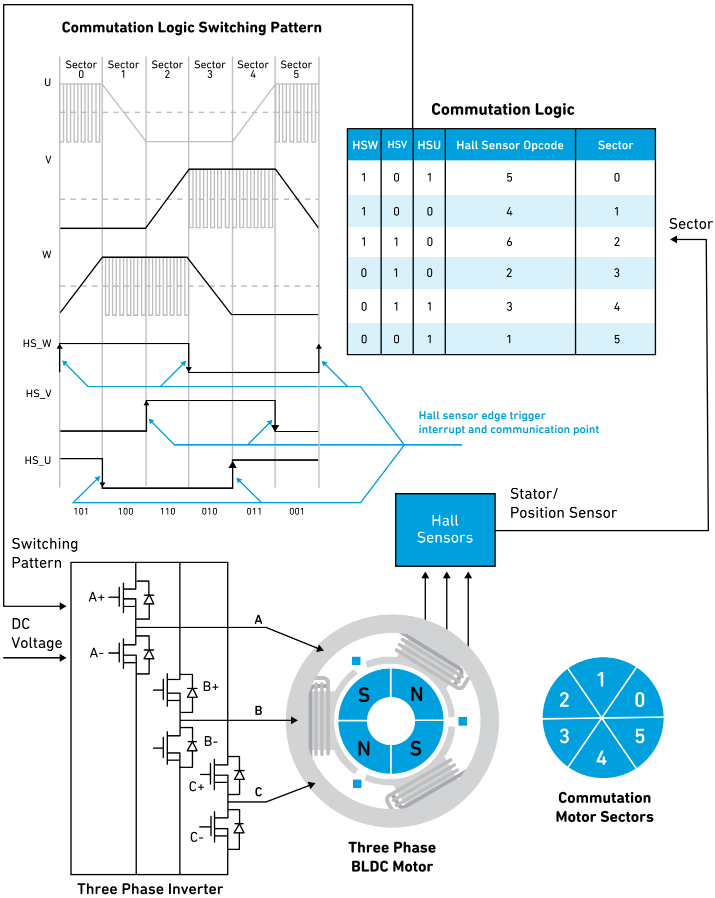


FIGURE 3-1: A block diagram of commutation logic functionality.

Understanding Pulse Width Modulation

Some motors only require one speed, so they need only a constant DC voltage into the inverter, as shown in Figure 3-1. However, many products today, including many power and gardening tools, require variable motor speeds. Such motors use pulse width modulation (PWM) to vary the motor speeds. PWM offers precise control over the motor's speed and torque and allows for variable speeds.

TECHNICAL STUFF

PWM is a square wave signal with a constant frequency, as shown in Figure 3-2. PWM converts the inverter DC voltage into a modulated effective voltage. For example, a 12V battery can be used to apply any voltage from 0V to 12V to the motor by using a PWM control signal that's between a 0 percent and 100 percent duty cycle. Algorithms take advantage of this control methodology to efficiently limit the startup current and to regulate motor speed and torque.

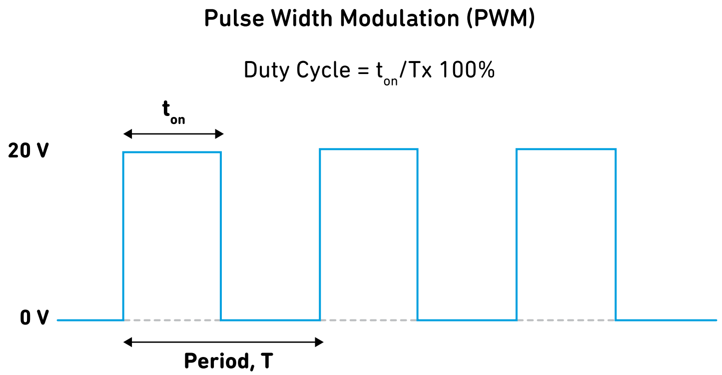
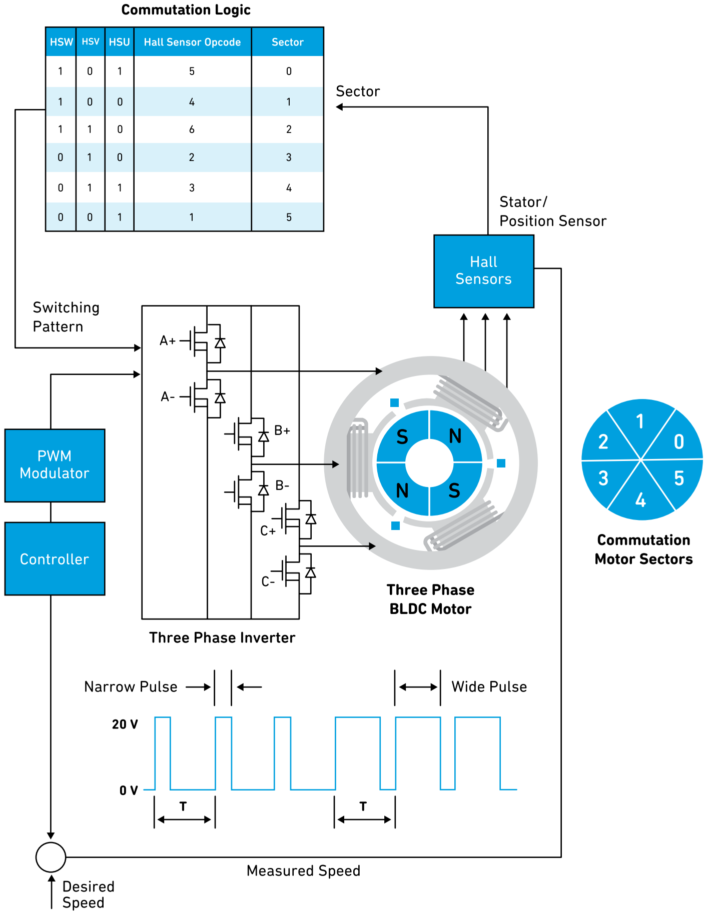


FIGURE 3-2: Pulse width modulation.

PWM switching frequency is an important design factor to keep in mind during power stage development. Raising the switching frequency increases switching losses but improves current regulation in low-inductance motors. Lowering the switching frequency increases current ripple, which translates into torque ripple (for example, vibrations). Application voltage and motor inductance will steer the designer into choosing the correct PWM switching frequency. As a rule of thumb, the higher the voltage or current, the lower the switching frequency will need to be.

Continuing to change the PWM signal changes the duty cycle, as shown in Figure 3-3. It gives a range of voltage values, which in turn changes the speed of the motor. You can use these PWM duty cycle changes to vary the voltage into the motor winding.



HSW	HSV	HSU	Hall Sensor Opcode	Sector
1	0	1	5	0
1	0	0	4	1
1	1	0	6	2
0	1	0	2	3
0	1	1	3	4
0	0	1	1	5

FIGURE 3-3: A block diagram of commutation logic functionality with PWM applied.

Identifying Typical Applications for BLDC Motors/PMSMs

In this section, we look at some common uses for BLDC motors/PMSMs in some key product types: power tools, garden tools, white goods, and vehicles.

Power tools

Battery-powered cordless power tools offer users the freedom they want, especially if they use long-lasting, high-energy-density batteries. This convenience and freedom have driven the sector's rapid migration to BLDC motors/PMSMs.

An electric power tool is traditionally built with a universal AC/DC brushed motor, a switch or potentiometer, and a cord to connect the tool to the power outlet. For almost a century, this approach was adequate for designing and implementing an incredible variety of power tools. However, in cordless power tools, it's imperative to consider operating time, which is limited by the battery's performance.

Drills, circular saws, and similar tools need to start under load, so they use sensors and sensor-based algorithms. Most use BLDCs and six-step trapezoidal commutation schemes. However, many other power tools, like grinders and oscillating saws, use sensorless algorithms, as do the vast majority of garden tools like leaf blowers, string trimmers, and hedge trimmers. Designers are always looking to improve power tool performance, so PMSM and field-oriented control (FOC) implementations are starting to show up in higher-cost, higher-performance power tools.

Garden tools

Garden tools include lawn mowers, line trimmers, chain saws, leaf blowers, and edge-trimmers. They may look like a subset of power tools, but whereas conventional power tools such as drills and saws have been electric, garden tools have been mostly powered with gas combustion engines, with the occasional corded version making it into our tool sheds.

Reliable battery-operated garden tools have had a slow adoption. They started to become available about 20 to 30 years ago but were weak and not very impressive. However, with the technology advancements in BLDC motors/PMSMs and high-voltage batteries, their fate has been reversed!

Using 40V to 80V battery technologies, today's garden tools perform as well as their gas-powered counterparts. These higher voltages allow for even lawn mower tractors powered with BLDC motors/PMSMs!

White goods

The white goods industry brings us many of the appliances in our homes, such as refrigerators, washing machines and dryers, vacuum cleaners, and ceiling fans. Traditionally, all these appliances have used AC induction motors that didn't need a special driver/controller. However, with the advent of power-saving initiatives, as well as users' desire for variable speed in some appliances, AC induction motors have been steadily replaced by BLDC motors/PMSMs.

In refrigerators, the compressor, fan, and water pump are all migrating to BLDC motors/PMSMs. Power saving is of paramount importance because these appliances are included in green power initiatives. At the same time, it's highly desirable to reduce vibration and audible noise as much as possible inside the home environment. Thanks to low-ripple PMSMs with FOC commutation, refrigerators are now not only more energy efficient and reliable, but also quieter and, therefore, less obnoxious to cohabitate with. Ceiling fans, hood extractors, and vacuum cleaners are also taking advantage of these technological improvements.

Automotive

Of all the machines you own, the one with the largest number of motors will most likely be your transportation machine — your car! Power seats, power windows, power mirrors, door locks, wipers, water pumps, oil pumps, fans, blowers . . . you name it. Your car probably contains anywhere from a couple dozen to as many as 50 electric motors, and they all need to be driven and controlled.

Traditionally, all the motors in cars have been simple brushed DC motors. However, concerns about energy use and climate change have heralded a new era focused on energy conservation. Any energy wasted as heat must be generated by burning more fossil fuel, so using more efficient motors can reduce your carbon footprint. Even though each motor only accounts for a relatively small amount of energy, if you multiply that by the number of motors in each car and the fact that there are about 1.4 billion cars in the world, it becomes apparent that migrating brushed DC motors to BLDC motors/PMSMs will make a big difference.

IN THIS CHAPTER

» Recalling BLDC motor and PMSM basics

» Reviewing DC motor phases and speeds

Chapter 4

Ten Key Important Facts and Trends in Motor Control

Here are ten important facts and trends in motor control:

- **Due to technological advancements, integration is taking over the motor control market.** Brushless DC (BLDC) and permanent magnet synchronous motors (PMSMs) of every size and power density are quickly replacing motor topologies such as brushed AC/DC and AC induction.
- **The BLDC/PMSM motors are mechanically the same structure except for the stator windings, which are wound using a different geometry.** The stator is always opposite of the motor magnets. These motors deliver high torque at low speeds, which makes them a good fit for servo motor applications.
- **BLDC motors and PMSMs eliminate the need for brushes and a commutator to move the motor, making them more efficient and reliable than brushed motors.**

- **BLDC motors and PMSMs use software control algorithms instead of brushes and a mechanical commutator to provide motor movement.**
- **The mechanical structure of the BLDC motor and PMSM is simple.** The motor has an electromagnet winding on a nonrotary stator. The rotor is made using permanent magnets. The stator can be inside or outside, with the stator always being on the opposite side of the magnets. However, the stator is always the part that stays put and the rotor is the part that moves (rotates).
- **Brushless DC motors can have one, two, three, four, or five phases.** They may have different names and different actuation algorithms, but they're all brushless in nature.
- **Some brushless DC motors have sensors to aid in obtaining their rotor position.** Software control algorithms use these sensors (Hall sensors or encoders) to aid in motor commutation or motor movement. These sensored DC brushless motors are required when the application needs to start under high loads.
- **If a brushless DC motor lacks sensors to obtain its rotor position, mathematical models are used instead.** These mathematical models represent sensorless algorithms. In sensorless algorithms, the motor is the sensor.
- **BLDC motors and PMSMs offer major system advantages over brushed motors.** Their ability to use electronic commutation schemes to drive the motor improves energy efficiency by 20 percent to 30 percent.
- **Many products today require variable motor speeds**. These motors require pulse width modulation (PWM) to vary the motor speeds. PWM offers precise control over the motor's speed and torque and allows for variable speeds.

Highly Integrated Power Application Controllers (PAC™)