BLDC Motor Control Design & Safety Guide

PAC52xxx/PAC55xxx

Table of contents

Integrating Cutting-Edge Safety Features for Rugged BLDC Motor Control Applications

Get help integrating safety features with a plug-and-play solution from Qorvo

Next-gen battery-powered tools need motors and controllers that can tap the high voltages needed to drive outdoor tools while integrating safety features to protect the user and equipment. This is where Qorvo steps in, with its expertise in high-voltage controllers for brushless DC (BLDC) motors. The highly integrated portfolio of intelligent PAC (power application controller) SoCs (system on a chip) can implement a BLDC or PMSM (permanent magnet synchronous motor) programmable motor controller and driver into a single IC to control today's power tools across voltages ranging from 44V to 600V.

BLDC motors are widely used in applications requiring high efficiency, reliability and precise control. When these applications involve critical safety functions, they often need to meet stringent safety standards, such as Class B certifications. Here are some key areas where BLDC motor control applications require Class B safety certifications:

Power Tools: These include power drills, saws and even inspection and mapping drones. They provide the flexibility needed for lawn and garden maintenance with the latest electric mowers, trimmers and leaf blowers.

Automotive:

- Electric power steering (EPS): ensures the steering system operates safely, reducing the risk of accidents.
- Electric vehicles (EVs): motor control systems for propulsion and various subsystems need to meet high safety standards to ensure passenger safety and vehicle reliability.
- E-Bikes and Autonomous Vehicles: where precise control and power efficiency are essential.

Industrial automation:

- Robots and automated machinery: ensures safe and reliable operation in manufacturing processes and tracking inventory in warehouses, protecting both workers and equipment.
- Conveyor systems: Requires safe and consistent operation to handle materials without incident.

Consumer appliances:

- Washing machines: Ensures safety in motor control, preventing overheating or mechanical failures.
- Refrigerators: Reliable motor operation is critical for maintaining consistent temperatures and avoiding spoilage.

Home automation and smart devices

- HVAC systems: safe motor control is essential for reliable and efficient heating, ventilation and air conditioning.
- Smart locks and security systems ensure reliable operation to maintain security and prevent unauthorized access.

Aerospace and defense

- Drones: motor control systems require high reliability and precision for navigation and stability.
- Aircraft actuators: ensures safety and reliability in controlling various aircraft components.

Key Aspects of Class B Safety Certifications

To achieve Class B safety certifications, BLDC motor control systems must address several critical aspects:

- **Fault detection and management:** implementing robust fault detection mechanisms to handle issues such as overcurrent, overvoltage and thermal overload.
- **Redundancy**: incorporating redundant systems to ensure continued operation in case of a failure.
- **Isolation**: ensuring proper electrical isolation to prevent safety hazards.
- **Safety monitoring**: continuous monitoring of the motor's operational parameters to detect and mitigate potential failures.
- **Compliance testing:** rigorous testing to ensure compliance with safety standards, such as IEC 60730 for household appliances or ISO 26262 for automotive applications.

Qorvo has evolved its intelligent motor controllers to reflect those advancements with its PAC52xxx/55xxx platforms that simplify rugged system designs with integrated advanced protection for systems operating in the 44V-to-72V range. These devices retain the company's highly integrated approach that packs an ARM® Cortex® MCU, analog front end, power management and drivers on a single chip, but goes beyond the feature set of the original PAC5xxx SoCs by adding functionality that is more conducive to safety-critical applications.

The original PAC5xxx series of intelligent controllers can handle the BLDC motors found in most power tools and pack a 50MHz Arm Cortex-M0 32-bit microcontroller, a high-speed 10-bit 1µs analog-to-digital converter (ADC) with dual auto-sampling sequencers, flexible clock sources, timers, PWM engine and several serial interfaces. The SoC is also outfitted with a programmable multi-mode power manager, configurable analog front end and application-specific power drivers.

The **multi-mode power manager (MMPM)** is like a Swiss Army knife for power management, capable of handling different voltages with efficiency, and includes a multi-mode switching supply controller that can function in either buck or SEPIC mode, along with up to four linear voltage supplies.

The **application-specific power drivers (ASPD)** can take advantage of high-voltage power drivers tasked with specific control applications such as H-bridge, 3-phase, intelligent power modules (IPMs) and general-purpose driving.

The **configurable analog front end (CAFE)** acts as the brain of the SoC and features programmable gain amplifiers, comparators, digital-to-analog converters (DAC) and more. These allow for flexible signal sampling, feedback amplification and sensor monitoring. Together with the microcontroller, these solutions facilitate a myriad of compact applications with integrated power management, driving, feedback and control capabilities for DC power supplies up to 600V.

Product	Max Input Voltage	QFN Package Pin Count	A23 ARM Cortex	V_{DS} Sensing	nDRVDIS/ nBRAKE	DC-DC	Gate Drive (Source/Sink)	Pin-to-Pin Compatible w/ cur. generation
PAC55713	72V	64	M4F	✓	✓	✓	1.2A / 1.8A	-
PAC55712	72V	64	M4F	✓	-	✓	1.2A / 1.8A	-
PAC55724	72V	64	M4F	-	-	✓	1.2A / 1.8A	✓ – PAC5524
PAC55711	72V	48	M4F	✓	✓	✓	1.2A / 1.8A	-
PAC55710	72V	48	M4F	✓	-	✓	1.2A / 1.8A	-
PAC55723	72V	48	M4F	-	-	✓	1.2A / 1.8A	✓ – PAC5523
PAC52711	72V	48	M0	✓	✓	✓	1.2A / 1.8A	
PAC52710	72V	48	M0	✓	-	✓	1.2A / 1.8A	-
PAC52723	72V	48	M0	-	-	✓	1.2A / 1.8A	✓ – PAC5223
PAC52700	72V	48	M0	-	-	-	.75A / .75A	-
PAC52411	44V	48	M0	✓	✓	✓	1.2A / 1.8A	-
PAC52410	44V	48	M0	✓	-	✓	1.2A / 1.8A	-
PAC52422	44V	48	M0	-	-	✓	1.2A / 1.8A	✓ – PAC5222
PAC52400	44V	48	M0	-	-	-	.75A / .75A	-

Integrated safety features: Safety is a critical aspect of motor controller design, particularly in power tools that operate under demanding conditions. Qorvo's controllers integrate safety through firmware with temperature sensing and protection features for all applications.

Temperature sensing and protection: The SoCs are equipped with a temperature sensor that can be accessed via an ADC channel on the CAFE with the parameters set and measured through the firmware. Two levels of temperature protection are in play, including Temperature Warning and Temperature Fault, with the former declaring an over-temperature warning when the die temperature reaches 140°C, and the latter generating an over-temperature fault when the die temperature reaches 170°C. The nature of the warning and fault is expressed in the firmware using an alphabet and number system that denotes where the problem occurred, and the temperature and voltage readings encountered. These can then be reset after the problem is rectified.

VDS sensing: The new controllers come equipped with VDS sensing for fast overcurrent and short-circuit protection, which features a separate comparator and level shifter for high-side MOSFETs. It also provides programmable DAC-level references and programmable blanking intervals for each MOSFET, which allows designers to use smaller dies and lower-cost electronics due to the tighter control of current within the SOA. This improves reliability and protects the MOSFETs during unexpected current transients.

CBC protection: The new family of controllers is also equipped with cycle-by-cycle protection that ensures the controller acts quickly to address any adverse conditions or faults that occur within the cycle of operation. This allows designers to maintain the safety and integrity of the motor and controller and significantly reduces power losses. It can also help reduce BOM costs, reduce processor overhead and help minimize the complexity of the overall design.

Driver Disable and Brake functions: The motor-control products provide additional safety features with Gate Driver Control options that allow designers the ability to deactivate or turn off the driver circuitry powering the motor should problems arise. The controllers are outfitted with an AIO2 pin to disable gate drivers (nDRVDIS) and a dedicated AIO4 pin to force the gate drivers to brake (nBRAKE) the motor should problems occur. The controllers are equipped with additional ADC inputs, including AIO3 and AIO5 pins with dedicated buffer feeding that's single-ended with programmable gain, which further helps to reduce BOM costs.

Qorvo's family of motor controllers can also benefit applications outside the scope of power tools, including in the latest E-bikes where power efficiency is paramount, in warehouses where autonomous robots track inventory and in manufacturing where automated systems are the backbone of production. Home appliances, robotics, HVAC systems, medical equipment, autonomous vehicles and CNC machining are just a few of the applications that can benefit from Qorvo's next-gen PAC family of intelligent motor controllers, and that future looks bright.

Design Challenges and Considerations for Brushless DC Motors and Their Drives

Introduction

Electric motors are integral to modern industry and technology, responsible for more than half of global electricity consumption. With the increasing need for energy efficiency, Brushless DC (BLDC) motors have become essential, offering significant potential to reduce electricity demand and carbon emissions. This white paper explores the various motor types, with a particular focus on BLDC motors, their design challenges and the advanced control systems that optimize their performance.

Motor Types Overview

Electric motors can be broadly classified into several types, each with distinct characteristics and applications:

- **AC Induction Motors:** AC induction motors dominate the market with around 70% share, particularly in industrial settings. These motors operate based on electromagnetic induction, where a rotating magnetic field in the stator induces a current in the rotor, causing it to turn. They are robust and cost-effective, making them suitable for constant speed applications like fans, pumps and conveyor belts. However, when variable speed is required, a Variable Frequency Drive (VFD) is necessary. VFDs modulate the frequency of the AC power supplied to the motor, allowing precise speed control. Despite their versatility, VFDs can introduce challenges such as stress on motor insulation, electromagnetic interference (EMI) and common-mode currents that can accelerate bearing wear.

- **Synchronous Motors:** Unlike induction motors, synchronous motors operate without slip, meaning the rotor turns at the same rate as the rotating magnetic field in the stator. Examples include wound-rotor synchronous motors (WRSM) and synchronous reluctance motors (SyRM). These motors are more efficient and offer better performance in specific applications, such as high-precision machinery. However, their higher cost and complexity limit their widespread adoption.

- **Brushed DC Motors:** Brushed DC motors are simple and provide high starting torque, making them useful for applications like power tools, automotive starters and household appliances. These motors use brushes and a commutator to mechanically switch the direction of current in the windings, generating rotation. However, the physical contact between the brushes and commutator leads to wear and tear, necessitating regular maintenance. Additionally, brushed motors are prone to generating electrical and acoustic noise.

- **Brushless DC Motors (BLDC):** BLDC motors eliminate the drawbacks of brushed motors by using electronic commutation instead of mechanical brushes. The stator in a BLDC motor contains windings, and the rotor is equipped with permanent magnets. Electronic control circuitry switches the current in the stator windings, creating a rotating magnetic field that drives the rotor. BLDC motors are highly efficient, potentially exceeding 96%, and are known for their long lifespan and minimal maintenance requirements. Their precise control and high torque-to-weight ratio make them suitable for a wide range of applications, from consumer electronics to industrial automation.

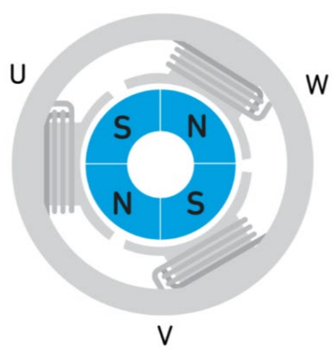
	UNIVERSAL	DC BRUSHED	AC	BLDC
Voltage	AC,DC	DC	AC	DC-Controlled AC
Speed (RPM)	8,000-20,000+	1,000-5,000	1,600-3,400	>50,000
Horsepower	Very High	Medium	Low-Medium	High
Efficiency	55-70%	60-70%	40-80%	>90%
Life	Medium	Medium	Very High	Very High
Maintenance	High	Medium	Very Low	Very Low
Speed Regulation	Poor	Fair	Good	Excellent
Starting Torque	High	Very High	Low-Medium	Very High

***Figure 1** compares the headline characteristics of some of the motor types mentioned from one manufacturer, for the same physical size.*

BLDC Motor Design and Control

The design of BLDC motors involves several technical considerations to ensure optimal performance:

- **Electronic Commutation:** Unlike traditional motors that rely on brushes for commutation, BLDC motors use electronic controllers to manage the switching of current in the stator windings. This electronic commutation is achieved using semiconductor switches like MOSFETs or SiC-FETs, which are arranged in a bridge configuration, providing six voltage combinations, with appropriate 'dead' time between each phase to avoid 'shoot through'. These switches are controlled by a microcontroller or digital signal processor (DSP) that generates precise Pulse Width Modulation (PWM) signals to regulate the motor's speed and torque.



	U	V	W
1	+	-	off
2	+	off	-
3	off	+	-
4	-	+	off
5	-	off	+
6	off	-	+

Figure 2: A three-phase brushless DC motor outline with the sequence of drive voltages necessary, here shown with 'trapezoidal' drive arrangement of coils.

Each switching phase is initiated in turn, triggered either by a sensor on the shaft or some other way, as the rotor spins through 360 degrees. Without feedback, the motor spins up to a maximum speed set by the supply voltage, any delays in sensing and evaluating rotor position, plus also by the winding inductance. As speed increases and applied voltage duration consequently decreases, the inductance limits peak current attainable and therefore torque, to progressively lower values. With feedback of rotor angle, speed and coil current, the controller applies the right correct timing to maximize torque and minimize torque ripple – which is periodic dips multiple times per revolution, producing vibration.

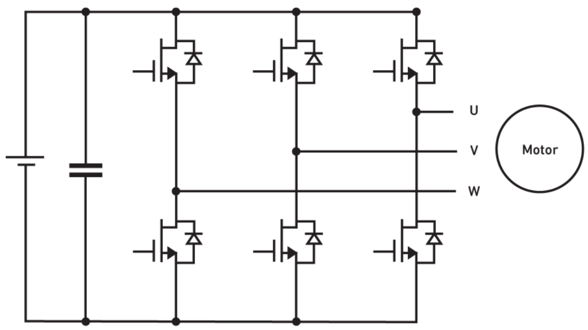
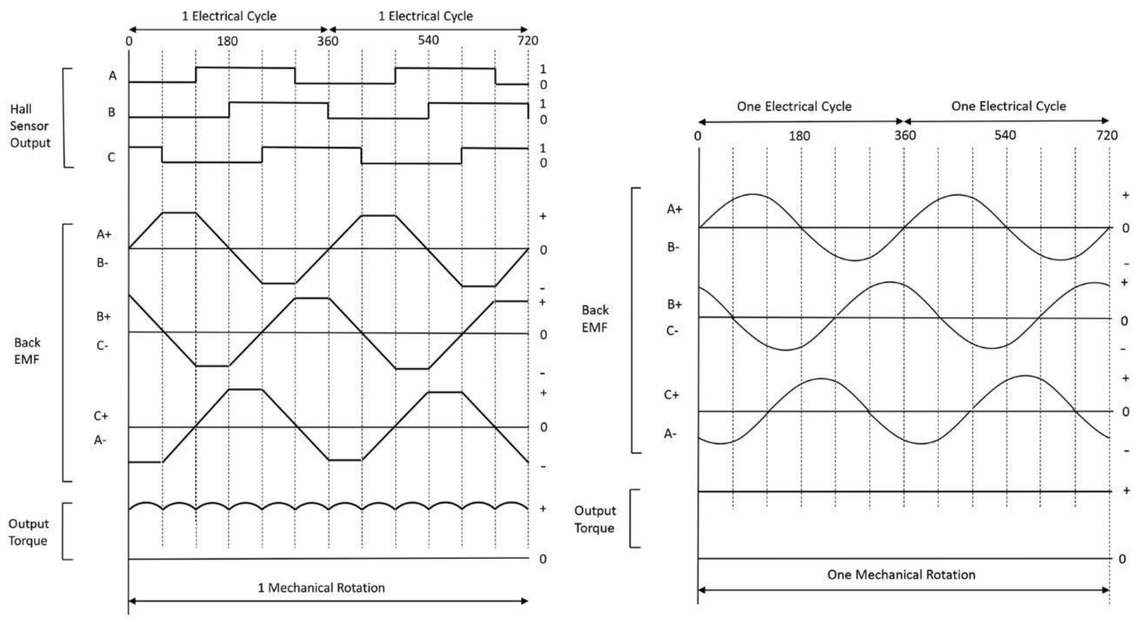


Figure 3. A bridge arrangement of switches provides BLDC drive voltages.

- **Sensor feedback:** BLDC motors often rely on sensors like Hall-effect sensors or rotary encoders to provide feedback on the rotor's position. This feedback is crucial for synchronizing the commutation with the rotor's position, ensuring smooth and efficient operation. In sensorless designs, advanced algorithms estimate the rotor position based on back-EMF (electromotive force) signals, reducing the need for physical sensors and further simplifying the motor's design.

- **Continuous maximum, intermittent torque and speed requirements** will be considerations for BLDC selection. An advantage of the BLDC motor is that maximum torque is independent of speed. Power rating will be specified as will be operating voltage. Other parameters might be insulation rating of the windings and sensors to frame to meet safety standards and the type of position sensor built-in, if any. The characteristics mentioned define the performance requirements of the BLDC driver in terms of output voltage range, frequency range (defining speed) and current capability, including overload conditions. The controller for the driver requires scaled signals for these parameters and has to be set up for the type of rotor positional information available. Algorithms in the controller software then optimize the timing of the drive signals to the power stage in terms of repetition rate to set speed with pulse width modulation to set torque.

- **Commutation style** – the way that the stator coils are driven to ensure continuous rotation. A 'six-step' trapezoidal drive passes current at any one time through two windings at once, leaving the third floating showing a back EMF, the zero crossings of which can be used to determine rotor position. The term 'six step trapezoidal' refers to the six drive states shown in Figure 2 and the physical, concentrated, distribution of the stator windings which produces back EMF in a trapezoidal shape (**Figure 4,** left) and an inevitable level of torque ripple. In contrast, the motor can be wound with the coils distributed in a more complex mechanical arrangement, in which case the back EMF generated is sinusoidal (**Figure 4**, right). There is zero torque ripple with smoother running at low speeds, although practical implementations achieve around 1% of maximum. This version of a BLDC motor is called a permanent magnet synchronous motor (PMSM) and has lower peak torque and power density than the BLDC motor with trapezoidal commutation. All the PMSM windings are driven at any one time, so a 'floating' winding is not available to indicate rotor position, and a separate sensor is normally required. For both commutation schemes, the power driver is pulse-width modulated (PWM) at a high carrier frequency to form the required voltage shape, either trapezoidal or sinusoidal, to match the back EMF shape for optimum performance. The depth of PWM sets the overall voltage amplitude and hence torque demand.



(a) Six step commutation

(b) Field oriented control

Figure 4. Back EMF waveforms for BLDC motors and permanent magnet synchronous motors.

The optimum choice of motor commutation type depends on the application, with six-step trapezoidal easier to implement and able to start under high torque conditions. Switching losses must be mitigated in the driver, but it is suitable for very high speed, for example with power tools. Sine-wave commutation motors are more expensive and the algorithms to drive them are more complex. They are used when performance is critical, starting torque is limited and low stable speeds are needed such as in ventilation fans. Some drive schemes start the motor at high torque with trapezoidal commutation then switch to sine wave as the motor spins up.

Three Hall effect rotor position sensors can be used with six-step trapezoidal commutation, but for cost-sensitive applications, back EMF zero crossing can be used. For sinusoidal commutation, a more expensive optical encoder or resolver might also be used for better performance.

- **Vector or field-oriented control:** A technique for controlling sinusoidally commutated BLDC motors is vector or field-oriented control (FOC). FOC provides smooth operation over the whole speed range and superior dynamic performance with fast acceleration and deceleration. Rotor position can be determined by sensors, or schemes which are 'sensorless' and approximate the position from measurement of winding current and voltage can be coupled with a 'model' of the motor characteristics. The end-user benefits of FOC are better accuracy, smaller motors and lower cost and energy consumption. However, FOC is complex and requires significant processing power in the motor controller. Positional information is not available at start-up, so a separate open-loop drive is sometimes used to 'spin-up' the motor until the sensors or current monitors provide valid feedback.

FOC is a sinusoidal, variable-frequency commutation method which keep the rotor and stator magnetic fields at 90 degrees apart under all conditions for maximum torque and regulation of speed and torque under changing load conditions. Two parameters need to be derived and controlled optimally to achieve this: field flux linkage and torque. These parameters must be separated into orthogonal components (90 degrees apart in the static co-ordinates of the stator) and can be derived from the rotor position and winding currents. The three-phase winding currents I_U, I_V, I_W are first passed through an A-D converter and changed to equivalent two-phase currents I_α, I_β using the 'Clarke' conversion method.

I_α and I_β are stationary relative to the stator. Now we derive the rotating coordinates I_q, I_d, (*q*=quadrature, *d*=direct), representing field flux linkage and torque, from the 'Park' conversion and Θ, the rotation angle. Having determined I_q and I_d, these can be compared with target values I_{qref} and I_{dref} and a compensating error signal generated, typically by a proportional-integral (PI) controller. This outputs a signal proportional to the difference between actual and reference and also proportional to the integral of the difference. The result is good dynamic response with little over- and under-shoot. The compensating signal is now converted back to three-phase drive currents for the motor windings. A reverse Park, then reverse Clarke conversion is performed and drive signals generated for the switches in the power bridge. PWM is applied to achieve sinusoidal drive currents with rms values corresponding to demanded torque.

Qorvo's BLDC Control Solutions

Qorvo's PAC series represents a significant advancement in BLDC motor control technology. These integrated solutions provide a comprehensive set of features tailored for BLDC applications:

- **Integrated Functions:** The PAC series integrates essential functions such as power management, sensor interfacing and PWM generation, offering a complete motor control solution in a compact form. This integration simplifies the design process and reduces the time-to-market for new products.
- **Versatility and Scalability:** The PAC series is designed to support a wide range of applications, from small, battery-powered devices to high-power industrial machinery. These controllers can handle input voltages up to 600V and output power up to 6kW, making them suitable for demanding applications like HVAC systems, pumps, and compressors.
- **Customization and Flexibility:** Qorvo's controllers allow for easy customization of control algorithms, enabling manufacturers to optimize motor performance for specific applications. The PAC series also supports over-the-air updates, ensuring that the motor control systems can be easily upgraded to incorporate the latest features and improvements.
- **Power Electronics and Integration:** All of the drive and control functions can now be integrated into a Power Application Controller™ (PAC) such as the range offered by Qorvo in their PAC5xxx series. These are based on either an Arm® Cortex®-M4F running at 150 MHz with 128 kB flash and 32 kB SRAM memory with a 2.5 MSPS 12-bit ADC, or the -M0 variant at 50 MHz, 32 kB flash and 8 kB SRAM with a 1 MSPS 10-bit ADC (**Figure 5**).

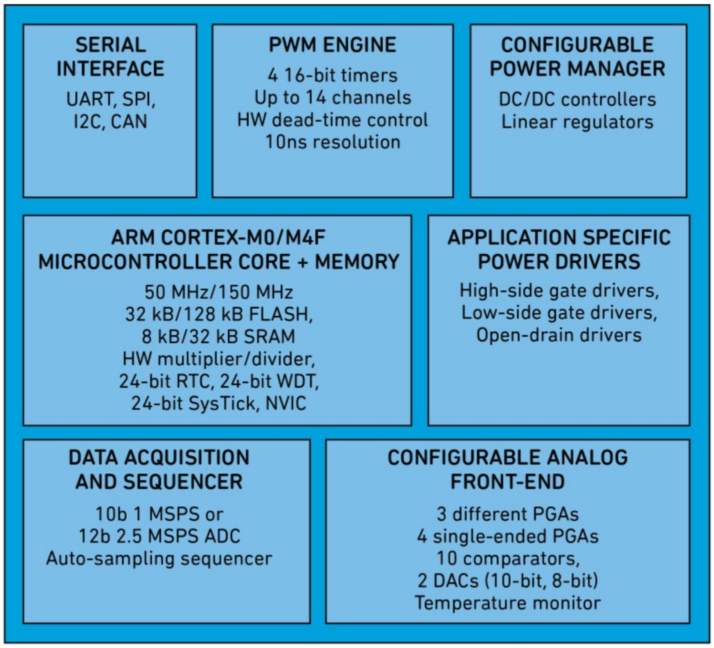


Figure 5. The Qorvo PAC series BLDC controller functions.

Applications and Reference Designs

Qorvo provides a variety of reference designs to assist manufacturers in implementing BLDC motor control across different industries. These reference designs demonstrate the PAC series' adaptability and ease of integration:

- **Consumer Electronics:** In applications like drones and power tools, where compact size and high efficiency are critical, Qorvo's solutions offer a streamlined approach to integrating BLDC motor control.
- **Industrial Automation:** For larger applications such as HVAC systems, pumps and compressors, the PAC series provides the power and flexibility needed to control high-performance BLDC motors effectively.
- **Household Appliances:** In products like washing machines and refrigerators, where energy efficiency and reliability are paramount, Qorvo's integrated motor control solutions enable manufacturers to meet stringent energy standards while maintaining product performance.

Conclusion

As industries increasingly prioritize energy efficiency and sustainability, BLDC motors are emerging as a preferred choice due to their superior performance, reliability, and low maintenance. The integration of advanced control solutions, such as Qorvo's PAC series, simplifies the design and implementation of BLDC motors, making them accessible for a wide range of applications. With the continued development of motor control technologies, BLDC motors are set to play a critical role in reducing global energy consumption and mitigating environmental impact.

Field-Oriented Control of Brushless DC Motors

Abstract

The Brushless DC (BLDC) motor has achieved widespread adoption due to its high efficiency, reliability and low maintenance. However, controlling these motors presents significant challenges, particularly in achieving smooth, efficient operation. This paper explores the application of Field Oriented Control (FOC) as an advanced method for optimizing BLDC motor performance, reducing torque ripple and enhancing overall efficiency.

Despite their advantages, the complexity of BLDC motor control, which involves precise electronic commutation and feedback mechanisms, poses significant design challenges.

BLDC motors operate by generating a rotating magnetic field in the stator, which interacts with the permanent magnets in the rotor. Unlike traditional motors that use mechanical brushes for commutation, BLDC motors rely on electronic controllers to switch the current in the stator windings. This electronic commutation is essential for precise control but also introduces complexity.

The relative complexity of the electrical drive, usually requiring three-phase 120 degree-shifted AC power at high frequency, with pulse-width modulation (PWM) to generate the demanded speed and torque.

The potential controllability, efficiency and weight savings from the use of BLDCs has driven the development of new integrated drive solutions that have opened up markets ranging from industrial to domestic appliances and new applications such as in drones and E-bikes.

BLDC motor basics

The simplest form of BLDC motor control is the six-step or trapezoidal drive, where each of the three stator windings is energized sequentially in a fixed pattern. While easy to implement, this method results in torque ripple due to the non-ideal alignment of the rotor and stator magnetic fields. The ideal solution is to use a sinusoidal drive that produces a smooth rotating magnetic field, aligning perfectly with the rotor at all times. However, achieving this requires sophisticated control algorithms and accurate feedback on the rotor's position.

The force on the rotor is not constantly in the desired tangential direction – a periodic radial component is present as the motor rotates. This does not contribute to shaft torque but serves only to reduce efficiency, produce heat and induce so-called ‘torque ripple’ (**Figure 1,** left). This simple drive is called six-step or ‘trapezoidal.’ The ideal situation is to use a sinewave rather than on-off drive to the windings, (**Figure 1,** right), to produce a smoothly rotating field from the stator coils and then control the AC excitation current so that the angle of the resulting field is always perpendicular to the field of the rotor magnet.

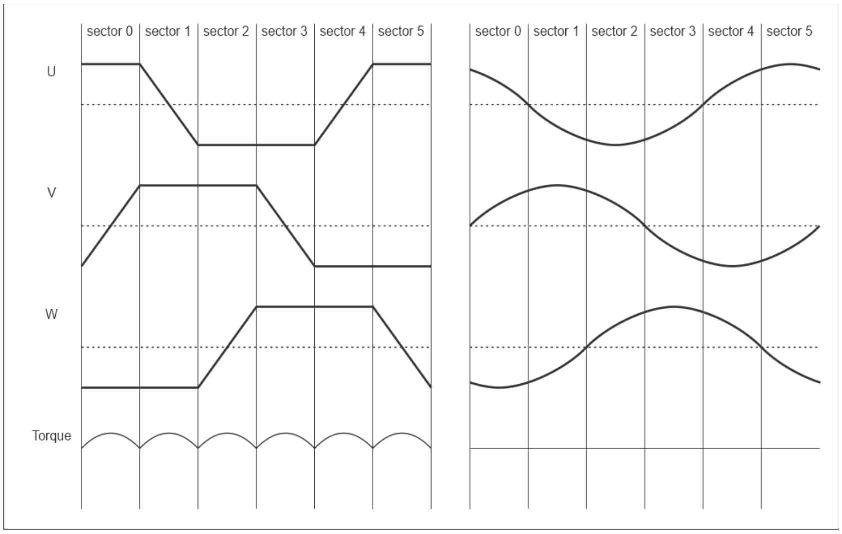


Figure 1: BLDC motor six-step trapezoidal compared with sinusoidal drive waveforms

This maximizes tangential force and, hence, torque through 360 degrees of rotation, resulting in minimal torque ripple and maximum efficiency. To achieve this, the angular position of the rotor must be determined with pinpoint accuracy. At the same time, the stator currents must be controlled, as this determines the field's intensity and direction at any instant from the overall contribution of the three windings. **Figure 2** shows an example – with the rotor in this position, and the field in the direction N-S, the magnet experiences maximum torque if the stator field direction is at 90 degrees, in the direction of the double gray arrows. This occurs when fields from the W and V windings are equal in one polarity and the field from the U winding is at a maximum with the opposite polarity, corresponding to position A-B in the drive current waveforms.

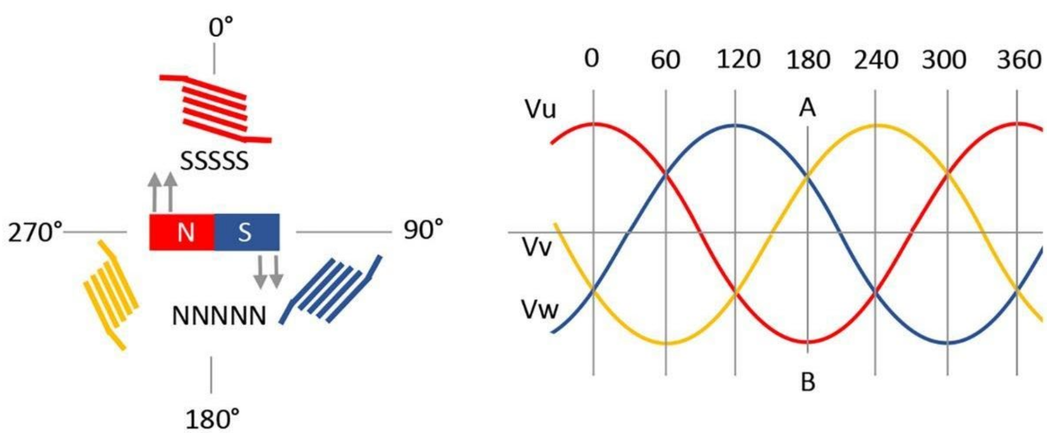


Figure 2: Rotor torque should be tangential for maximum effect

Just applying and controlling sinusoidal voltages to the three windings in the correct phase alone will not give accurate control, as winding inductance, back EMF and other effects cause a phase shift to the resulting current and field. This is where FOC comes in, dynamically correcting stator field amplitude and direction by optimizing winding currents for the instantaneous measured rotor position.

Using field-oriented control to optimize torque

FOC works by transforming the three-phase stator currents into two orthogonal components: one representing the torque-producing component (IQ) and the other representing the magnetizing component (ID). These components are then controlled independently to achieve the desired motor performance.

FOC involves several mathematical transformations. First, the Clarke transformation converts the three-phase currents into a two-axis system (Iα and Iβ). Then, the Park transformation rotates these axes to align with the rotor's position, resulting in the direct (ID) and quadrature (IQ) currents. By controlling these currents, FOC maintains optimal torque production throughout the motor's operation.

Stator winding currents and consequent field intensity and direction can be represented as three rotating vectors 120 degrees apart, in a common static frame. If the currents I_U, I_V and I_W are always balanced, adding to zero, this can be simplified into two rotating vectors amplitude $I\alpha$ and $I\beta$, 90 degrees apart in a static frame, by the 'Clarke' transformation:

$$I\alpha = \frac{2}{3}(Iu) - \frac{1}{3}(Iv - Iw) \quad \text{Eq.1}$$

$$I\beta = \frac{2}{\sqrt{3}}(Ib - Ic) \quad \text{Eq.2}$$

We now need to convert these into static vectors I_D (direct) and I_Q (quadrature) in a rotating reference plane so we can correlate them with the position of the rotor as it revolves. We achieve this using the 'Park' transformation, where θ is the rotor angle around the static $I\alpha$ and $I\beta$ frame:

$$Id = I\alpha\cos(\theta) + I\beta\sin(\theta) \quad \text{Eq.3}$$

$$Iq = I\beta\cos(\theta) - I\alpha\sin(\theta) \quad \text{Eq.4}$$

Under steady state conditions, I_D and I_Q are constant values and can be interpreted as the components of stator winding current that represent tangential torque and unwanted radial torque, respectively. These values can now be used as inputs to feedback loops, typically using proportional-integral (PI) controllers, that work to maximize I_Q and minimize I_D to zero. The resulting error amplifier outputs V_D and V_Q are passed through inverse Park and inverse Clarke transformations with subsequent pulse width modulation, to drive a power stage, generating the three sinusoidal stator winding currents. The programmable gain values in a PI controller, Kp and Ki, need to be optimized for transient response and steady state accuracy, respectively, and are heavily dependent on actual motor parameters, particularly winding resistance and inductance. However, advanced FOC controllers, such as those from Qorvo, have auto-tuning features where the characteristics of the connected motor are 'learned.' An outline of a BLDC motor controller using FOC is shown in **Figure 3**.

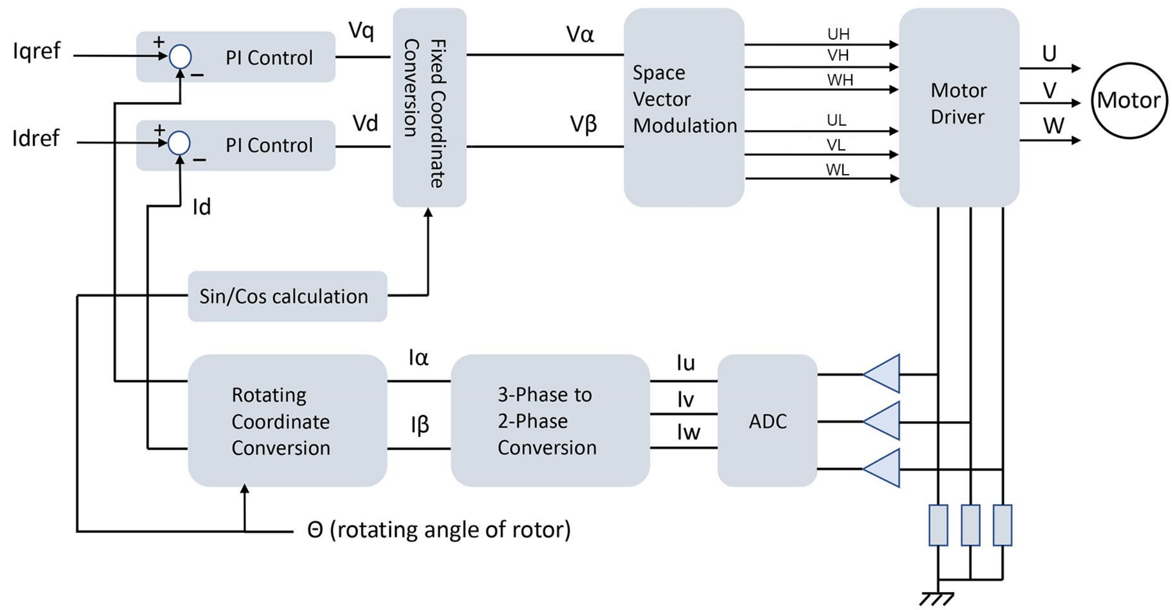


Figure 3: A typical BLDC motor controller using field-oriented control

Applications that benefit particularly the most from FOC include those demanding minimal noise and vibration, optimal low harmonic content and the ability to run at higher than nominal speed. In FOC, this is achieved with a technique known as 'field weakening,' where back-EMF is deliberately reduced by decreasing current ID to a negative value. This reduces the effective rotor magnetic field and allows higher speed, but at the expense of torque.

Measuring rotor position and stator winding currents

The key to FOC is accurately determining the rotor's position, which can be achieved using sensors like Hall-effect sensors or rotary encoders. In sensorless designs, the rotor position is estimated based on back-EMF signals, but this method is less precise and requires complex algorithms.

High-performance FOC relies on accurate measurements of rotor angular position and stator winding currents. Position can be determined in various ways. With trapezoidal drive, when one winding is de-energized, the zero crossings of the back-EMF can be used to indicate angular position with low cost and good accuracy. However, in FOC, all windings are continuously driven, so other methods are used. A 'sensorless' technique infers position from the winding current, voltage and a model of the motor characteristics, but this does not allow for easy start-up under high load and requires significant processing power from the controller. Another possibility includes starting with trapezoidal drive, sensing the back-EMF, then switching to sine FOC when the motor has started spinning. For sensor-based solutions, Hall sensors solve this problem using a simple interface and allowing start-up under high load conditions and more precise torque control. Another method to determine position measurement leverages a magnetic resolver or an encoder with quadrature outputs, which is a more expensive solution one that is but highly accurate and also senses the direction of rotation.

Measurement of the winding current can also be done in different ways. The most accurate approach is to sample each of the three winding currents simultaneously with resistive sensing and three ADCs. However, timing of the sampling is critical to avoid noisy PWM switching edges. Resistors can be placed directly in series with the windings for the best accuracy, but because measured voltages are not ground-referenced and are difficult to process with the high common-mode waveform levels present, a better solution is to measure the inverter leg currents (Figure 4, left). For cost-sensitive applications, a single shunt resistor can be used, as this effectively measures the DC-link current (Figure 4, right). Only one ADC is required for the single shunt approach, but the technique has limitations – the current measurement will not be accurate if the active vector duration is less than the minimum measurement time. To correct this, ‘asymmetrical’ current sampling may be necessary to provide better signal quality.

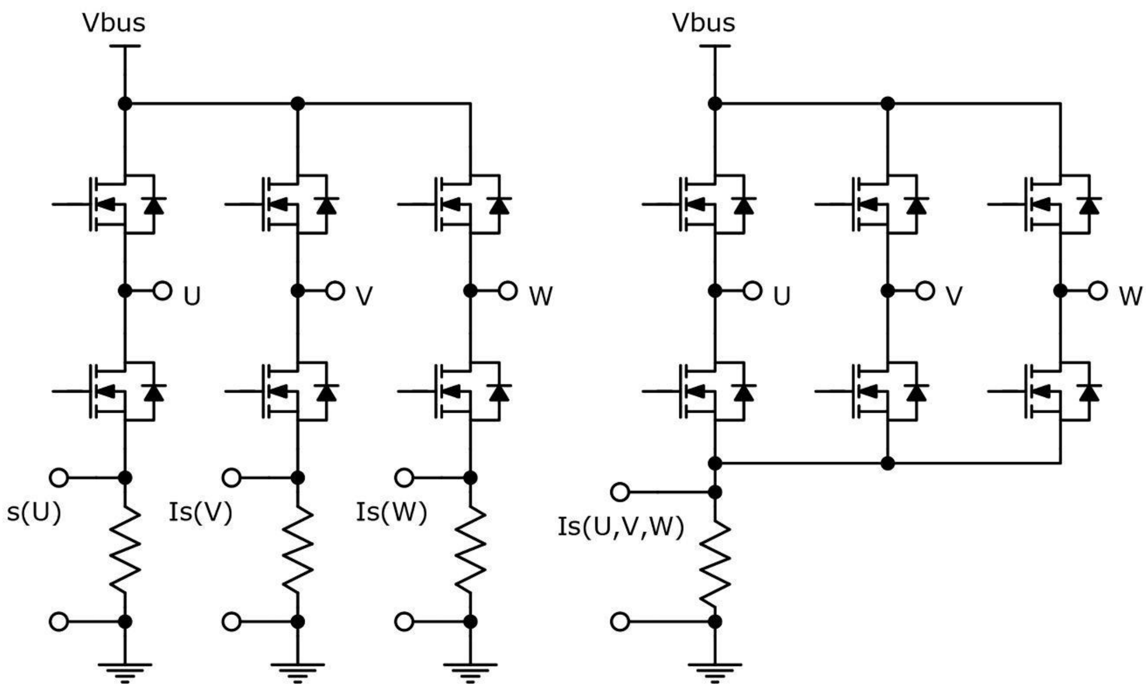


Figure 4: BLDC motor current-monitoring methods, three-shunt, left and single-shunt, right

Integrated solutions to BLDC FOC control

Implementing FOC requires precise control of the motor's stator currents, which can be challenging due to factors like winding inductance and back-EMF. Modern integrated circuits, such as Qorvo’s PAC5xxx series, simplify this process by integrating all necessary functions into a single chip. These ICs offer features like automatic tuning, sensorless operation, and comprehensive diagnostic capabilities, making FOC more accessible and practical for a wide range of applications.

In addition to basic motor control, these advanced controllers support functions like field weakening, which allows motors to operate beyond their base speed by reducing the rotor's magnetic field strength. This is particularly useful in applications requiring a wide speed range, such as electric vehicles or industrial machinery.

All of the functions for trapezoidal or field-oriented control of BLDC motors can be integrated into single-chip controllers, such as the PAC5xxx series from Qorvo, which is based on the ARM® Cortex® processor. The parts are highly configurable and are intended for up to 3 kHz electrical speed. Control modes include torque, speed and power, with ‘sensorless’, Hall or quadrature encoder position sensing options, while single or three shunt current sensing can be used. A hybrid trapezoidal/FOC mode is included for assured start-up, along with auto-tuning to identify motor parameters for optimum performance. Field weakening is supported and a range of protection features detect issues such as under-voltage, over-temperature, stall and open phases, all of which are reported through on-board diagnostics. One version even includes the motor driver MOSFETs for low power applications, such as hand-held devices and tools. All features can be configured through a GUI and comprehensive support is provided through reference firmware, application notes, programming guides, a software development kit and hardware evaluation kit.

FOC is particularly beneficial in applications where precision, efficiency, and smooth operation are critical. This includes electric vehicles, where smooth torque delivery is essential for comfort and performance, and in industrial automation, where energy efficiency and reliability are paramount. The use of FOC in household appliances also helps meet stringent energy standards while maintaining performance.

Conclusion

Field Oriented Control offers a sophisticated solution for optimizing BLDC motor performance, enabling higher efficiency, reduced torque ripple, and greater control precision. As integrated solutions become more advanced and cost-effective, FOC is likely to become the standard for BLDC motor control across a wide range of applications.