Design Challenges and Considerations for Brushless DC Motors and Their Drives

By José Quiñones

Introduction

Generating rotary motion was one of the first experiments carried out with electricity in the 18th century – an 'electric whirl' was invented, actually an electrostatic reaction motor, but it was just seen as a novelty. Today, electric motors consume 53% of global electricity production, according to '4E Electric Motor Systems Annex' (EMSA) [1]. Another report by the International Energy Agency (IEA) states that typically 95% of a motor's lifecycle cost is electricity to power it and if users change to the most efficient motors and drives, by 2030, global electricity demand could be reduced by 24-42 TWh, representing 16-26 Gt reduction in CO_2 emissions. All this is in a market worth nearly USD 142 billion, growing at an expected 6.4% CAGR according to market analysis in 2020 [2].

When the long view of capital expense payback, operating costs and environmental loading is considered, there is therefore every incentive to update to, and build-in the best performing motors with smart control. There is also regulatory pressure to improve, with international standards for efficiency being imposed, for example IEC 60034-30-1 for line-operated AC motors, defining levels IE1 to IE4 with increasing efficiency. The ideal motor does depend on the application however and there is a range to select from. Qorvo [4] estimates that in a typical affluent western home, there might be 48 induction motors, 14 brushed DC, 4 universal AC-DC and 26 brushless DC motors. In all, 61 line-powered and 31 battery-powered.

Motor Types

The dominant motor in the overall market including industrial is the AC brushless induction type with around 70% share, running with 'slip' at a speed slightly below a value synchronous with a fixed multiple of the supplied line AC frequency. Single-phase types are versatile but not very efficient and require special starting methods with capacitors, switches or relays. However, three-phase types are more powerful, efficient and self-start. AC induction motors are very reliable and low cost, but in their simplest form are only suitable for constant speed/load applications such as fans and pumps. Where variable speed and torque is required, they can be driven by variable frequency drives (VFDs), which can make the process controlled more efficient and versatile. VFDs can be retrofitted in theory to any AC synchronous or asynchronous motor, although in practice they can stress insulation, generate excessive EMI and cause common-mode bearing currents and associated wear, if precautions are not taken.

Truly synchronous motors without 'slip' are an option such as the wound-rotor synchronous motor (WRSM) or the synchronous reluctance motor (SyRM) which can be efficient but are more costly and not very widely used.

Motors that 'self-commutate' do not rely on an AC mains supply directly to progressively rotate a magnetic field to produce attraction and repulsion and consequent rotation. These types typically use 'brushes' to energize coils on the rotor in sequence as it turns, maintaining continuous rotational torque. In this category, brushed DC or universal AC/DC types are good performance and can be compact with high starting torque and low initial cost. For this reason, they are popular in a wide range of applications including small appliances and tools. Their disadvantages are maintenance of the brushes which wear and often high levels of acoustic and electrical noise. Speed control of brushed motors can be relatively simple up to tens of thousands of RPM but in the case of DC supplies, it is often done in an inefficient way, simply reducing the voltage with a 'linear' regulator or possibly a 'DC chopper'. For brushed motors with an AC supply, speed is similarly controlled by the voltage applied, so phase angle control is typically utilized with triacs or possibly in a crude way by switching taps on the field coil. Regulation of speed with load changes can be achieved with closed loop control from a sensor back to the input voltage for both DC and AC brushed motor types.

In the pursuit of better efficiency, performance and long life, the brushless DC (BLDC) motor has now come to the fore. These types typically have stator coils and magnets on the rotor and require a multiphase AC supply at variable voltage and frequency to operate, a version of a VFD. This potentially adds to initial cost, but the performance benefits and energy savings, with potentially over 96% efficiency, can give quick payback while maintenance overhead is very low and lifespan is long. The stator coil drive electronics can use a battery as a supply in portable equipment such as tools, or equally, rectified mains with power factor correction (PFC) as appropriate for larger appliances. With equipment required to be ever-more controllable and energy-efficient, the potential market for the BLDC motor is vast, so the necessary drive circuitry is becoming more and more integrated and cost-effective. **Figure 1** compares the headline characteristics of some of the motor types mentioned from one manufacturer, for the same physical size.

	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. One manufacturer's comparison of their motor performance (Source: Groschopp).

BLDC Motors – A Closer Look

We will now take a closer look at the BLDC motor and particularly the electronics required to generate the multiphase AC for the stator windings and how control is implemented for optimum performance.

The outline of a three-phase BLDC motor is shown in **Figure 2**, with the sequence of applied voltage to the three coils for 'trapezoidal' drive. The drive is normally generated by an arrangement of six semiconductor switches, typically MOSFETs, or increasingly wide band-gap devices such as SiC-FETs in a bridge configuration, providing the six voltage combinations, with appropriate 'dead' time between each phase to avoid 'shoot through' (Figure 2). 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 and any delays in sensing and evaluating rotor position, and 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 has to apply exactly the right switch timing to maximize torque and minimize torque ripple – its periodic dip multiple times per revolution, producing vibration.
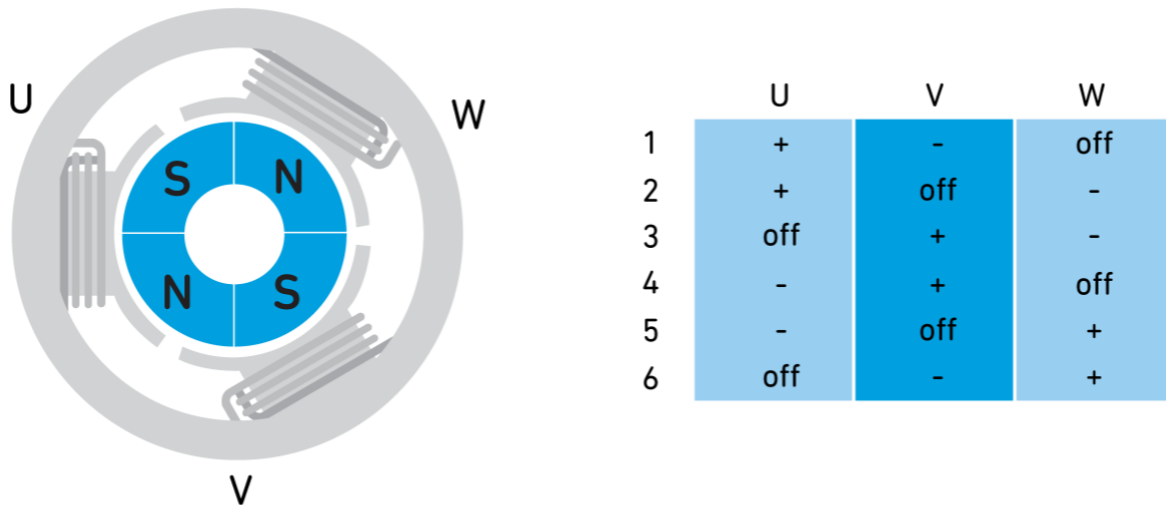

	U	V	W
1	+	-	off
2	+	off	-
3	off	+	-
4	-	+	off
5	-	off	+
6	off	-	+

Figure 2. A three-phase brushless DC motor outline with the sequence of drive voltages necessary, here shown with 'trapezoidal' drive arrangement of coils.
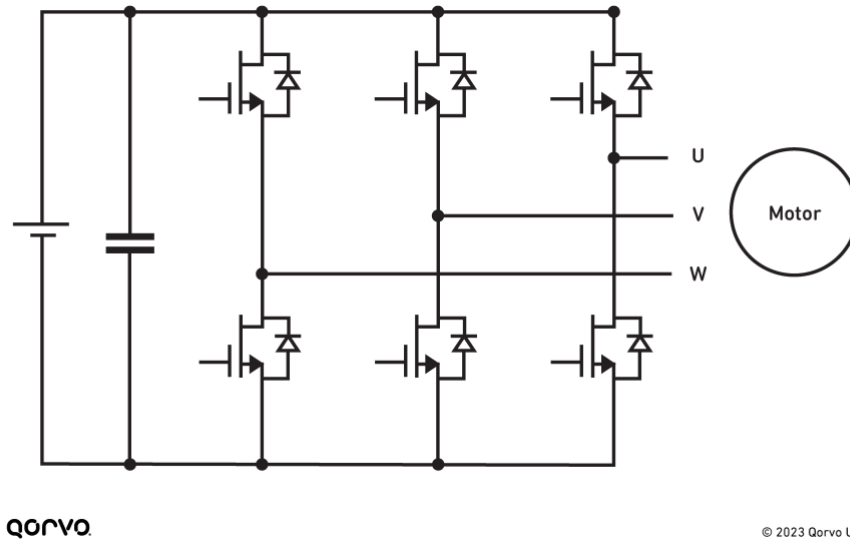
Figure 3. A bridge arrangement of switches provides BLDC drive voltages. Here Qorvo SiC-FETs are shown.

Depending on the application, different BLDCs will be selected. Continuous maximum, intermittent torque and speed requirements will be parameters and 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. We will now consider the commutation methods that can be used, position sensing techniques and how they interact.

Controlling the BLDC Motor

Firstly, there is a choice of commutation style – the way that the stator coils are driven to ensure continuous rotation. '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) and there is in theory 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.
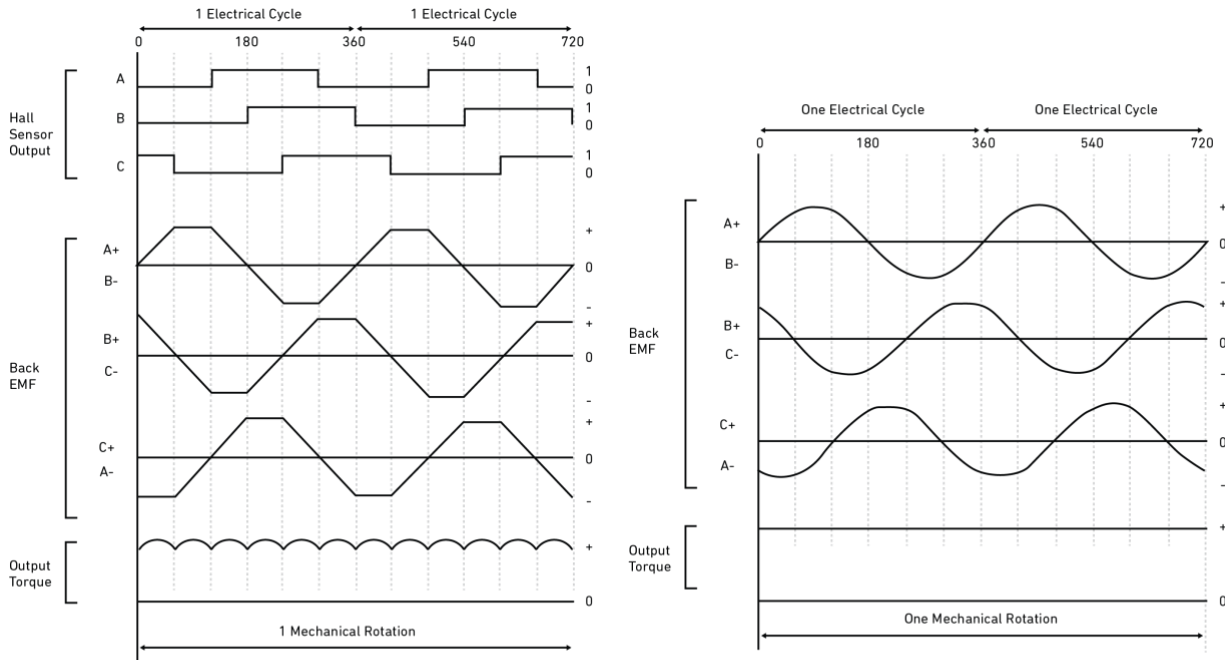
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Figure 4. Back EMF waveforms for BLDC motors and permanent magnet synchronous motors.

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, as seen 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) [3]. 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 there are schemes which are 'sensorless' and approximate the position from measurement of winding current and voltage, 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. FOC however 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 can achieve close to the ideal of keeping 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 IU, IV, IW are first passed through an A-D converter and changed to equivalent two-phase currents Iα, Iβ using the 'Clarke' conversion method.

Iα and Iβ are stationary relative to the stator. Now we derive the rotating coordinates Iq, Id, (q=quadrature, d=direct), representing field flux linkage and torque, from the 'Park' conversion and Θ, the rotation angle. Having determined Iq and Id, 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, so a reverse Park, then reverse Clarke conversion is performed and drive signals generated for the switches in the power bridge. Pulse-width modulation is applied to achieve sinusoidal drive currents with rms values corresponding to demanded torque. **Figure 5** gives a block diagram for a typical FOC scheme.
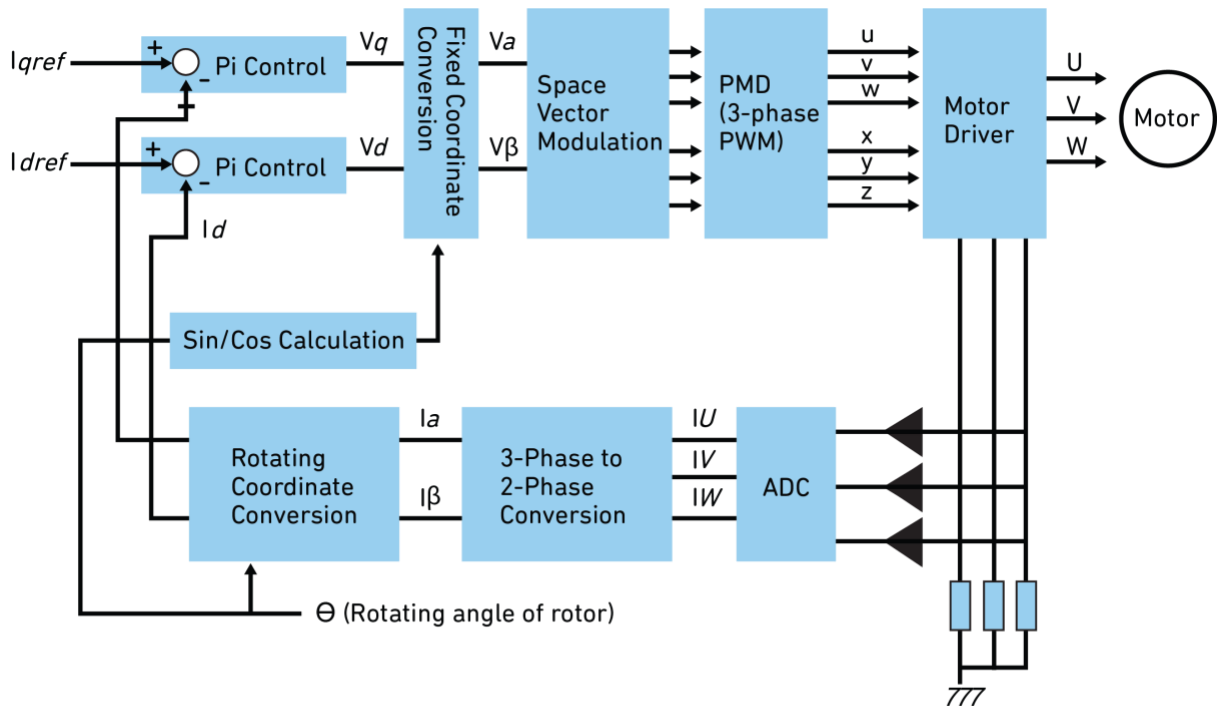

Figure 5. FOC or 'vector' control of a BLDC motor.

Qorvo BLDC Motor Control Solutions

Providing the optimum drive for a BLDC motor is difficult with a multitude of parameters to sense and complex algorithms required to generate the appropriate multiphase PWM waveforms. In real applications, the supply voltage could be anything from around 8V for small battery operation up to 400V from rectified and power-factor corrected mains for domestic appliances, for example. The motor may need to be able to reverse, it may or may not have sensors built-in and increasingly, users expect equipment to be capable of field updates that might change the motor control characteristics. Fortunately, all of the drive and control functions can now be integrated into a Power Application Controller™ (PAC) such as the range offered by Qorvo [4] 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 6**).
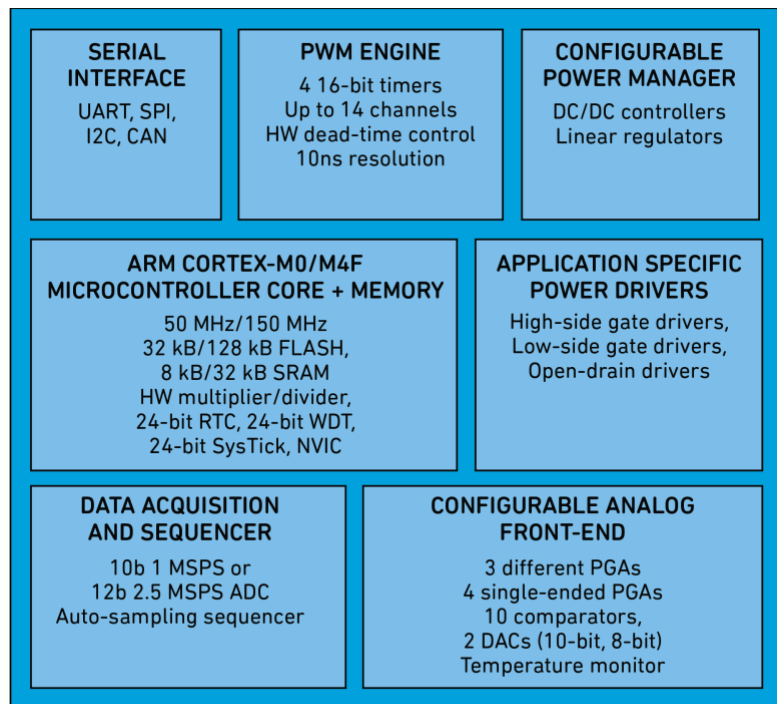
Figure 6. The Qorvo PAC series BLDC controller functions.

The PAC devices integrate multiple sensor and communication interfaces for any BLDC motor control application with the ability to configure, update at will and optimize the PWM in an 'auto-tune' mode for a particular motor with fine resolution. Three-phase gate drivers with high peak current ratings are also integrated with high-side voltage ratings of up to 600V, a first in the market. Internal linear and switching regulators are also included to minimize board space and BOM cost. A configurable analog front end (CAFE) comprises differential programmable gain amplifiers, single-ended programmable gain amplifiers, comparators, digital-to-analog converters, I/Os for programmable and inter-connectible signal sampling, feedback amplification, and sensor monitoring of multiple analog input signals. A version for low power BLDCs, type PAC5285, also integrates power MOSFETs for the most compact solution for applications such as handheld tools and devices. All devices in the PAC range incorporate comprehensive protection, including over-current, under-voltage, over-voltage and over-temperature.

Reference Designs Make Design-in Easy

Reference designs are available and an example is the RD5556, which showcases the PAC5556 motor controller and silicon carbide SiC FET cascode power switches from Qorvo. The design can be used for three-phase motor control up to 600VDC and 3kW, as is found for example, in AC appliances. In industry, the design suits applications including motor control for pumps, compressors and fans (**Figure 7**).


Figure 7. The Qorvo RD5556 reference design featuring SiC FETs for applications to 600V/6kW.

Reference designs are available from Qorvo for applications such as drone motor drives with the PAC5223 device, showcasing a 'Tiny' FOC solution just 9x15mm with an input voltage of 4.5-18V and up to 17A rms output current. Another reference design, RD5223PT, demonstrates how the PAC5223 can be used in power tools with a single-shunt method of winding current detection in a size of 24x10mm, designed to fit in the device handle.

For 240 VAC applications a reference design for a pump BLDC motor is available using the PAC5253 on a 64mm diameter 4-layer PCB, **Figure 8**.
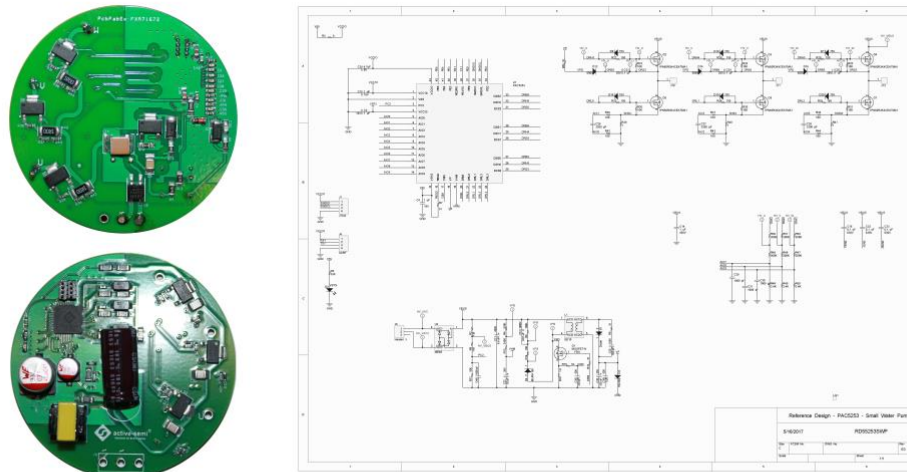
Figure 8. A Qorvo BLDC motor controller reference design used for a 240 VAC water pump.

The Qorvo PAC devices are part of an ecosystem of hardware and software support with full data sheets, reference firmware, programming GUIs and guides, software development kits and application notes. Schematics, BOMs and layout drawings are available for all reference designs.

Conclusion

The efficiency of brushless DC motors has made them the ideal choice for applications where small size, low weight, controllability and high torque are also desirable, such as in appliances, power tools and a wide range of industrial and consumer uses. The complexity and cost of advanced control and drives has in the past been a barrier to the widespread adoption of BLDC motors, but now, the integrated drive solutions from Qorvo in their PAC series controllers and SiC FET switches from Qorvo are an integrated, versatile and cost-effective solution. With the comprehensive support available, the implementation of an ultra-high performance BLDC motor controller is now quick and easy across a wide range of applications in the industrial and consumer markets, de-risking the design process and improving time-to-market.

José Quiñones has been spinning motors for more than 25 years. With a BSSE in electronics and a MSEE in power electronics from the University of Puerto Rico, Jose works as an embedded system designer generating motion control designs for brushed, brushless DC and stepper motors. As an applications engineer, he enjoys helping customers design their respective motor drive and control applications, ranging in all sorts of power levels and sizes. From conception, through hardware, and software/firmware implementation, he helps customers create better and novel products using the most efficient power management solutions.

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