

QORVO®

# Powering Up Your Design



**MOUSER  
ELECTRONICS**



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# Power Efficiency is Advancing Electronics Innovation

The efficient use of power is at the heart of electronic device design.

From 5G base stations, phased array antennas, data centers and vehicles to tablets, smartphones and video doorbells – designers know that smaller, smarter and more reliable power management are essential competitive differentiators.

As a global leader in RF and power technologies, Qorvo is helping customers solve their most difficult power challenges. We are ready today with next-generation solutions that Connect, Protect and Power™ people, places and things – faster and further with more reliability.

Qorvo's scalable platforms for power supply and management are used for charging, powering and embedded digital control in end applications in the industrial, commercial and consumer equipment markets, as well as in mission-critical defense applications.

Qorvo's turnkey solutions deliver energy-saving power conversion architectures that minimize energy usage, reduce solution size and cost, improve reliability, and compress system development time to market by more than 50 percent.

Our highly integrated and configurable architecture uses an intelligent, system on chip (SoC) approach that significantly simplifies the design process by eliminating the need for external components.

In addition, we offer customers a family of multi-time programmable power management ICs that enable designers to change configurations multiple times without special software or firmware. Manufacturers can debug designs and change settings in real time without changing external components.

Qorvo's innovation in power products is delivering compelling simplicity, efficiency and flexibility. And we're not finished yet. We continue to advance levels of programmability, power efficiency, capability and size. By doing so, we empower our customers to innovate enterprise and consumer electronics with greater functionality, reliability and extended battery life.



Qorvo is all around you – making a better, more connected world possible.

Qorvo's Programmable Power Management business unit delivers power management and intelligent motor drive expertise to key growth markets. The company's portfolio of analog and mixed-signal SoCs provides scalable core platforms used in charging, powering and embedded digital control systems for industrial, commercial and consumer applications. Qorvo offers Power Application Controllers® (PAC™) and DC-DC power management products that significantly improve system reliability

while reducing solution size, cost and system development time. Learn more at [www.qorvo.com/products/power-management](http://www.qorvo.com/products/power-management).



**Rodney Hsing**  
Qorvo Sr. Director of Global Distribution

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# Power Up Your Power Management Knowledge

Although power management plays a critical role in almost all electronic devices, it's often not a huge focus. The power management system improves product reliability, increases performance, and usually handles a wide range of other functions.

Power management integrated circuits (PMICs) are especially important in battery-powered electronic devices, including smartphones and wearables, because of their small size, high efficiency, and design flexibility.

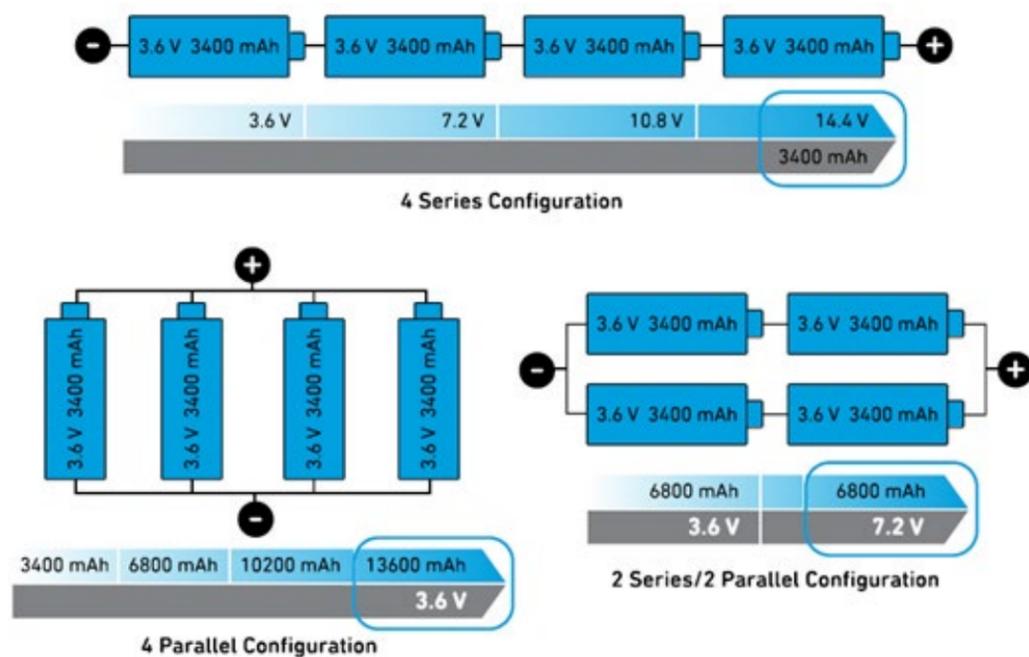


Figure 1: Batteries can be arranged in various ways to provide different current and voltage outputs. (Source: Qorvo).

## DC Battery Configurations

The type of power management subsystem that an electronic device uses depends on its power source. These sources can include AC, DC, or ultra-low-power DC sources such as solar power. Many of our devices get their DC power from individual batteries or battery packs containing multiple batteries. These batteries can be arranged in various ways to provide different current and voltage outputs. In the **Figure 1** example:

- ▶ Arranging batteries in series increases a battery pack's peak voltage and increases its capacity.
- ▶ Arranging batteries in parallel doesn't increase the voltage, but it does increase the battery packs' overall current capability and capacity.
- ▶ Configuring batteries in series and **in parallel** increases voltage, current, and capacity simultaneously.

## Types of DC Voltage Regulators

In some battery-powered applications, the system components might not be able to use the battery's power directly, so DC-DC converters are used to monitor and stabilize the voltage delivered to the system. These converters are also called voltage regulators because they regulate and adjust the supplied voltage. Voltage regulators are classified into two main categories, depending on the voltage conversion method they use.

- ▶ Linear regulators convert an input voltage ( $V_{in}$ ) to a different voltage output ( $V_{out}$ ) using a linear (resistive) component to regulate  $V_{out}$ . They are typically used for lower power output applications. Linear regulators provide low noise output, so they are suitable for sensitive analog components such as sensors. One drawback is that they are not very efficient.
- ▶ In contrast, switching regulators are efficient, flexible, and small, but they emit high-frequency noise. Switching regulators use Field Effect Transistors (FET) to transform the DC input voltage into an AC waveform, which is then converted back to DC at a different output voltage using capacitors and inductors.

## Switching Regulators

Switching regulators are classified according to the relationship between their input and output voltage.

- ▶ **Buck switching regulator:**  $V_{out}$  is less than  $V_{in}$ .
- ▶ **Boost switching regulator:**  $V_{out}$  is greater than  $V_{in}$ .
- ▶ **Buck-boost switching regulator:**  $V_{out}$  is variable: it could be lower, higher, or the same as  $V_{in}$ .

Figure 2 below compares the four commonly used regulator topologies: Low-Drop linear regulators (LDOs) and the three switching regulators —buck, boost, and buck-boost.

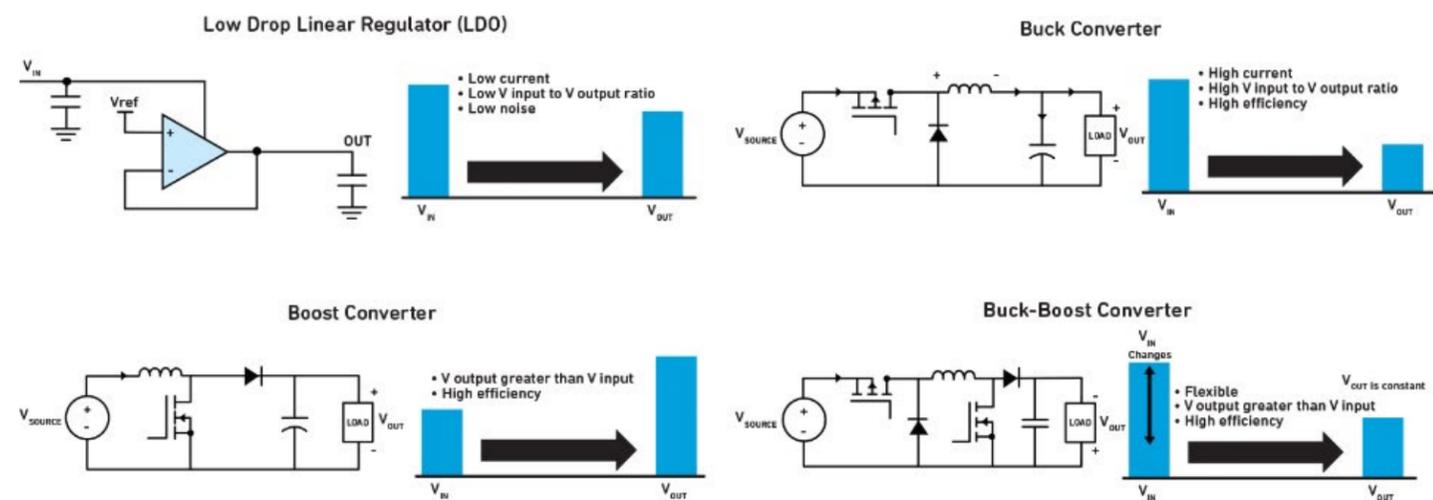


Figure 2: A comparison of four commonly used regulator technologies. (Source: Qorvo).



# Meeting Complex Objectives While Simplifying Designs

Today's PMICs can handle several or even all the voltage regulation functions needed within an electronic device.

## Today's Power Management Integrated Circuits (PMICs)

PMICs are small, versatile integrated circuits used for voltage conversion, voltage regulation, and battery management (Figure 3). Today's PMICs can handle several or even all the voltage regulation functions needed within an electronic device. They can be adapted for different applications by simply changing the firmware or register settings, eliminating the need for costly hardware changes. This helps develop new applications faster at a lower cost.

**ACT88321 Advanced Power Management ICs (PMIC)**



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**ACT85610 PLP Power Management IC (PMIC)**



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**ACT85610EVK1-101 Evaluation Kit**



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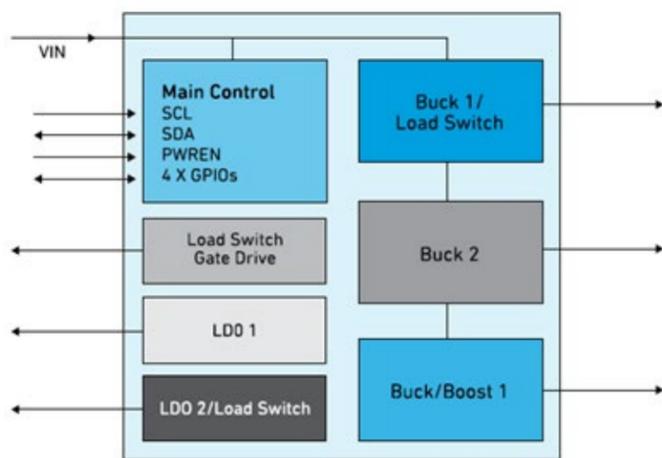
**ACT81460VM101 Low Power PMICs**



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Today's power management ICs combine multi-rail buck, boost, and LDO regulation with sophisticated configurability of each rail's parameters and interaction with other rails.



**Figure 3:** PMICs are small, versatile integrated circuits used for voltage conversion, voltage regulation, and battery management. (Source: Qorvo).

PMICs are used across many different industries and product categories. They can perform a wide variety of functions, including charging, power loss protection and DC-DC conversion and regulation. Because of their tiny size and low power consumption, PMICs are used in many small devices such as wearables; hearables such as earbuds, mobile devices, sensors; and Internet of Things (IoT) devices. They maximize product performance and efficiency, increase design flexibility, and reduce bill-of-materials cost, helping manufacturers reduce overall cost and accelerate time-to-market.

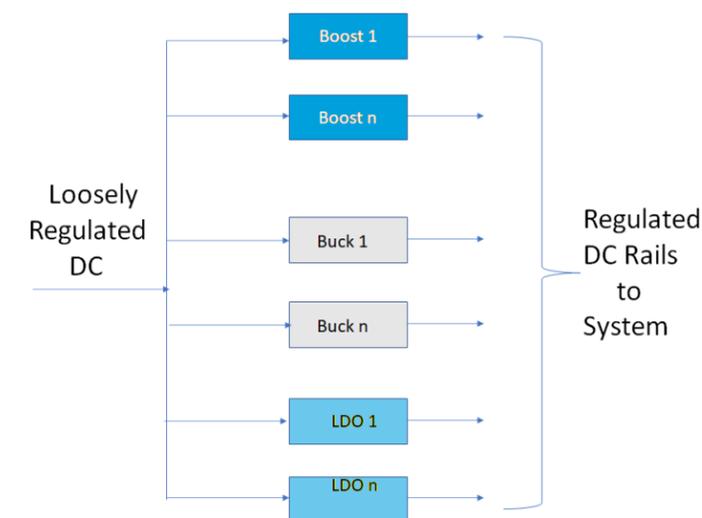
Experienced circuit designers know that stable, accurate, and efficient direct current (DC) power rails are necessary for achieving reliable and consistent system operation. Various voltages are usually provided by a combination of DC/DC switching regulators (converters) and low-dropout regulators (LDOs), each matched to the particular voltage, current, accuracy, noise, transient response, and other needs of the rail they support.

At the same time, designers know that a set of independent DC rails, even if individually suitable, is not enough to meet the complicated requirements of today's designs. It's not unusual for a system to have four, six, or more DC rails in close physical proximity. Because of the large number of rails, it is critical to manage these rails both individually and as a group to ensure the needed timing, sequencing, and relationships among them (Figure 1).

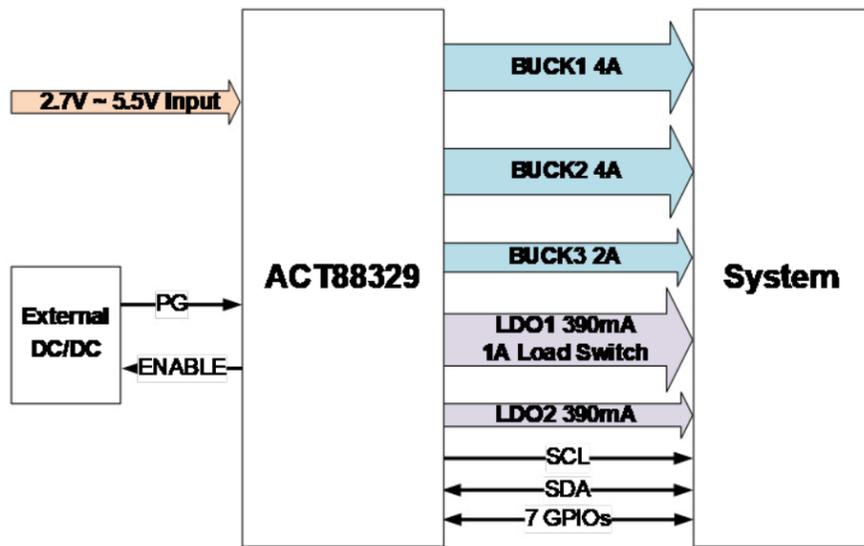
That's where power management integrated circuits (PMIC) play a major role. As the name implies, this component manages multiple rails and choreographs their interaction to meet the system's specific needs. Although the earlier

generation of PMICs was primarily managers of other DC/DC regulators, today's PMICs are integrated with multiple switching converters and LDOs in the same package. This integration brings many immediate advantages, of course, concerning smaller overall footprint, need for fewer passive components, and tightly functional linkage among the various rails. Even better, latest-generation PMICs are also highly configurable by design to tailor their operation to the priorities of the system they power.

**Figure 1:** Today's systems use an array of multiple DC rails provided by boost, buck, and LDO regulators, which have independent outputs, but their actions need configurations, and their outputs must also be coordinated to some extent depending on the application specifics. (Source: Mouser Electronics).







**Figure 3:** The Qorvo ACT88329 PMIC supports configuration of key regulator functions, sequencing, switching frequency, and other operating modes to optimize system-level performance. (Source: Qorvo).

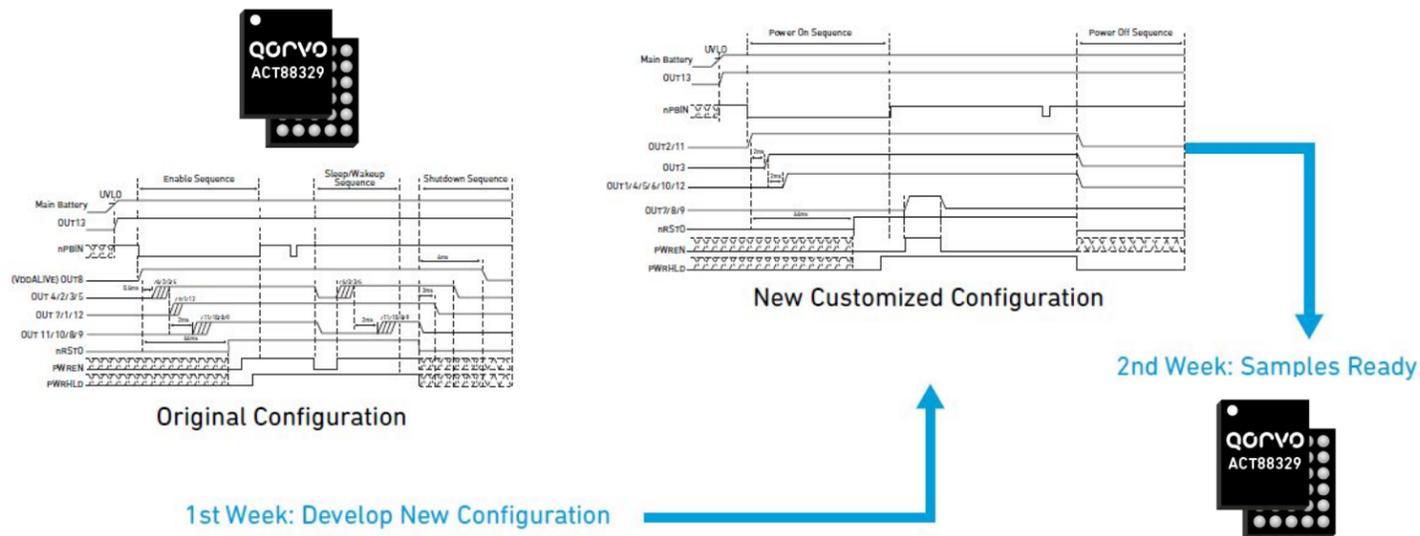
For example, the **ACT88329** PMIC features four DC/DC step-down converters (one with bypass function) using integrated power FETs, and two LDOs; each regulator can be configured for a wide range of output voltages (**Figure 3**). In addition, other functions such as startup time, system-level sequencing, switching frequency, sleep modes, and operating modes can be configured and even reconfigured through the I<sup>2</sup>C interface without the need for circuit-board changes. The ease of configurability is among the critical factors allowing users of ActiveCiPS™ PMICs to quickly establish and even change the settings for their design via a USB-to-I<sup>2</sup>C dongle and GUI to optimize performance for their specific design (**Figure 4**).

The combination of the high integration and I<sup>2</sup>C configurability for this tiny 36-pin WLCSP package (2.7mm x 3 mm) device

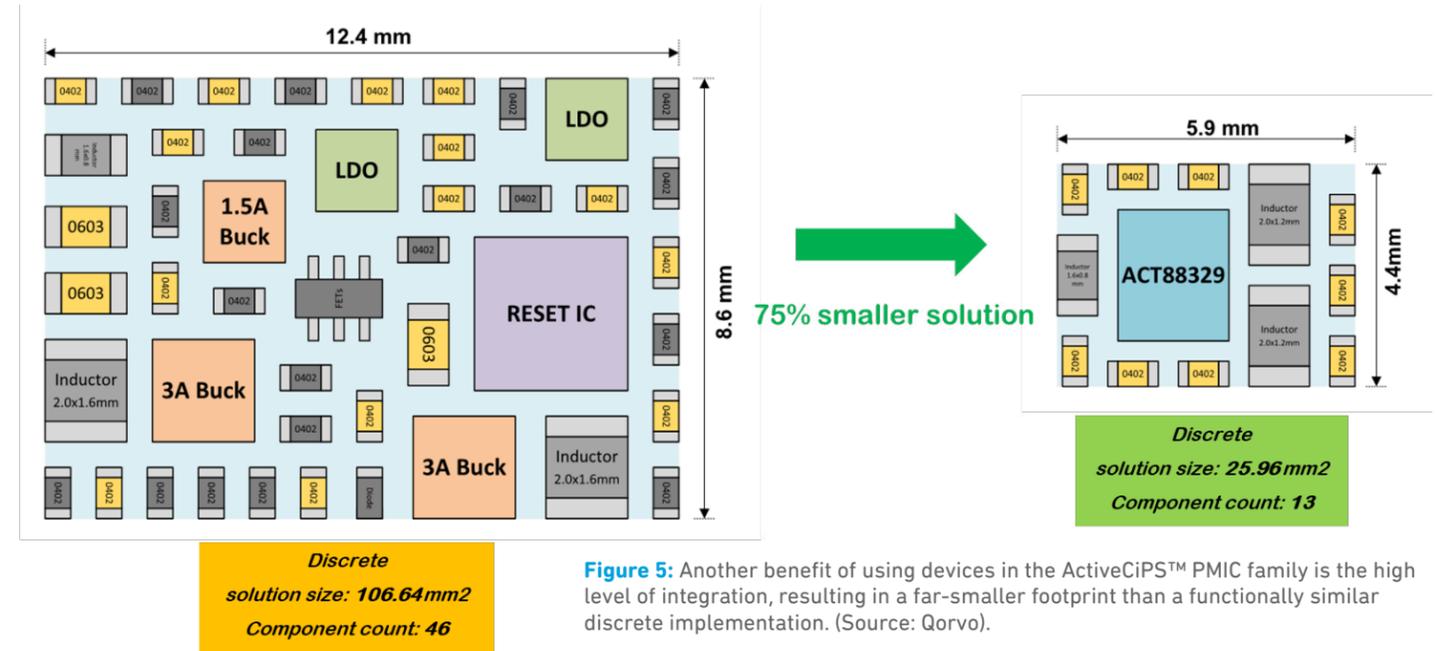
results in an overall solution with about one-third the footprint of discrete-solution alternatives and with a far-shorter BOM (**Figure 5**).

### Evaluation kits, GUIs pull it all together

Fitting a configurable device into a design brings up two related issues. Unlike a fixed-function device, where the datasheet alone defines the operating parameters and envelope, the designer must determine the optimal settings and then implement these values for the configurable device in this situation. To simplify this process, Qorvo offers evaluation kits and programming dongle for its ActiveCiPS™ PMIC family. These include all the hardware, software, and hooks needed to set, adjust, and assess PMIC performance in a given application.



**Figure 4:** Designers can assess performance with various parameter configurations and then easily reconfigure them for optimized performance using a Qorvo-supplied GUI and a PC linked to an ACTIVECiPS™ PMIC. (Source: Qorvo).



**Figure 5:** Another benefit of using devices in the ActiveCiPS™ PMIC family is the high level of integration, resulting in a far-smaller footprint than a functionally similar discrete implementation. (Source: Qorvo).

For example, consider the **ACT88329** PMIC and its evaluation kit. This 2.18mm x 2.58 mm device in a 30-ball WLCSP package is optimized for solid-state drive (SSD) and field-programmable gate-array (FPGA) applications but is also a good fit for video processors, FPGAs, wearables, peripherals, and microcontrollers (**Figure 6**).

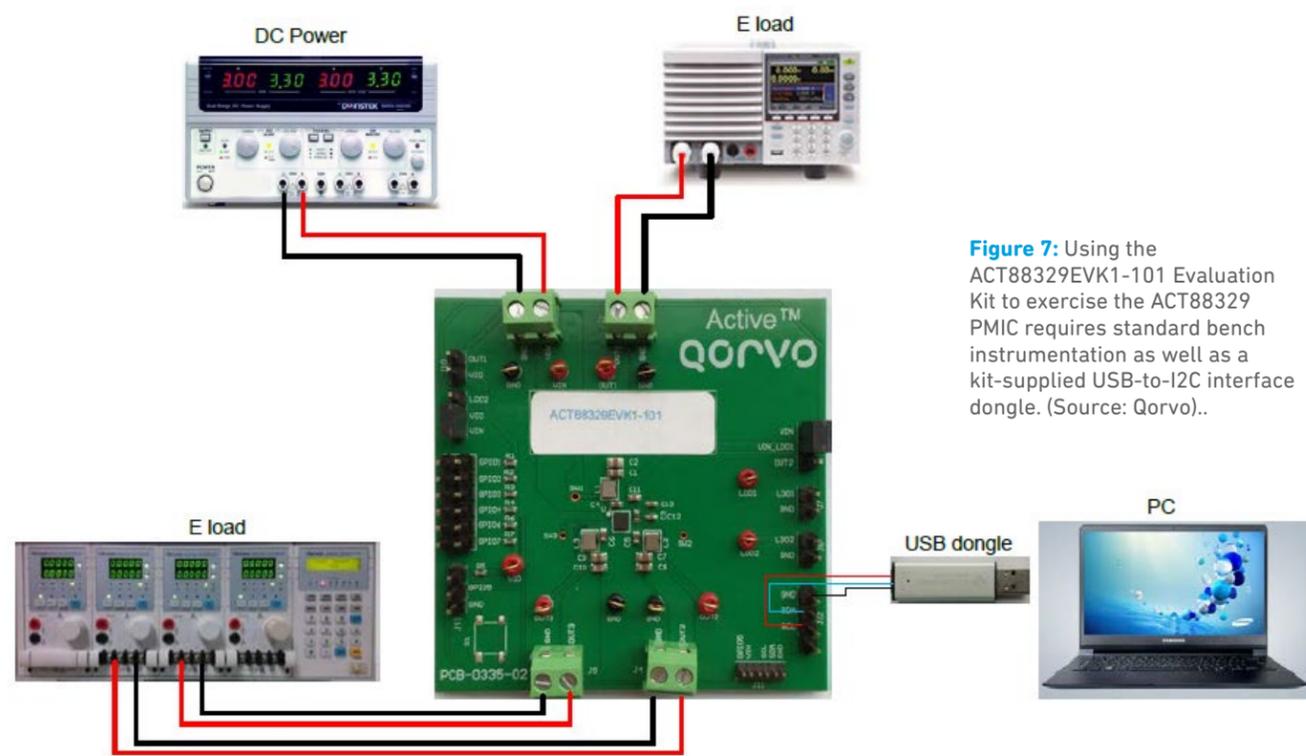


**Figure 6:** ActiveCiPS™ Dongle enables you to debug your design and change the PMIC default settings on your boards on the spot. (Source: Qorvo).

ACT88329 includes three DC/DC step-down converters using integrated power FETs and two LDOs. Buck1 and LDO1 can be configured as a load switches. Buck1 is a peak-current mode, fixed-frequency DC/DC step-down converter optimized for output voltage close to the input voltage. It can be set to switch at either 1.125MHz or 2.25MHz and requires only three small components for operation. Buck2 and Buck3 use asynchronous constant on-time control architecture to optimize the load transient response with smaller output capacitors. The LDOs only require small ceramic capacitors.



Qorvo offers evaluation kits and programming dongle for its ActiveCiPS™ PMIC family.



**Figure 7:** Using the ACT88329EVK1-101 Evaluation Kit to exercise the ACT88329 PMIC requires standard bench instrumentation as well as a kit-supplied USB-to-I2C interface dongle. (Source: Qorvo)..

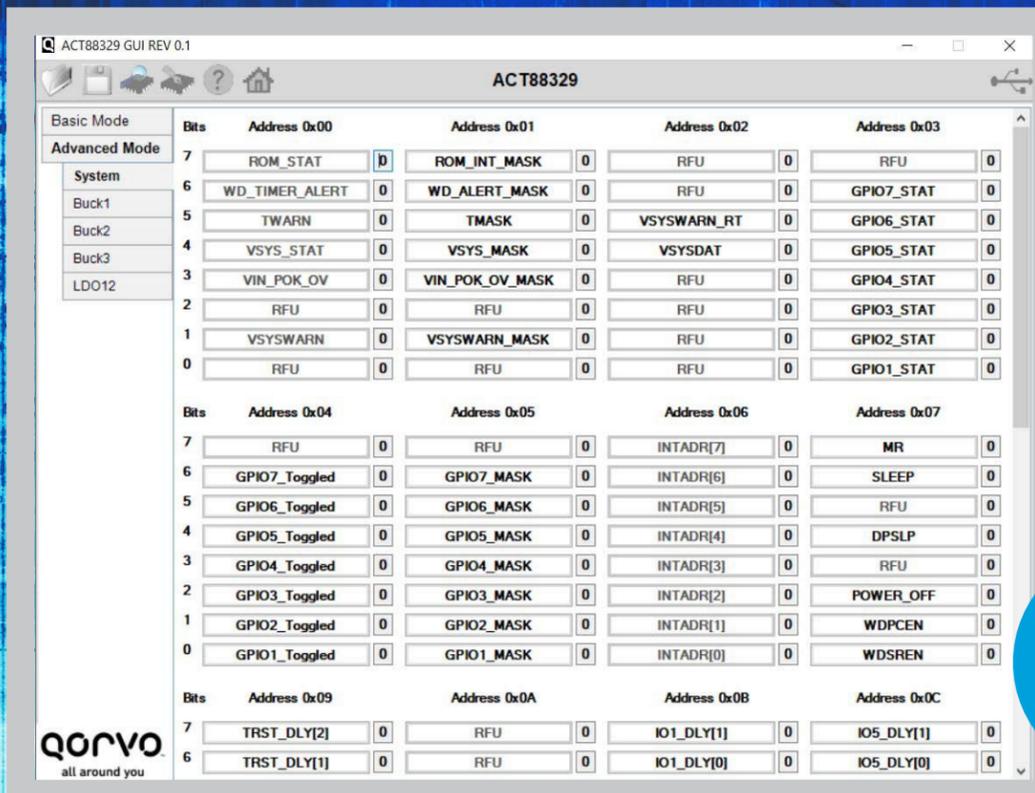
Configuring this versatile, flexible device involves examining and characterizing multiple parameters.

Configuring this versatile, flexible device involves examining and characterizing multiple parameters. The task is greatly simplified by the corresponding **ACT88329EVK1-101 Evaluation Kit (Figure 7)**. Using this kit requires just a few standard engineering items. (If you don't have an electronic load, the power level is low enough—on the order of a few tens of watts—that a traditional resistive load can be used, but the e-load is much more versatile). All that is required are the following:

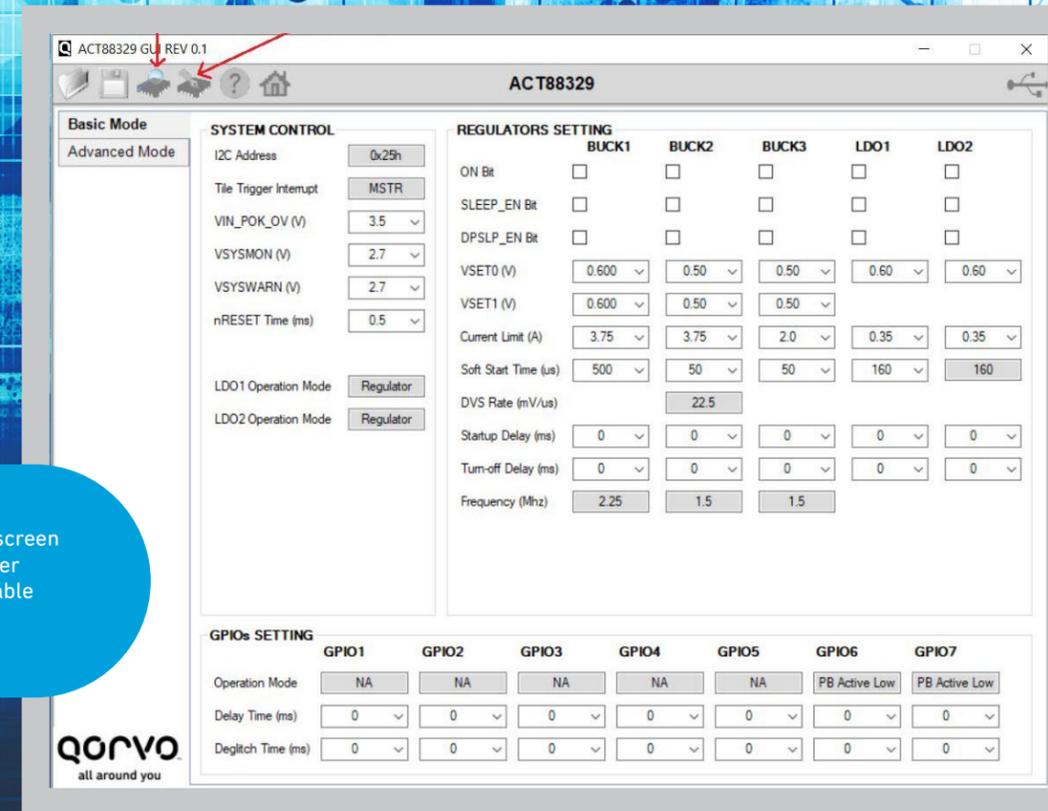
- ▶ A supplied USB-to-I<sup>2</sup>C “dongle”
- ▶ Power supply (3.3V/4A for full-power operation)
- ▶ Oscilloscope (100MHz, two channels)
- ▶ Loads, electronic or resistive (3A minimum-current capability)
- ▶ Digital multimeters (DMM)
- ▶ Windows-compatible computer with available USB port

The PC-based GUI begins with a basic mode that allows the user to easily change one or more IC settings (**Figure 8**).

The basic mode is followed by an advanced mode that lets designers see all available user-programmable options (**Figure 9**).



**Figure 8:** The Qorvo-supplied PC-based GUI features easy-to-use screens such as this basic one used to begin the configuration process. (Source: Qorvo)



**Figure 9:** A subsequent screen of the GUI provides further insight into the configurable options. (Source: Qorvo).

### ACT88329 Advanced Power Management ICs (PMIC)

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### ACT88329EVK1-101 Evaluation Kit

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### Conclusion

Designers benefit from PMICs, which do more than just provide multiple DC rails via buck, boost, and LDO regulators and manage their sequencing and interaction. Sophisticated PMICs in the Qorvo ActiveCiPS™ family also support the initial configuration of various critical performance attributes of the multiple power rails along with reconfigurability. The result is that designers can develop tailored, optimized multi-rail performance for their power-distribution topology.

Using the evaluation kit arrangement, designers can set up, evaluate, and modify the many operating parameters and modes of these PMICs, such as sequencing among rails (Figure 10). The kit also eases measurement of figures of merit such as efficiency under various conditions, critical for meeting run-time and thermal objectives (Figure 11).

The EVK User's Guide also provide a complete schematic, BOM, and layout of the four layers of its PC board if designers want to use that as a starting point for their own implementation.

Figure 11: The evaluation kit also simplifies the measurement of important performance metrics such as the efficiency of the various PMIC rails under different operating conditions, shown for Buck1 and Buck2 of the ACT88329 PMIC. (Source: Qorvo)

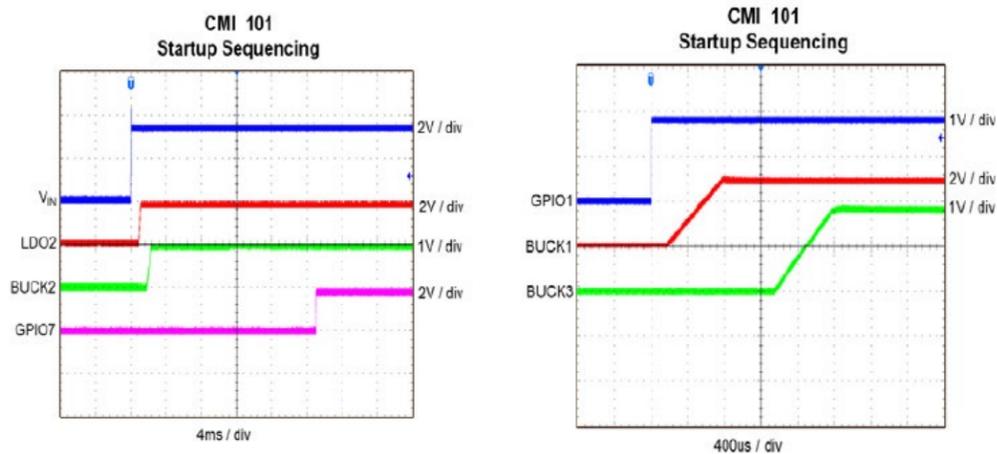
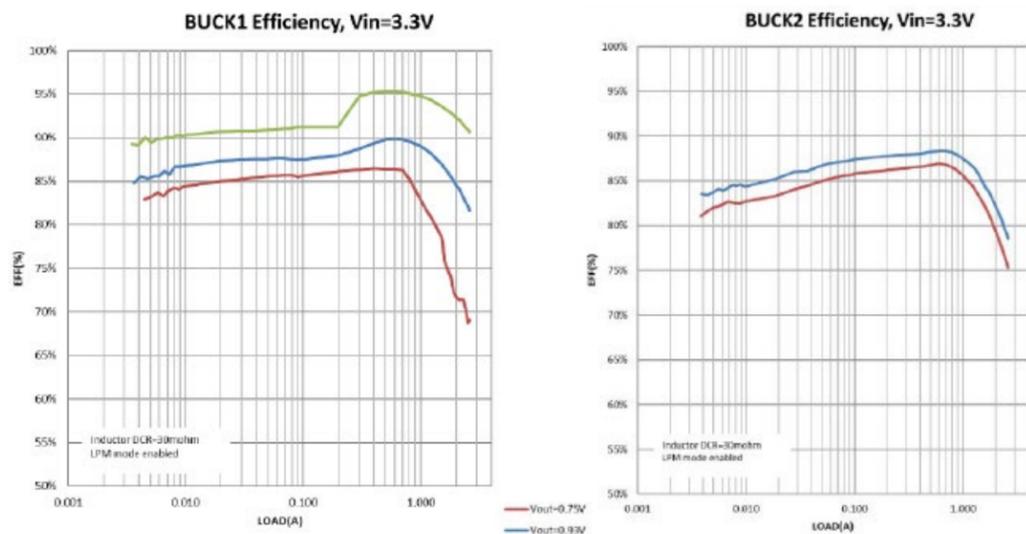


Figure 10: Using the evaluation kit and associated instrumentation, designers can configure, evaluate, and reconfigure key parameters such as relative sequencing of the various power rails. (Source: Qorvo)



# You've Got the Power: 6 Essentials for Brushless DC Motor Control

Consumer demands for more power, reliability, functionality, and performance shape the rapid evolution of electronic devices—from lawnmowers, refrigerators, vacuums, automobiles, and more. Manufacturers are eager to deliver on all fronts. Motor control plays a chief role in making these promises, and understanding the fundamentals is the first step to getting there.

### The Different Motor Types

Today, several motor control topologies—brushed, brushless DC (BLDC), stepper, and induction—are available. The two most closely related brushless motor types are BLDC and permanent magnet synchronous motors (PMSMs).

Brushless motors have become very popular for many of today's applications because they eliminate the need for motor brushes. These BLDC topologies use commutation logic to move the rotor, making them more efficient and reliable. Let's examine in detail.

### Understanding BLDC and PMSM Type Motors

BLDC and PMSM motors work on the principle of a synchronous motor. 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 winding, allowing them to produce different back-electromotive force (BEMF) responses. The BLDC BEMF is trapezoidal. The PMSM motor has a sinusoidal BEMF, so the coil windings are wound in a sinusoidal fashion. To maximize performance, these motors generally use sinewave commutation.

BLDC and PMSM motors (Figure 1) generate BEMF by their windings when operated. In any motor, because of motion, the EMF produced is known as back-EMF (BEMF) because the EMF induced in the motor opposes the EMF of the generator.

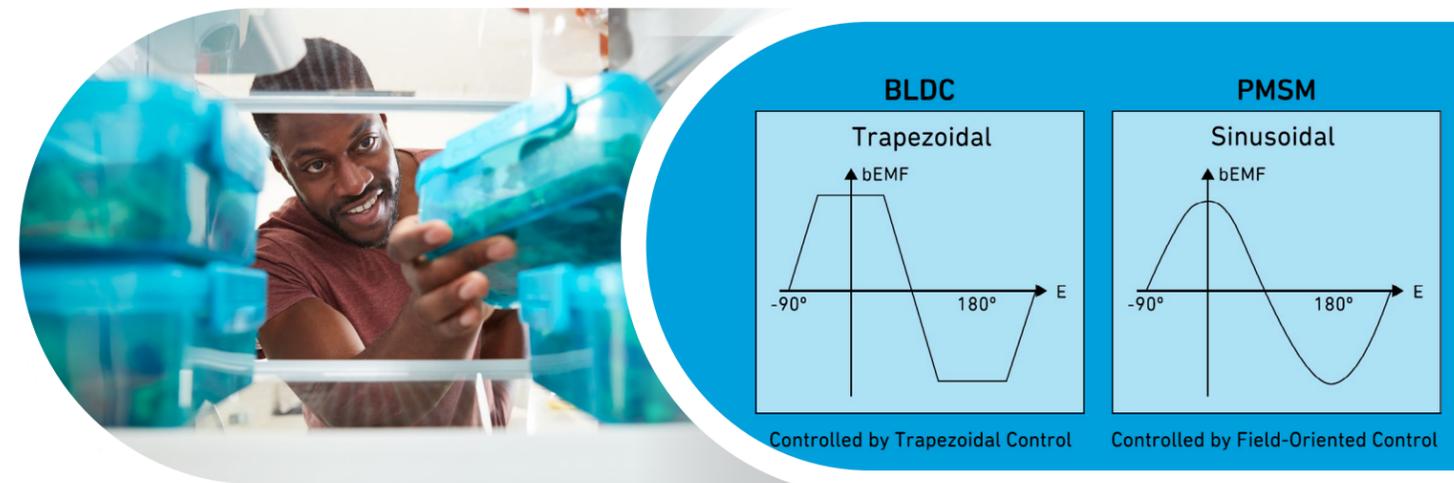


Figure 1: BLDC and PMSM motors generally use sinewave commutation (Source: Qorvo).

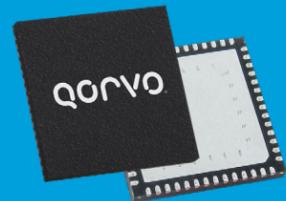


The main advantage of the BLDC is it is easier to control. Ultimately, the choice of which motor is best depends on its application.

### An Explanation of Field-Oriented Control

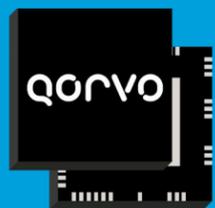
To achieve the sinusoidal waveform that controls the PMSM motor, a field-oriented control (FOC) algorithm is required. FOC is typically used to maximize the efficiency of the PMSM three-phase motor. The sinusoidal controller for the PMSM is more complex and costlier than the BLDC trapezoidal controller. However, this cost increase has advantages such as lower noise and less harmonics in the current waveform. The main advantage of the BLDC is it is easier to control. Ultimately, the choice of which motor is best depends on its application.

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### Sensored and Sensorless BLDC and PMSM motors

BLDC and PMSM motors can be sensed or sensorless. Sensored motors (Figure 2) are used in applications requiring the motor to start up under a load condition. They use Hall sensors, which are embedded into the motor stator. The sensor is essentially a switch with a digital output equal to the sensed magnetic field polarity. The motor requires a separate Hall sensor for each phase. A three-phase motor requires three Hall sensors. Sensorless motors require algorithms to operate using the motor as the sensor. They rely on BEMF information. By sampling the BEMF, the rotor position can be deduced, eliminating the need for hardware-based sensors. Regardless of motor topology, controlling these motors requires knowing the rotor position so the motor can be efficiently commutated.

### Motor Control Software Algorithms

Today, software algorithms (a set of instructions designed to perform a specific task), such as computer programs, are used to control BLDC and PMSM motors. These software algorithms improve efficiency and reduce operating costs

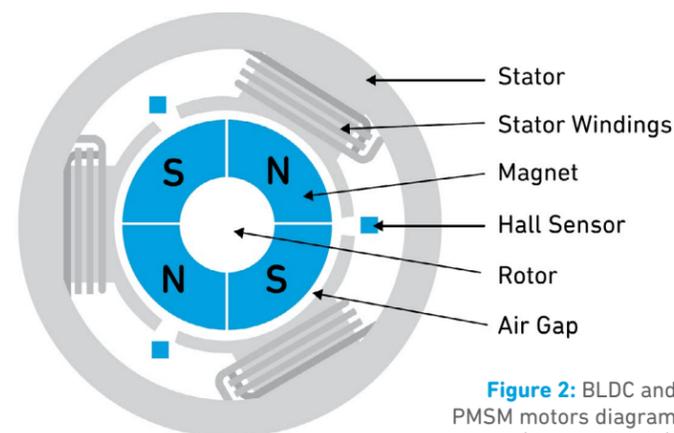


Figure 2: BLDC and PMSM motors diagram (Source: Qorvo).

by monitoring and controlling motor operations. Some of the primary functions of algorithms are motor initialization, Hall sensor rotor position detection, and switch signal checking for increasing or decreasing the current reference.

### How Controllers Process Motor Sensor Information

A three-phase BLDC motor has six states. As shown in Figure 3, a three-bit code can represent an opcode number between 1 and 6. 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 has been issued and act on the legal opcodes (1 through 6). The algorithm obtains the Hall sensor opcode and decodes it. When the Hall sensor opcode changes in value, the controller changes 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.

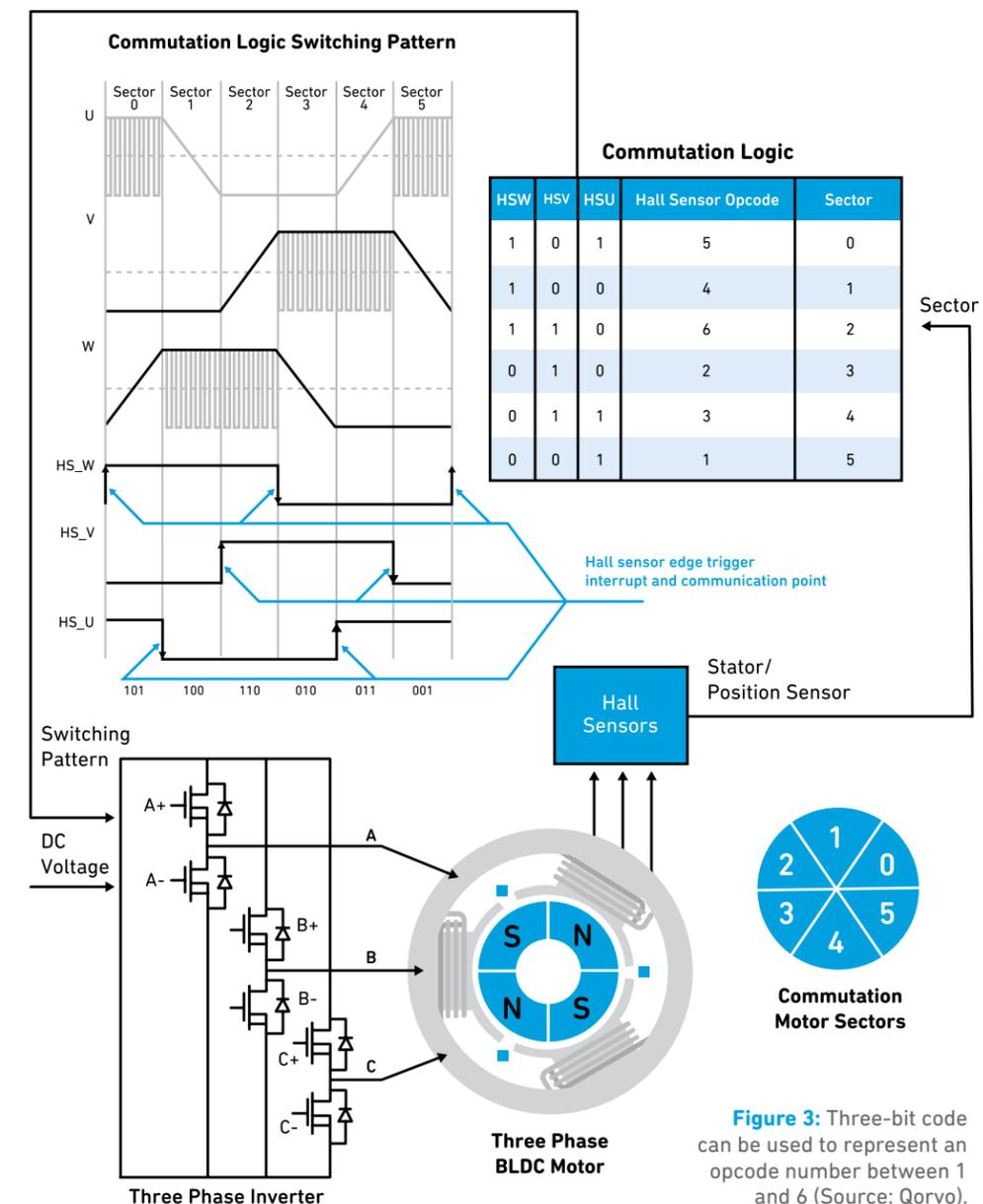


Figure 3: Three-bit code can be used to represent an opcode number between 1 and 6 (Source: Qorvo).

# Power Tool Design 101: Rev Up Your Knowledge of Brushless DC Motor Functionality



Jose Quinones, Senior Applications Engineer – Programmable Power Management

Over the past century, power tools have noticeably evolved. Today, they are wireless, light weight, battery-operated, and work hard, so we don't have to. So, what's fueling the evolution of power tools? Besides power-tool enthusiasts, much can be attributed to the many advancements in semiconductor technology, specifically cordless power tools.

In the following, we'll cover the key aspects of the cordless, battery-powered variant, including what's propelling the evolution and the challenges along the way. We'll also review how the microprocessor and the brushless DC motor play an instrumental role in transforming the power tools we use today. Additionally, we'll outline how the incorporation of brushless DC motors in power tools provides a competitive edge for manufacturers.

## Power Tool Main Components

The first component of an electric power tool is the power source. All electric-powered tools can be subdivided into corded and cordless.

- ▶ Corded tools—The power source is AC and needs to be plugged into to operate.
- ▶ Cordless or wireless power tools—Rely on the electric energy stored within batteries of different chemistries such as Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), and Lithium-Ion (Li-Ion).

The Lithium Ion-based battery has become the most prominent because of its increased energy density and resilience to hold a charge.

The second component is an actuator or a motor that will transform the electric energy into mechanical energy. This motor can be a universal AC/DC brushed motor, a brushed DC motor, or a brushless DC (BLDC) motor. Many of today's tools have moved to the tri-phase BLDC motor topology.

Finally, a switch is employed to control the source-to-motor energy transfer. This component could be as simple as an interrupter, controlling whether there is a current flow. Or it could be something slightly more sophisticated, such as a potentiometer, allowing the user to specify how much energy flows from source to motor.

## Power Tool Challenges

For the first 100 years of electric power tool development, a power source, a motor, and a switch/potentiometer were all that were needed to design and fabricate drills, sanders, grinders, screwdrivers, blowers, saws, etc. However, in the 20th century, the emergence of high-energy-density batteries changed this. Additionally, we saw the emergence of green energy solutions and their integration into all forms of design.

The challenge was to continue using a potentiometer to control tool speed without passing the high current through its resistive component. As we will see later, this is a relatively simple fix. The motor, on the other hand, proved to be a far more substantial and complex challenge.

Early in power-tool development, the motor employed was either a brushed universal AC/DC motor for corded tools or a brushed DC motor for cordless tools (**Figure 1**). Because both motor topologies are brushed in nature, motion is obtained by using carbon brushes to pass a current into a copper commutator, generating an internal revolving magnetic field. By placing the electromagnet winding along with the commutator in the rotor, and the permanent magnets in the stator, we obtain two magnetic fields continuously fighting each other and causing the motion we need.

Unfortunately, this comes at the cost of considerable friction between the brushes and the commutator. The friction is considerable, and after prolonged use, the motor will eventually destroy itself. This friction is energy wasted in the form of heat. That is energy that flowed out of the power source and did not generate any useful work. Systems revolving around this topology give an efficiency no higher than 80 percent (in the best-case scenario). This means 20 percent of the energy inside of the battery is used to generate heat.

When trying to make holes with a battery-powered drill, using a fifth of your power source to generate heat does not sound very appealing.

## Brushed DC Motor

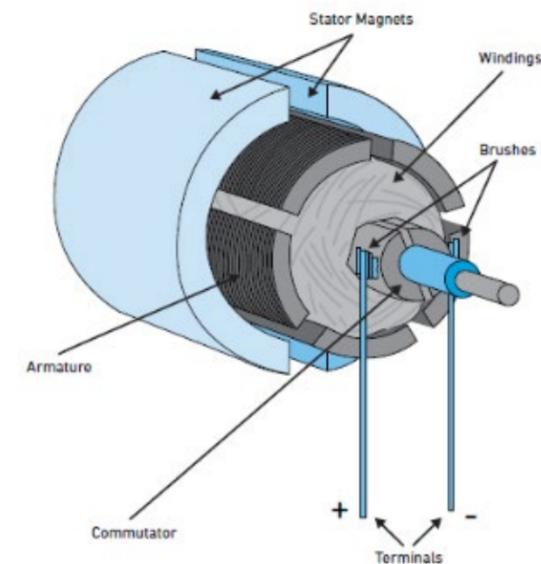


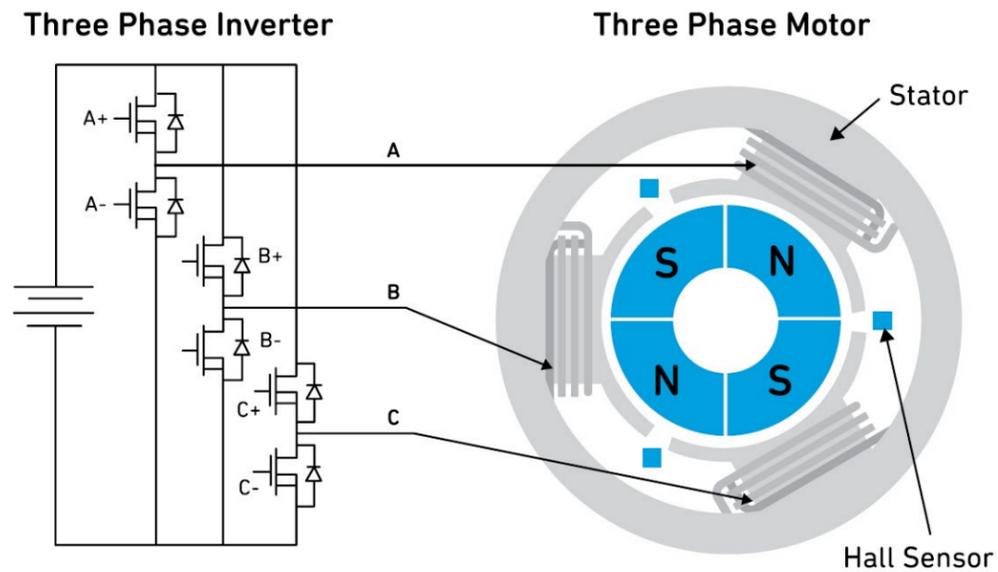
Figure 1: Brushed DC motor. (Source: Qorvo).

**PAC5527 48V Charge Pump and Programmable Driver Motor Controller**

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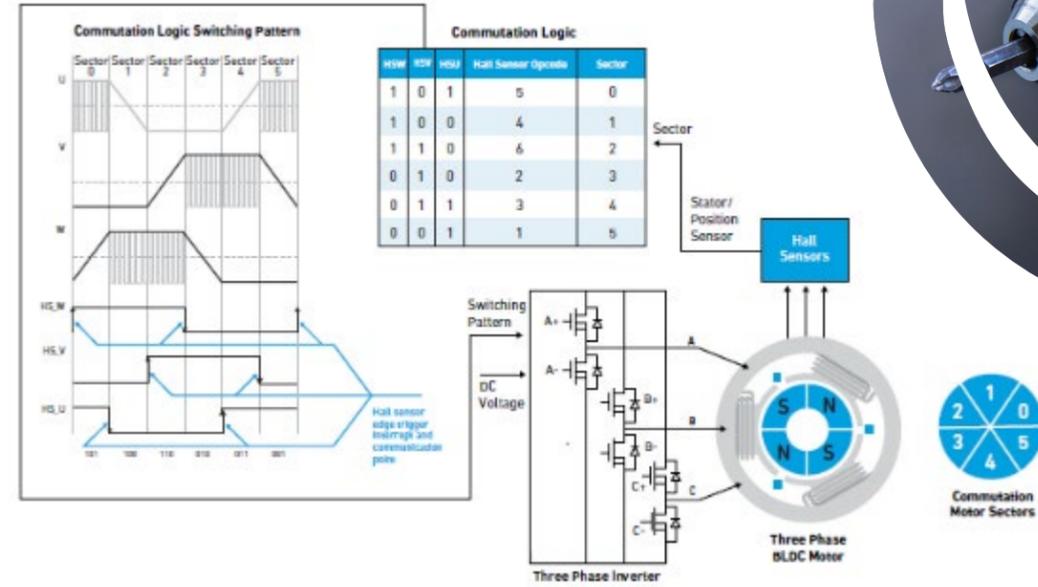


The use of BLDC motor manufacturing is revving up...



**Figure 2:** Replacing or removing brushes and commutators is essential in the tri-phase BLDC motor topology (Source: Qorvo).

### BLDC Motor Commutation



**Figure 3:** BLDC motors do not have a physical commutator and must use commutation logic sequencing. To obtain efficiencies, both magnetic fields must be aligned as perfectly as possible using a control circuit. (Source: Qorvo).

### Meeting the Challenges Using BLDC Motor Topology

Given the challenges discussed above, it becomes apparent that replacing or removing the brushes and commutator is essential. This is highlighted in the tri-phase BLDC motor topology (**Figure 2**). A BLDC motor can give us the same rotational motion without using brushes or a mechanical commutator. Instead, we generate the revolving magnetic field electronically. Using electronic circuitry, we can create two magnetic fields fighting each other to develop motor motion. The advantage: is no friction between the rotor and stator components, which increases reliability and energy efficiency.

Tri-phase BLDC motors can reach efficiencies as high as 96 percent. This means our battery will only waste a 20th of its energy in the form of heat.

As with all designs, employing BLDC motors has some challenges. Brushed DC motors solve the inherent problem of aligning magnetic fields to obtain the most efficient motion profile. They achieve this when the commutator sequence is designed and placed so that the revolving magnetic field is always in tune with the permanent magnets' field. However, because BLDC motors do not have a physical commutator, this action is done using commutation logic sequencing. To obtain the efficiencies we referenced, we must align both magnetic fields as perfectly as possible using a control circuit such as the one in **Figure 3**.

This sophisticated circuitry extracts the rotor's position to align both magnetic fields electronically. In the case of a tri-phase BLDC motor, this block is most often made of a microcontroller and a tri-phase inverter power stage employing sensors, such as a Hall Sensor, to extract the rotor's position information. Adding this circuitry does take up some space and adds some cost. However, manufacturers are seeing the benefits of being untethered, and consumers demand these types of motor solutions. Thus, more power tools are being designed using tri-phase BLDC motor topology.

### The Sophisticated Power Tool

Modern power tools still consist of a power source, a motor actuator, and a means to control energy flow, such as a potentiometer. However, to provide all the energy preservation, we need to add intelligence.

A microprocessor provides intelligence. With a microprocessor, we can now monitor the power source and provide the required actuation. We can also monitor the value of the potentiometer and control the motor speed without having to pass the current through its resistive component. We achieve this by using Analog to Digital Converters (ADC). The energy expenditure in this action is negligible.

However, the most important aspect of the microprocessor is to provide an efficient mechanism to properly energize tri-phase BLDC motors to obtain the efficiency improvements that battery-powered tools require. The microcontroller-based power stage provides all the tools to generate a properly aligned revolving magnetic field, which translates into the best possible motion profile.

The PAC5527 contains a DC/DC converter that takes the battery voltage and steps it down to the different rails required to power the system's different blocks. Three high-current pre-driver stages required to drive a very powerful tri-phase inverter (over 1kW) are included. Its ADC, with a programmable sequencer, allows for the coordinated capture of multiple analog parameters without affecting the

central processing unit's (CPU's) real-time. It encompasses protection blocks to ensure the system current is kept within bounds, protecting against hazardous conditions that can induce tool damage while at the same time removing the user from harm's way, such as a fire. Multiple general-purpose input/outputs (GPIOs) to monitor different signals are provided. Even the circuitry to extract rotor position allows us to generate a fully aligned revolving magnetic field, which forms part of the arsenal of tools encased within a single PAC5527 device.

The PAC5527 generates one of the smallest possible tri-phase inverter power drivers. They're so small, power tools revolving around this solution can be shaped to be ergonomically efficient while enhancing the power tool's energy efficiency. Additionally, because of its small footprint and high level of integration, the entire application's cost structure is also optimized.

### The Next Wave of Power Tools

The use of BLDC motor manufacturing is revving up, and as technology continues to evolve, these motors will become even more user-friendly, effective, and reliable. Because of the onset of electronically controlled BLDC motors, tools are more powerful, more efficient, smaller in size, and lighter in weight. With each passing year, Qorvo will continue to provide innovative products such as the PAC5xxx series of parts to further propel tri-phase BLDC motor topology.

**PAC5526 48V Charge Pump and Programmable Driver Motor Controller**



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# Solving BLDC Controller Design Challenges with the Qorvo PAC5556

Robert Huntley for Mouser Electronics

Brushless DC motors have become a popular choice for use in a wide range of consumer and industrial appliances. Building a controller for a BLDC requires several key functions, all of which are combined in the single-package Qorvo PAC5556 Power Application Controller® (PAC™).

## Brushless Motors Gain Traction

Brushless DC (BLDC) motors have become the default choice of motor for a wide range of battery and line-powered equipment and appliances. More reliable and requiring significantly less maintenance than their brushed DC motor counterparts, brushless DC motors have benefited from a broader industry understanding of how to control them using simple microcontroller algorithms. In today's complex and sophisticated control applications, brushed motors also create too much electrical noise, which means designers need to employ substantial electromagnetic immunity mitigation techniques. Audible noise from brushed motors is now considered undesirable, particularly for portable battery-powered appliances such as vacuum cleaners and personal power tools, including jigsaws and drills/drivers.

Manufacturers construct brushless DC motors using fixed permanent magnets on the rotor drive shaft and a series of field windings (typically three) inside the motor casing. Switching the current through the three field windings in sequence results in the rotation of the drive shaft. Controlling the pulse width and the switching frequency of the drive to each field coil provides control of motor speed, acceleration, and output torque. A closed-loop feedback of the rotor's operation to the three-phase motor control algorithm is required to closely monitor and control the current state of the drive shaft's rotation. The two most popular methods of providing this feedback are:

- ▶ Affixing an encoder disk or other form of rotational sensor to the rotor shaft.
- ▶ Sensing the back electromagnetic field induced by the rotor's permanent magnets within the field windings. Field-oriented control (FOC) refers to using the induced field voltage.

A sensorless method helps improve overall motor reliability and reduces the bill of materials (BOM) cost.

**Brushless DC (BLDC) motors have become the default choice of motor for a wide range of battery and line-powered equipment and appliances.**

## The Architecture of a BLDC Motor Controller

As mentioned, three distinct circuit functions are required for a brushless motor controller. These three distinct circuit functions are achieved through:

- ▶ A microcontroller that runs the motor control algorithm
- ▶ Pulse Width Modulation (PWM) circuitry that provides the switching signals
- ▶ A power output stage that drives the motor

An analog-to-digital function converts the shaft rotational sensor signals into the digital domain for processing by the microcontroller. When designing an embedded motor controller, several designs can be a consideration. The initial factors that help shape the overall design of an embedded motor controller are:

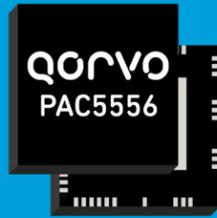
- ▶ The power/torque required
- ▶ The power supply source
- ▶ The shaft speed

Today's fast-paced prototype-to-production focus tends to dissuade design engineers from developing a custom controller using discrete parts. The more popular design route is to use an off-the-shelf microcontroller to run the control algorithm. Most microcontrollers incorporate a wide range of ADC/DAC conversion functions in addition to different peripheral interface options, clocks, and timers. A suitably equipped microcontroller might provide most of the required circuit functions. Still, many microcontrollers tend not to be optimized for motor control applications or incorporate the necessary half/full H bridge motor drive functions. Also, energy management is an essential function of most applications today and is especially important in motor control applications where the energy efficiency rating is usually a key selection criterion for customers. Power management ICs are available, but this requires the engineering team to integrate another IC into the design, increasing the BOM cost and board space requirements.

As more consumer and industrial motor-based appliances adopted a brushless DC motor design, the need for a device that includes all of the necessary functions drove Qorvo to develop a full-featured power application controller (PAC™). Qorvo's **PAC5556 Power Application Controller® (PAC™)** integrates all the required analog, power management, and gate drive signal sources within a single, compact package.

# PAC5556 Power Application Controller

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## Introducing the Qorvo PAC5556

The Qorvo PAC5556 Power Application Controller<sup>®</sup> (PAC™) is supplied in a slim QFN-52 package, can operate motors up to 600V<sub>DC</sub>, and incorporates a comprehensive set of features and functions necessary for any BLDC or smart energy application (Figure 1). The highly integrated PAC architecture makes the Qorvo PAC5556 especially well-suited for applications where the PCB is shrinking, such as white goods, compressors, and power tools.

A 150MHz 32-bit Arm<sup>®</sup> Cortex<sup>®</sup>-M4F microcontroller core with 128kB of user-programmable flash memory is at the heart of the device. A nested vectored interrupt controller (NVIC), capable of accommodating up to 25 external interrupts, provides a wake-up function to enable the device to come back from different sleep modes. Clock-gating of the 24-bit real-time clock permits low-power operation. The microcontroller unit (MCU) also incorporates a high-speed 12-bit ADC. Configured for little-endian operation, PAC5556's Arm<sup>®</sup> Cortex<sup>®</sup>-M4F microcontroller core includes hardware support for multiplication and division, DSP instructions, and an IEEE754 single-precision Floating Point Unit (FPU). The integrated FPU supports complex high-resolution control algorithms, such as the ones used with FOC. The high-performance features of this MCU enable design engineers to easily implement complex real-time algorithms, safety software, and diagnostics in their applications.

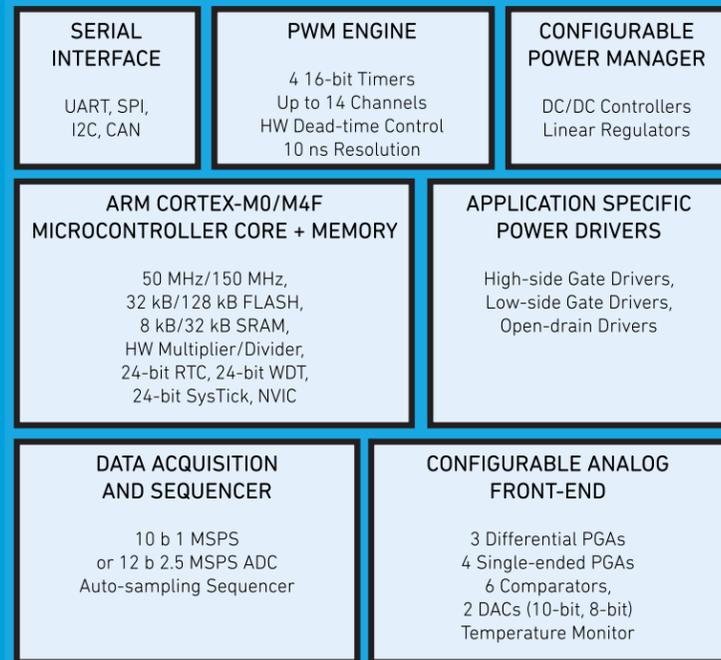
A pulse-width modulation (PWM) engine provides the drive signals for the motor gate drivers. Capable of fine motor control, down to 10ns, the PWM engine consists of four 16-bit timers and 32 channels.

The analog front end of the PAC5556 is highly configurable and offers both differential and single-ended programmable gain amplifiers, 6 comparators, 10-bit DACs, programmable over-current protection, integrated VM ADC sampling, and I/Os for inter-connectible and programmable signal sampling, feedback amplification, and sensor monitoring of multiple analog input signals. These analog capabilities make the device suitable for use in field-oriented control or sensor-based BLDC control applications.

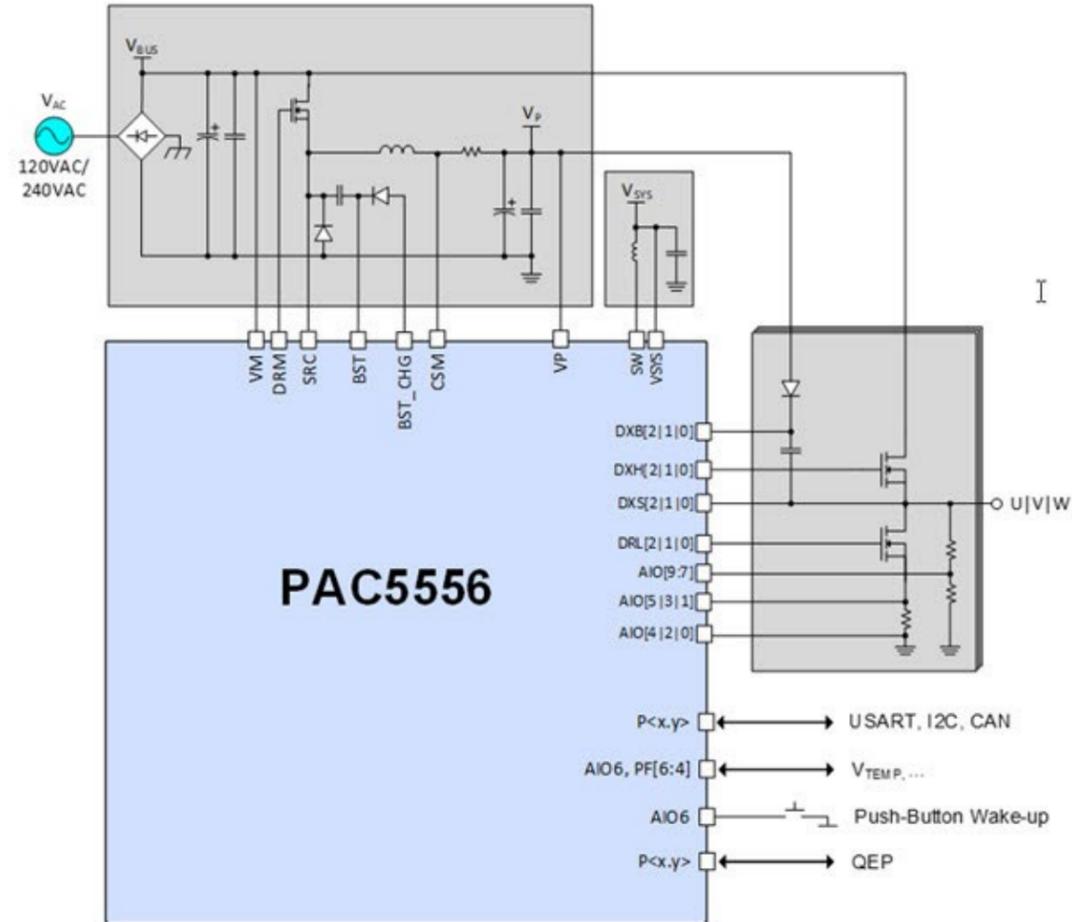
Other salient attributes of the Qorvo PAC5556 include a configurable power manager and application-specific power drivers. The configurable power manager contains a multi-mode switching supply converter that permits the IC and the motor-drive circuits to be powered using a buck-converter topology. On-chip linear regulators provide the IC supply rails, and the power management functions control the available sleep and hibernate modes. Designers can optimize the power manager for run-time and standby modes. PAC's very small standby current results in very good battery life in battery-powered tools when not in use. In equipment that is always connected to an AC (such as white goods), the power manager can help with ENERGY STAR ratings. The power driver block provides all the necessary high- and low-side gate drivers suitable for use in various motor-drive configurations, including half-bridge and full H bridge.

A simplified diagram of the Qorvo PAC5556 used to drive a BLDC motor is illustrated in **Figure 2**.

To aid the prototyping and development process, an evaluation board based around the Qorvo PAC5556 is available. The Qorvo **PAC5556EVK1** is a complete, fully featured evaluation and prototyping platform for the PAC5556 (Figure 3). The evaluation board supports gate driving for up to three half H-bridge inverters with ratings up to 220V<sub>AC</sub> or 450V<sub>DC</sub>. A virtual COM port connection to a computer and a GUI-based software suite permits configuration and control of any application running on the PAC5556EVK1.



**Figure 1:** The image provides a simplified functional block diagram of the Qorvo PAC5556 power application controller. (Source: Qorvo).

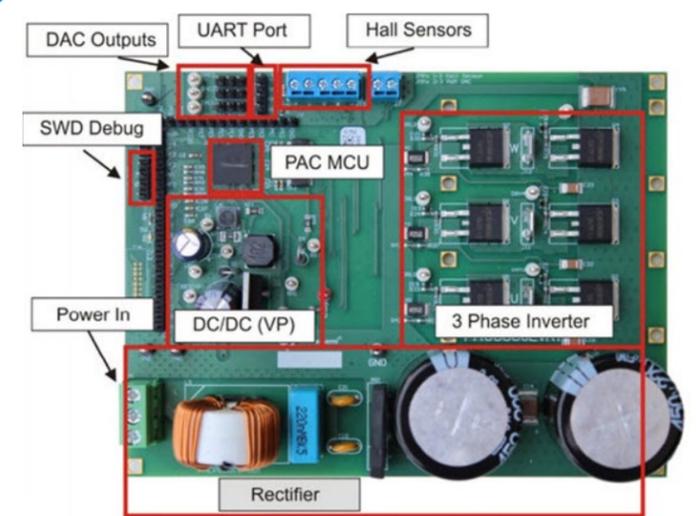


Brushless DC motors have become a popular choice in a wide range of consumer and industrial appliances.

**Figure 2:** The image provides a simplified diagram of a Qorvo PAC5556 used to control a BLDC motor. (Source: Qorvo)

## Conclusion

Brushless DC motors have become a popular choice in a wide range of consumer and industrial appliances. As brushless motors are incorporated into a broader range of applications, the ability to quickly design, prototype, and test motor controllers are keys to speeding the overall product design process. As a result, design engineers need a device that integrates all the required analog, power management, and gate-drive signal sources within a single package. The highly integrated Qorvo PAC5556 Power Application Controller meets the need for a compact power-control solution that reduces energy consumption, bulk, and noise in consumer and industrial motor applications. This design also meets tighter board space requirements and keeps the BOM cost to a minimum.

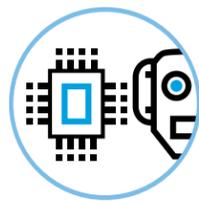


**Figure 3:** The Qorvo PAC5556EVK1 evaluation board. (Source: Qorvo)

# Power Application Controller® Ecosystem (PAC)

## Full System and Development Support

Qorvo's PAC, a family of single-IC solutions for motor control and power control applications, offers configurable, integrated and scalable solutions from 5.5 V to 600 V BLDC motor control applications. Just as important, Qorvo delivers best-in-class, full system and development support called the PAC ecosystem. From evaluation boards to free of charge (FOC) IP to applications support for sensor/sensorless BEMF and FOC to advanced algorithms, customers have tools and IP options at the ready.



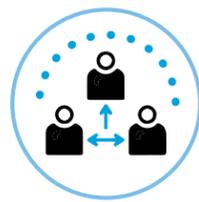
### Hardware Support

- Motor Control EVK
- Application Expertise Design



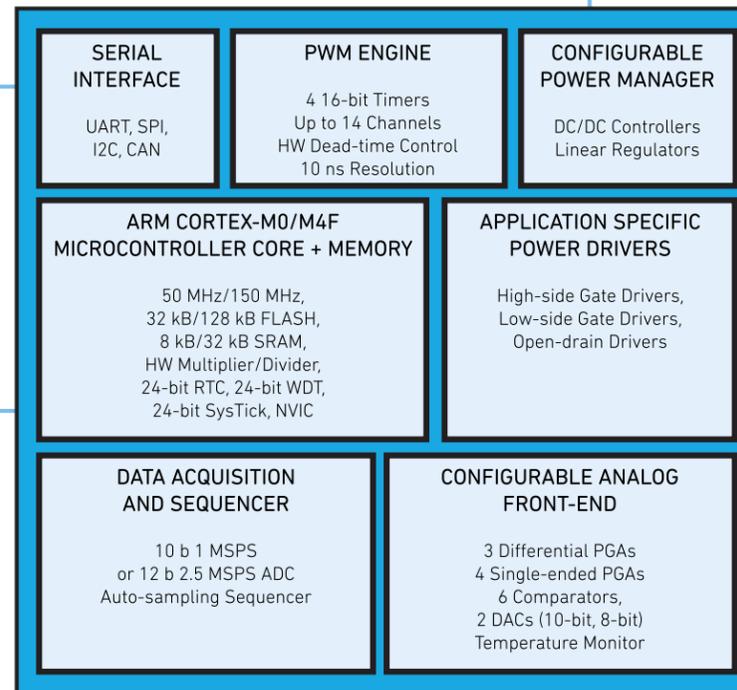
### Motor Control Applications

- Sensored/Sensorless BLDC
- Sensored/Sensorless FOC
- Peripheral Examples



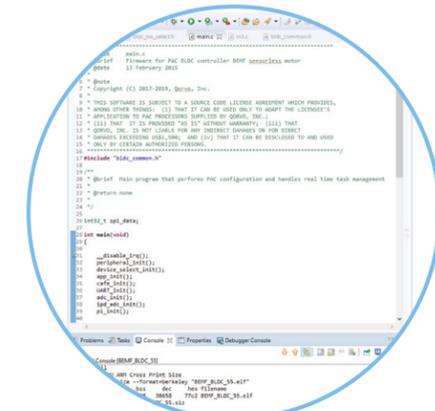
### Miscellaneous Tools

- UART Boot Loader
- UL/IEC 60730 Class B Safety
- LIN Master/Slave Driver
- CAN Controller/Driver
- Gang Programmers



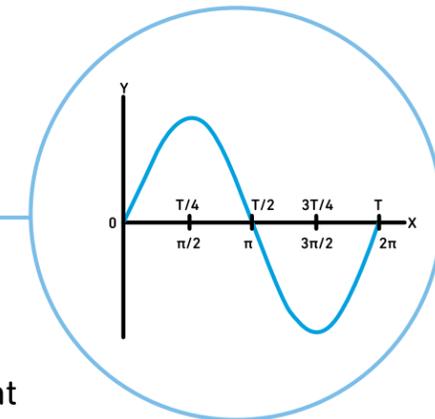
### Advanced Algorithms

- FOC Motor Auto-tuning
- Motor Failure Detection



### IDE/Programmer

- IAR/Keil/Eclipse
- J-Link/I-Jet



### FOC IP Features

- FOC Control
- Control Modes
- MTPA
- Single/Triple Shunt
- Sensorless Estimator
- FOC Configuration GUI
- Initial Position Detection (IPD)
- Start-in-motion (SIM)
- Field Weakening
- Stall Detection
- Open Phase Detection (OPD)
- Etc.

View Qorvo's full line of Power Management Products here:  
[qorvo.com/products/power-management](http://qorvo.com/products/power-management)

# Modern Motor Design Cleans Up the Portable Vacuum



## Motor Design Acronym Guide

ADC - Analog-to-Digital Converter  
BLDC - Brushless DC Motors  
FOC - Field-Oriented Control  
IEC - International Electrotechnical Commission  
MCU - Microcontroller Unit  
PMSM - Permanent Magnet Synchronous Motor  
PWM - Pulse-Width Modulator  
VFD - Variable Frequency Drive

The 21<sup>st</sup>-century home offers abundant examples of how the electric motor—a simple, everyday device—has evolved through modern design to become an integral part of an expanding number of home appliances. You can find electric motors in refrigerators, computers, microwave ovens, fans, washing machines, and vacuum cleaners inside the home. Outside the home, motors are present in garage-door openers, shop vacuums, garden trimmers, cordless tillers, electric lawnmowers, pressure washers, and other yard equipment.

We have come a long way since the early 20th century where simple A/C induction and Brushed DC motors powered washing machines, refrigerators, and fans. Today's motor designs have advanced to Brushless DC style. This design accommodates consumer preferences, providing greater efficiency, powering cordless devices for extended periods, fitting into smaller and lighter devices, and offering extended reliability. A study conducted by the [Advisory Committee on Energy Efficiency](#) (ACEE), an adjunct of the International Electrotechnical Commission (IEC), determined that electric motor systems represent more than 50 percent of the global electricity used, of which the large majority of electric motors are used in machines, pumps, fans, compressors, conveyor belts, and more. "It is a genuine opportunity to increase energy efficiency," according to the study.

## Trends in the global vacuum cleaner market

Globally, the market for vacuum cleaners reached \$9.2 billion (USD) in 2018. According to [Grand View Research](#), this market shows strong growth. It projects the compound annual growth rate (CAGR) will be 9.1 percent from 2019 to 2025. An increasing population of working women and new consumer expectations related to rising standards of living will drive the growth.

A significant portion of this market growth is fueled by consumer preferences for energy-efficient appliance operation and environmental concerns. Another growth factor is the increasing demand for workplace vacuum cleaners to reduce hazardous dust and improve hygiene practices in environments, including hospitals, manufacturing centers, retail stores, and healthcare facilities.

## Challenge

The vacuum cleaner design group involved in this project and Qorvo engineers were presented with a set of rigorous customer requirements for a cordless vacuum cleaner. The resulting design combines high-speed motor operation for maximum suction, a lightweight form factor, and components selected for a long, reliable product lifecycle. The level of suction specified for this vacuum was higher than most conventional portable vacuum cleaners. Another consideration affected design decisions: In most vacuum cleaner designs, the important factors are torque and motor speed. However, the requirements in this case were slightly different, emphasizing the need for power and speed.

The customer design specifications called for a PMSM motor equipped with field-oriented control (FOC) for variable frequency drive (VFD) capabilities to meet the product requirements.

## Solution

Qorvo and the design group began the project from an understanding that the end product would be a high-performance vacuum. For that reason, they chose a three-phase PMSM because of its use of sinewave commutation, which helps maximize performance. The design relied on FOC and used an algorithm for controlling the stator's revolving magnetic field, relying on two orthogonal components to regulate the magnetic flux generator and determine the available torque.

The FOC and the custom algorithm developed by Qorvo enabled precise control over motor speed and made it possible to maximize the overall efficiency of the vacuum. The collaborative work between the design group and Qorvo over several months resulted in a product that successfully fulfilled the product requirements. As a result of this cooperative design effort, this powerful, efficient cordless vacuum cleaner is now available commercially.

## Overview—Vacuum Cleaner Operation

Handheld vacuums generate suction by spinning a motor-driven fan that pulls air through the vacuum's head and—after trapping the ingested dust and debris in a bag or canister—expels it through an exhaust port. Typically, a filter placed in the exhaust stream prevents tiny particles from being discharged. The speed of the fan motor and the dimensions of the intake port (or accessory attachments) determine the degree of suction, ascertained by the negative pressure created when the air is drawn through the head and forcefully discharged from the exhaust. Fan speeds up to 100,000 revolutions per minute, and above are commonly reached in high-end vacuums, such as the product design to which Qorvo contributed.

## Key Components of a High-Power Vacuum

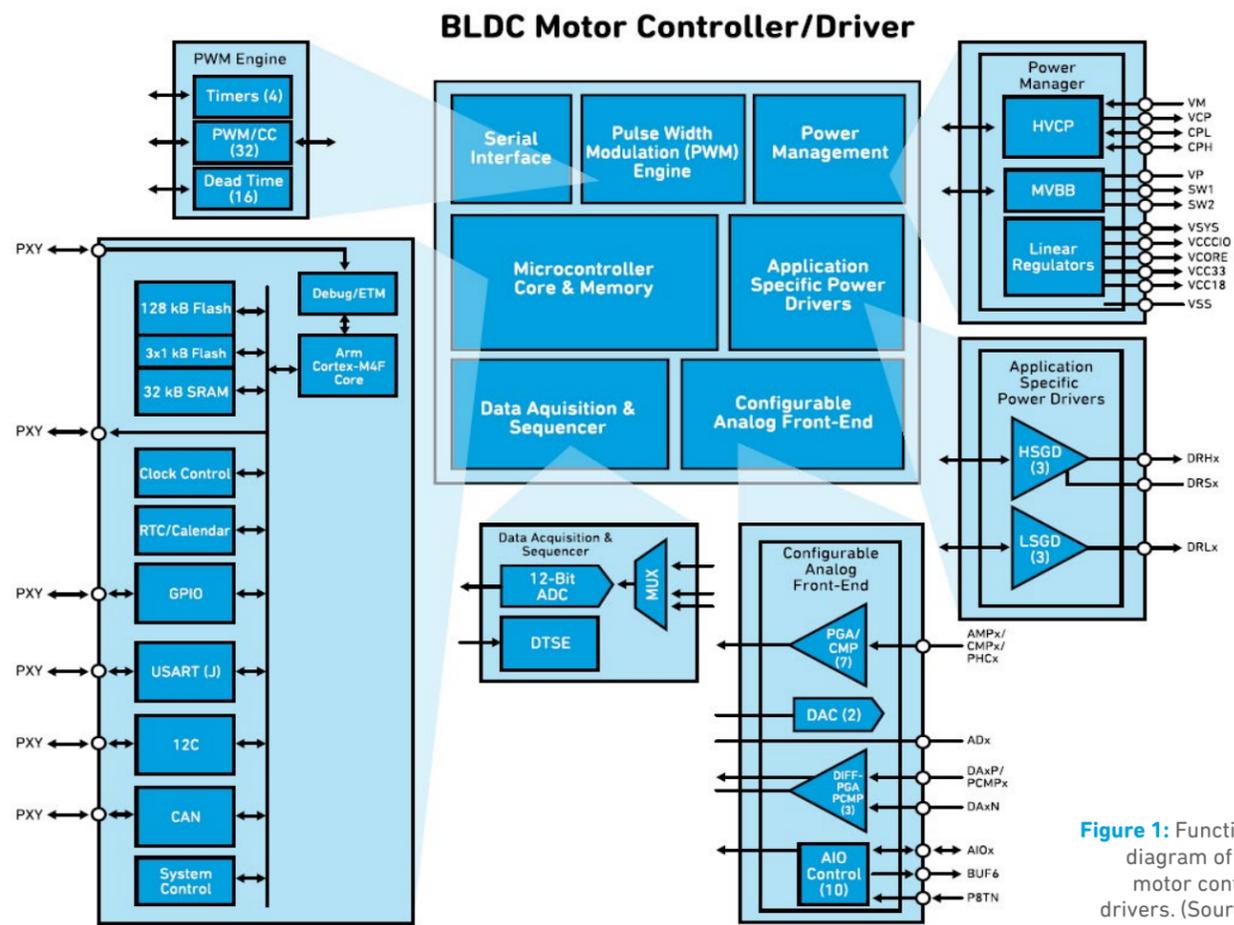
Modern handheld vacuum cleaners incorporate brushless DC (BLDC) motors to achieve maximum performance, generating a rotating magnetic field within the motor enclosure. In this type of brushless design, the stator is stationary, with fixed coils, and permanent magnets are affixed to the rotor, which spins in response to the cycling magnetic fields. The stator coils are controlled by an external electronic motor controller, allowing variable rotational speeds to be produced. Advantages of the BLDC design, which is more complex but much more controllable than brushed DC and traditional induction motors, include highly efficient operation, a more compact footprint, greater reliability, and exceptional long-term durability.

The type of BLDC motor selected for this project was a three-phase PMSM, driven by a sinusoidal wave, representing the best choice for meeting the high-performance requirements. The criteria for the project included:

- ▶ Ultra-high-speed motor capabilities
- ▶ Constant power control with over-voltage protection
- ▶ Quick start-up operation
- ▶ Cost-effective design components
- ▶ The design features that enabled Qorvo and the team to satisfy these criteria are discussed in the following section.

**Today's motor designs have advanced to Brushless DC style.**





**Figure 1:** Functional block diagram of the PMSM motor controller and drivers. (Source: Qorvo).

## Design highlights

The Qorvo PAC5225 IC, a member of the **Qorvo Power Application Controller (PAC) family**, is at the heart of the vacuum cleaner project design. This system-on-a-chip (SoC) provides full functionality for building a simple, compact, cost-effective motor control board (**Figure 1**). The board in this design includes an integrated power management system, a 50MHz, 32-bit Arm® Cortex®-M0 microcontroller unit (MCU), gate drivers, operational amplifiers, comparators, and other supporting components. Adding a peripheral MOSFET for delivering constant power output under variable conditions completes the integrated design.

## Achieving Ultra-High-Speed Motor Operation

Exceptional motor speed was an essential design parameter in this project, aiming to reach levels substantially higher than standard vacuum cleaners on the market. To achieve a mechanical speed of up to 150,000rpm required closely managing operation of the analog-to-digital converter (ADC) and the pulse-width modulator (PWM), which the Arm® Cortex®-M0 MCU controls. The electrical frequency

required can range up to 2.5kHz, and—for precision FOC control—the ADC sampling speed and accuracy must be up to 1MSPS, and very fine resolution of the PWM is needed. The microcontroller ensures that these values are finely tuned for precise operation. The FOC algorithm developed by Qorvo is customized to meet these requirements and accelerate the FOC's operational sequences.

## Regulating Power for Optimal Results

Many different factors affect suction in a vacuum cleaner, including air duct volume of different attachments, battery levels, any ingested object that clogs the vacuum, and the exhaust filter getting saturated with dust and debris. This is where maintaining constant power under changing conditions is critical to maximizing suction. Designs based on the regulation of torque or motor speed don't respond as well to the full range of factors affecting suction strength, whereas regulating power—as monitored by microcontroller integrated into the SoC and controlled by the custom Qorvo FOC algorithm—delivers far more consistent results. Calculations are performed in real-time, using internal power-level data sampled by the ADC, and necessary power adjustments can be made rapidly.

The motor control functions provided by the Qorvo chip also support many protective measures, such as:

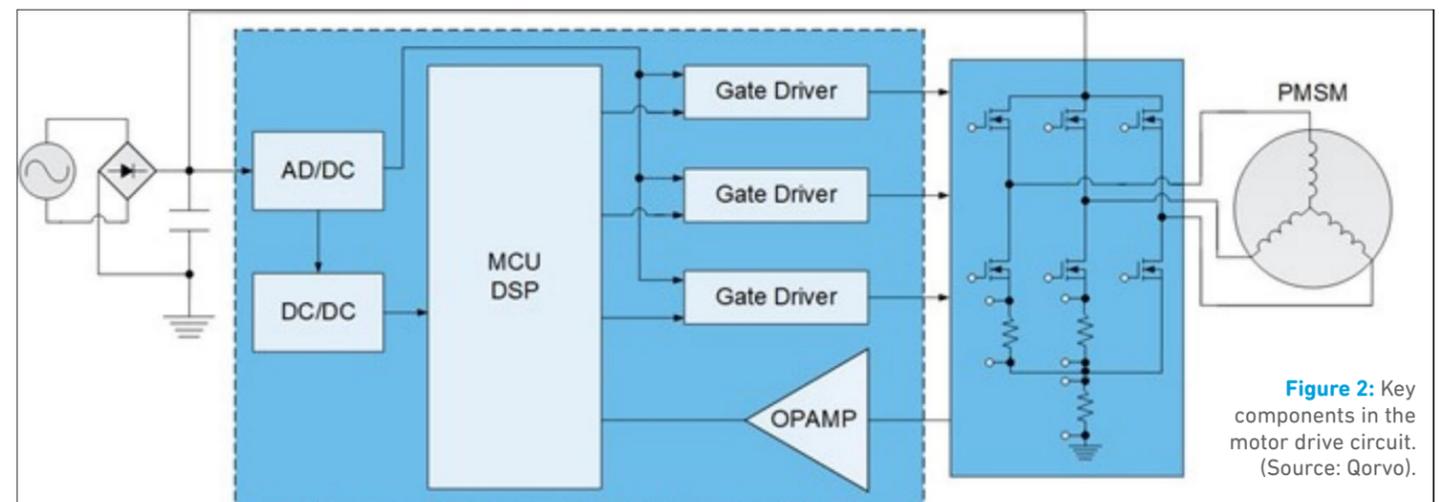
- Overvoltage, undervoltage, and overcurrent detection and regulation
- Internal power supply monitoring and protection
- Locked rotor protection
- Open circuit protection
- Over-temperature shutdown and reset of the MCU when required

From a design standpoint, without the computational capabilities available through the Qorvo chip, the challenges of controlling and protecting the power system in the vacuum would require substantial additional design work and many extra components. With the Qorvo SoC integrated into the product, a constant motor speed of 120,000rpms can be sustained through varying conditions. The chip provides everything required to drive the vacuum motor and maximize its efficiency.

## Ensuring Quick Startup Speed

The motor-starting algorithm needs information about the rotor position to ensure a smooth, quick startup for the vacuum. To accomplish this, Qorvo used its SoC to deliver a high-frequency signal to the motor to capture data on the inductance of the three-phase motor. The starting algorithm used this data to calculate rotor position. In past-generation brushless motor designs, expensive, failure-prone Hall Sensors were used to detect rotor position. But in this design, the built-in capabilities of the Qorvo SoC can handle this task without needing any additional Hall sensor components.

The information about the rotor position makes it possible to avoid reverse rotation during startup and contributes to enabling a fast start speed within approximately 5 seconds.



**Figure 2:** Key components in the motor drive circuit. (Source: Qorvo).

**PAC5225**  
Power Application  
Controllers®

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## Providing a Cost-Effective Design

Consolidating all the logic and circuitry for performing motor control functions into a single Qorvo PAC motor control chip is the key to the cost-effective design of this product. By avoiding using discrete components in the design, the maintenance requirements are minimized, and the product lifecycle is extended. The highly integrated SoC, providing the power supply, gate drives, analog front end, an economical embedded processor from ARM, and other parts, leads to lower bill-of-material (BOM) costs.

The sophisticated algorithm devised by Qorvo enables numerous motor control functions to be carried out through the available SoC hardware. For example, the design features sensorless FOC control based on a single-resistor sampling method, rather than requiring three sampling resistors as in many past-generation designs. **Figure 2** shows the circuit that performs these operations.

The custom algorithm also enables power conservation and efficiency features in the design, lowering overall power consumption while delivering impressive performance under an extended range of conditions. Power consumption during sleep mode, controlled by the Qorvo PAC, is 12 microamps, and standby power requirements for the vacuum are also very low.

As with this design, Qorvo works closely with customers to develop solutions that extend the boundaries of existing technologies, working collaboratively to design products that balance performance, efficiency, and cost.

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