Texas Instruments

Application Report
SLVAES1–June 2020

Brushless-DC Motor Driver Considerations and Selection Guide

ABSTRACT

The usage of Brushless-DC (BLDC) motors is becoming more commonplace in the automotive and industrial markets. Although more challenging to spin, Texas Instruments' BLDC motor drivers make spinning BLDC motors as simple as possible by reducing design complexity while improving system efficiency. TI offers a diverse portfolio of BLDC motor drivers that support various architectures, integration, and control methods to best suit a wide range of applications. The portfolio is grouped into driver, control, and safety families that each include key technologies. These technologies enable developers to design smaller and more efficient systems, decrease design complexity,and meet functional safety standards and certifications.

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1 Motor Considerations and Why Brushless DC Motors?

Brushless-DC (BLDC) motor usage is becoming more and more common for various applications due to the performance benefits they have over alternate motor types such as brushed-DC and stepper motors. As Table 1 shows, BLDC motors are more efficient, quieter, and have better power density, higher torque, higher speed, and longer lifetime when compared to brushed-DC and stepper motors.

Table 1. Comparison of Motor Types

Motor Type	Pros	Cons
Brushless DC	Long life, quiet, optimal power density	Design complexity, higher cost
Brushed DC	Low cost, easy to use	Noisy, EMI wear-out, sparking
Stepper	Long life, quiet, open-loop position and speed control	Current control needed, not as power efficient as BLDC, noisy

The significant benefits that BLDC motors have come with one important disadvantage: higher design complexity. Product development with BLDC motors requires knowledge of how to design an efficient system and get the motor to spin. Texas Instrument's BLDC team is working to reduce this barrier to entry and simplify BLDC design with innovative motor driver devices. This document serves to simplify BLDC design by exploring the considerations in selecting a BLDC motor driver (Figure 1).

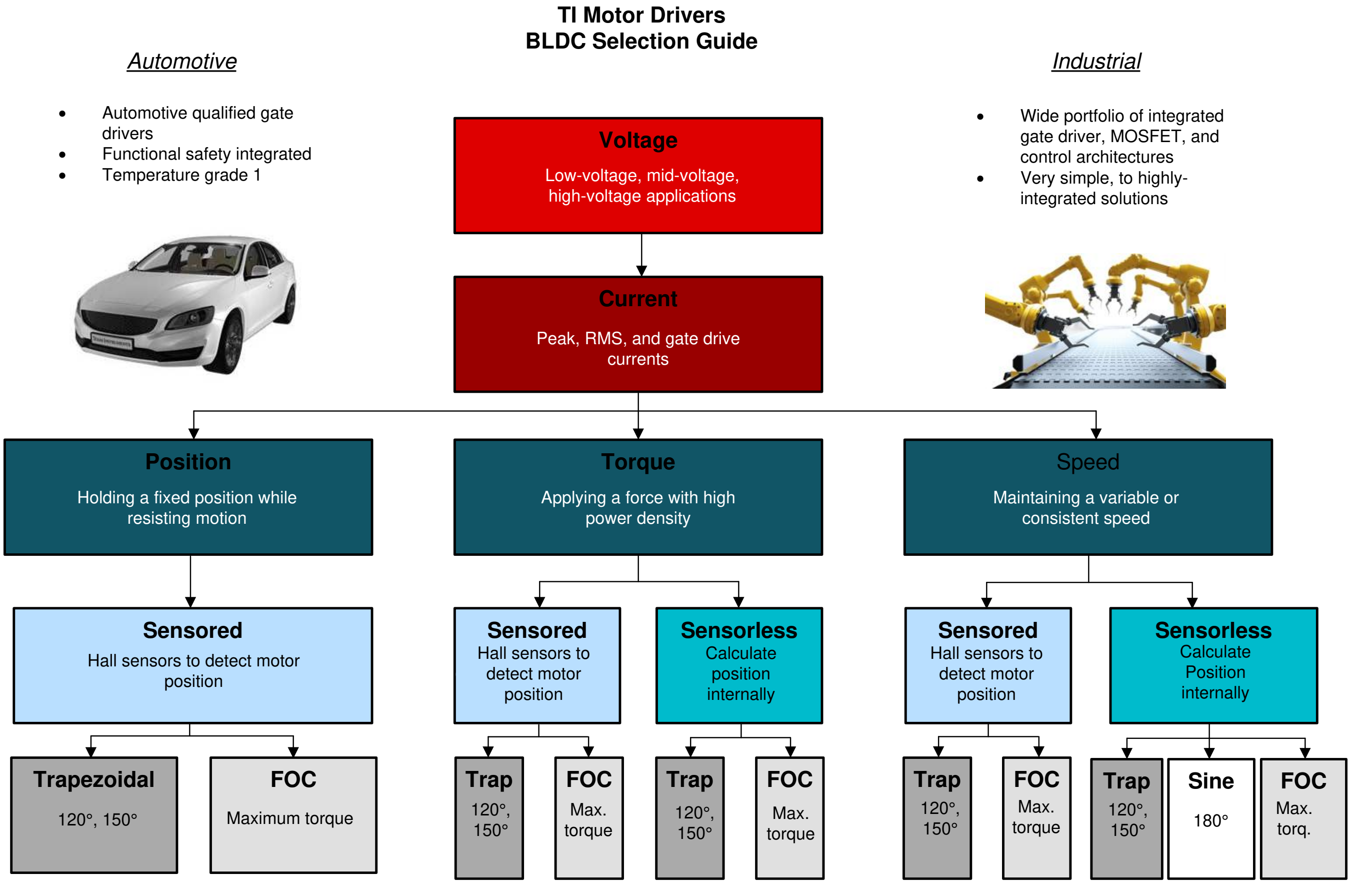


Figure 1. Motor Driver Considerations

2 Motor Driver Architecture

The first step in selecting a BLDC driver is to determine what type of architecture is best suited for an application. Architectures range from integrated FET drivers for low- to mid-power applications up to gate drivers enabling multi-kW motor drive systems. In addition, TI's BLDC portfolio offers integrated control drivers for both sensored and sensorless sinusoidal and trapezoidal control. Figure 2 illustrates the various motor driver architectures in TI's BLDC portfolio such as gate drivers (Blue), integrated FET drivers (Blue + Purple, and sensored vs sensorless integrated control (Green + Blue or Green + Blue + Purple).

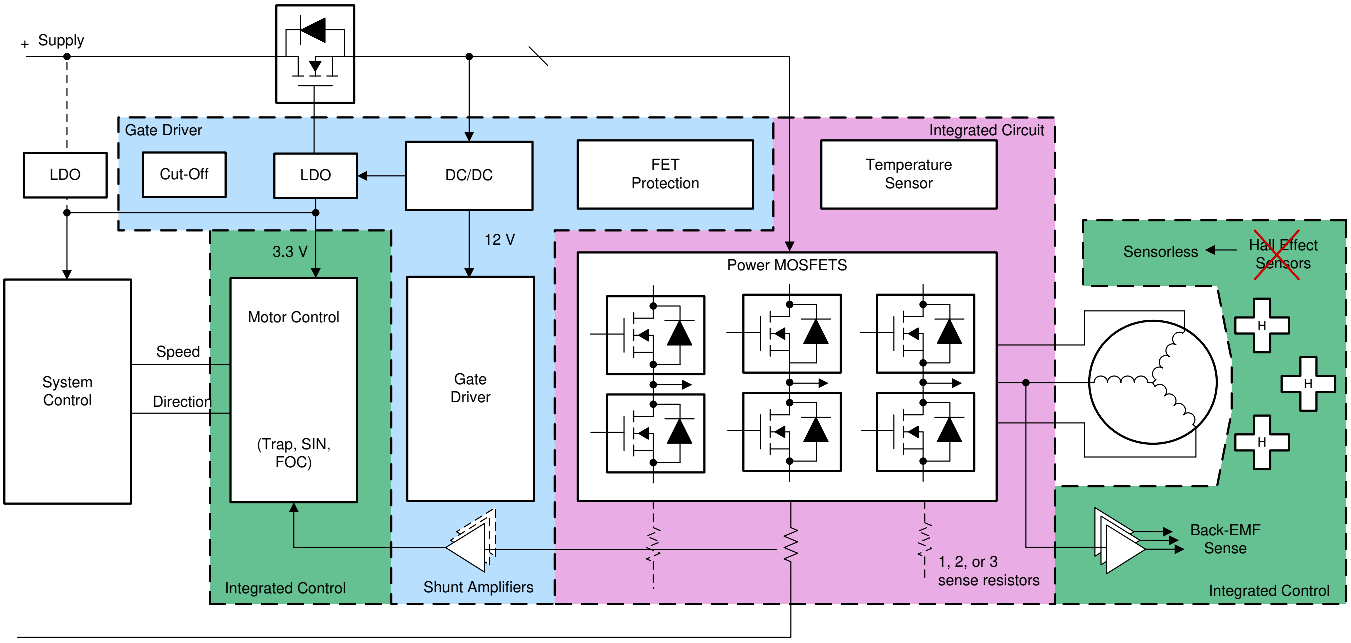


Figure 2. Motor Driver Architectures

2.1 Gate Driver vs Integrated FET Driver: Power, Voltage, and Current Requirements

Determining supply voltage, output current, and motor power in a system is one of the first steps in selecting what type of motor driver architecture is needed for an application.

Supply voltages come from two categories: battery powered and line powered. In both battery and line powered systems, the supply can vary in voltage, so a motor driver should support at least the maximum voltage of the battery with extra headroom in the case of voltage feedback or transients in the system. TI recommends using a motor driver rated up to 1.2 × the maximum voltage for well-regulated supplies and low-power motors, and 1.5 to 2 times for high-power motors and battery systems. Texas Instruments has a wide-ranging portfolio of motor drivers that support up to 56-V battery systems.

In general, integrated versus external FET architectures have different power requirements. High power (up to multi-kW) systems use gate drivers and low-to-mid-power systems (< 100 W) use integrated FET drivers. External FETs are able to drive higher power than integrated FETs because they are not constrained by the size of the single-chip integrated FET driver device. For integrated FET solutions, peak current, RMS current, and $R_{DS(on)}$ of the internal FETs are important considerations that directly relate to the motor power. For external FET solutions, the $R_{DS(on)}$ and current ratings of the external MOSFETs relate to the power the motor can drive.

- Integrated FET
  - Motor power for integrated FET architectures can be calculated by Equation 1, where VM is the motor voltage and IRMS is the nominal current of the motor.

$$P = VM \times I_{RMS} \tag{1}$$

  - **Peak current** is the maximum short duration current in a motor that can be caused by switching, inrush, or parasitic effects. Many motor drivers today have built in protection such as overcurrent protection. The peak current is the maximum current that can be driven before overcurrent protection kicks in. TI's Integrated FET drivers can drive up to tens of amps in peak current.
  - **RMS current** (or **continuous current**) is the nominal current of the motor and directly relates to the power dissipation of the motor.
  - For high-power systems, it may be difficult to find an integrated FET driver to meet peak and RMS current specifications, which means that the system needs to use a gate driver instead of an integrated FET driver.
- Gate Driver + External FET:

  - External FET architectures can drive much more power than internal FET architectures because ofthe lower $R_{DS(on)}$ of external FETs. The larger size of external FETs allows their $R_{DS(on)}$ to be much lower without affecting motor driver die size. For example, an internal device may have an $R_{DS(on)}$ of hundreds of milliohms while an external FET may have less than 10 mΩ.
  - **Gate driver current** is the current supplied to the gates of the external MOSFETS, which controls the rate of ON/OFF switching. Although not directly related to motor power, it is an important consideration as it relates to the slew rate, EMI performance, and thermal performance of the MOSFETs. TI gate driver architectures can source more than 1-A of current and sink up to over 2-A of gate driver current.
  - The relationship between gate drive current and rise time to switch the FET on is calculated in Equation 2, where Q_{GD} is the gate-to-drain capacitance of the FET (which is the major contributor of the VDS slew rate of the FET) and IDRIVE is the gate drive current.

$$Q_{GD} = \text{IDRIVE} \times t_{rise} \tag{2}$$

  - If IDRIVE gate current is too high, it can cause overshoot, undershoot, or switch-node ringing that negatively affects EMI performance. Conversely, if IDRIVE gate current is too low, thermal losses can increase in the MOSFETs due to power dissipation from switching losses, where the motor current is continuing to flow during the MOSFET saturation region.
  - In some gate drivers, such as TI’s Smart Gate Drivers, gate current can be easily configured through the IDRIVE setting without the need to redesign external circuitry between the gate drivers and external FETs. This provides designers more flexibility in configuring their system for EMI versus thermal tradeoffs. See Section 3.1 for more information on TI’s Smart Gate Drive technology.

Table 2 compares the specifications of gate driver and integrated FET driver architectures.

Table 2. Motor Driver Architectures

	Gate Driver	**Integrated FET driver**
Power	High power (typically > 100 W)	Low to mid power (typically < 100 W)
Voltage Range	Up to 100 V	Normally 60 V or less
Gate Driver Current	Greater than 1-A/2-A of source/sink current	-
Peak Current	-	Up to 13-A
MOSFETs	External	Internal
Thermal	Power is dissipated in external MOSFETs	Limited by the size of the integrated package
Solution Size	Larger	Smaller

2.2 Three Use Cases: Speed, Torque, or Position:

Motor Drivers are typically used for three applications that are well suited for specific motor driver architectures. As discussed in Section 2.1, the power, voltage, and current determine whether a gate driver or integrated FET driver architecture is best. The next consideration is whether or not to integrate control depending on one of the three following use cases and their typical applications:

- **Speed:** the motor should maintain a variable or consistent speed
  - Appliance fans, vacuum cleaners
- **Torque:** the motor should be used to apply a force
  - Power tools, electric bikes, automated doors and gates
- **Position (servo control):** the motor should move to a certain position, be able to hold the position and move back and forth
  - IP Network Camera, drone gimbal, collaborative robots, HVAC damper

Figure 3 highlights the relationship between the three use cases and their corresponding architectures.

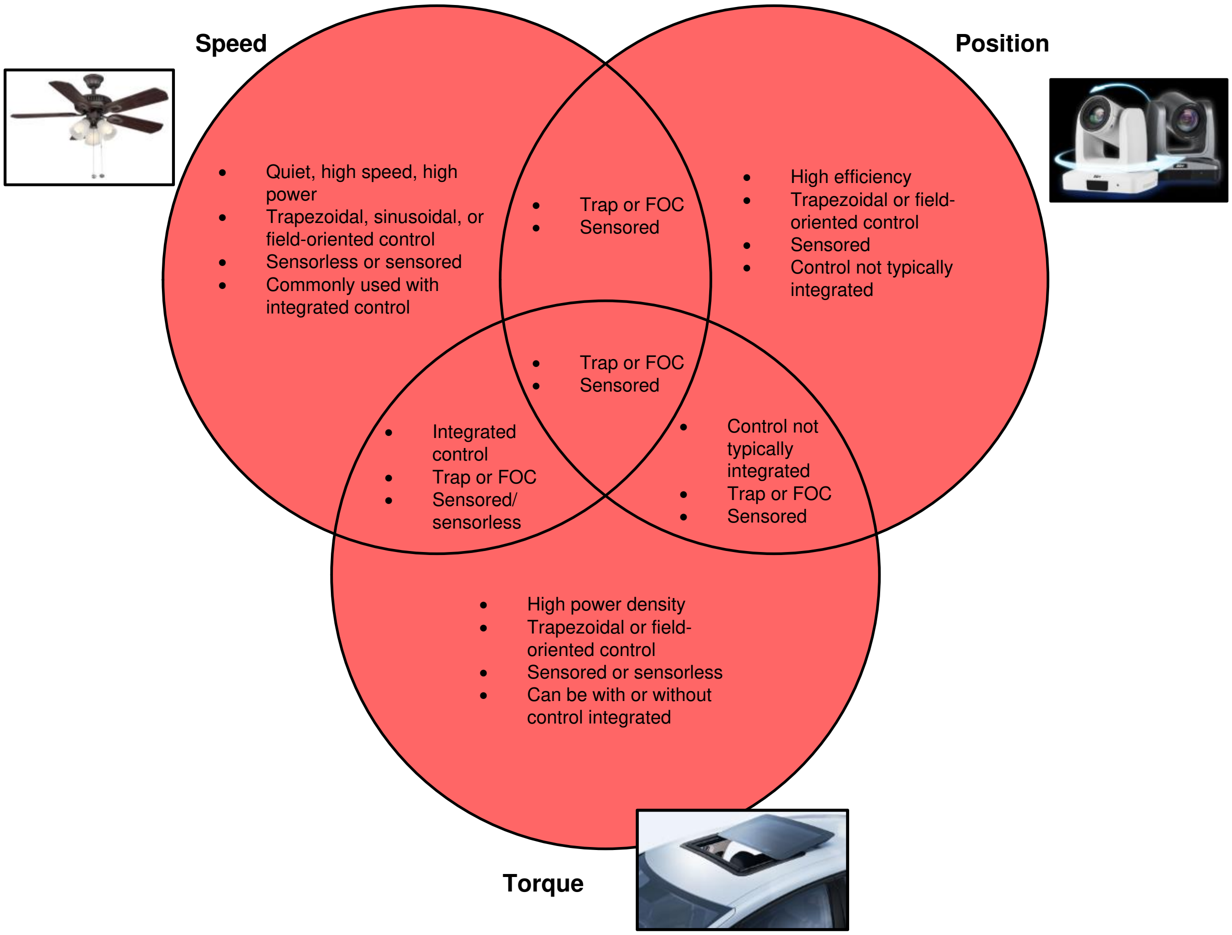


Figure 3. Comparison of Three Use Cases

2.3 Sensored Versus Sensorless

When commutating a Brushless-DC motor, the position of the rotor must be known at all times to spin the motor with high efficiency and directional control. TI Motor Drivers incorporate both sensored and sensorless solutions. They can be implemented with or without an external MCU to detect position feedback and satisfy a wide variety of system designs.

2.3.1 Sensored

Sensored solutions incorporate the use of encoders, resolvers, or Hall-effect sensors to detect the position of the rotor relative to the stator at all times for proper commutation. A popular solution is Hall-effect sensors, which detect magnetic fields of the permanent rotor magnet and translate the changing magnetic fields into logic-level signals. These signals can be used as direct inputs into the motor driver or MCU to efficiently commutate the motor driver (Figure 4).

Speed, torque, and position applications can all use sensored solutions.

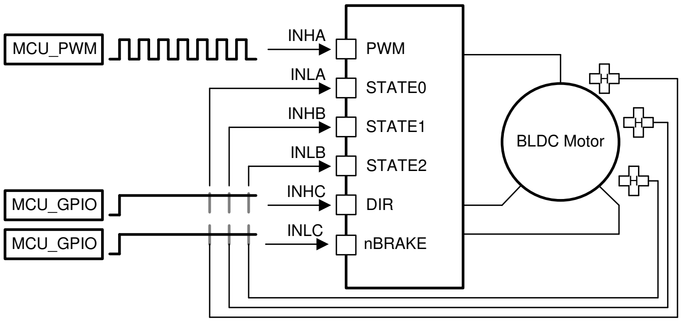
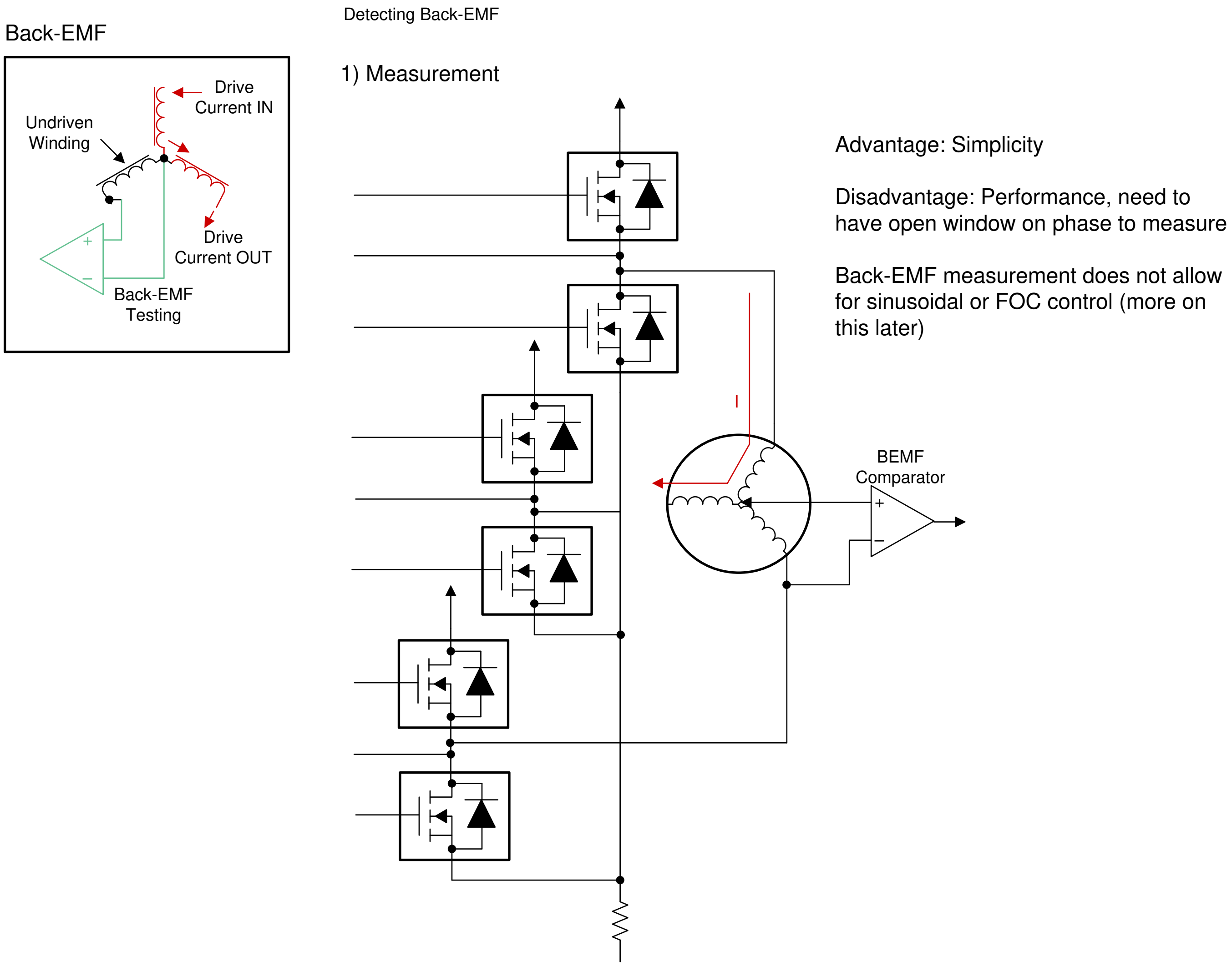


Figure 4. Determining Motor Position Using Hall Effect Sensors

2.3.2 Sensorless

Sensorless solutions remove any sensored components from the design, which helps save on BOM costs. Many TI motor drivers can detect the position of the brushless-DC motor without the use of Hall-effect sensors by either measuring back-EMF voltages generated on unconnected windings of the motor driver (Figure 5) or internally estimating the back-EMF voltage (Es) generated (Figure 6) using winding resistance (R), winding inductance (L), phase current (Is), and motor voltage (Vs).

Sensorless control is typically used for speed applications since the motor will generate enough Back-EMF when it is spinning at a constant speed. Position control cannot be sensorless, and torque control is difficult to implement sensorlessly.

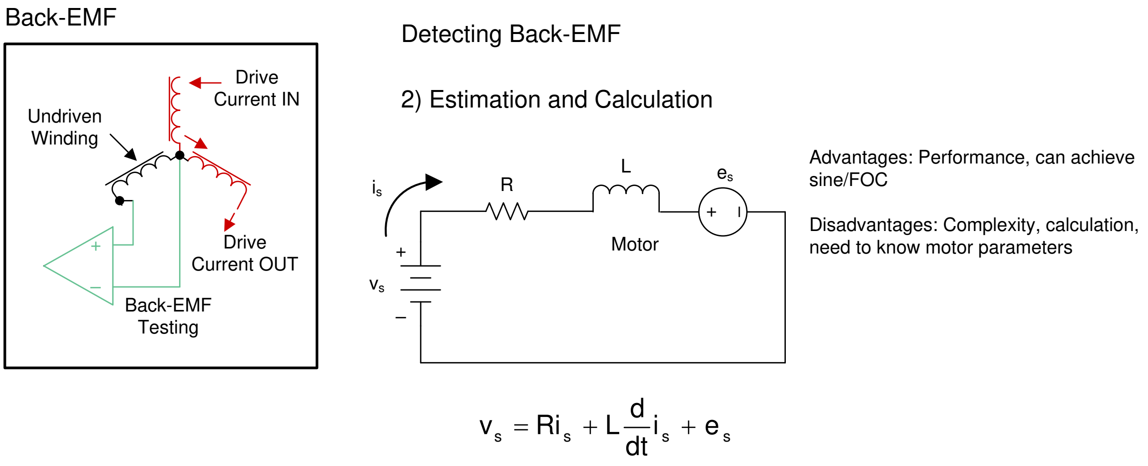


Advantage: Simplicity

Disadvantage: Performance, need to have open window on phase to measure

Back-EMF measurement does not allow for sinusoidal or FOC control (more on this later)

Figure 5. Estimating Back-EMF Using a BEMF Comparator



Advantages: Performance, can achieve sine/FOC

Disadvantages: Complexity, calculation, need to know motor parameters

$$v_s = Ri_s + L\frac{d}{dt}i_s + e_s$$

Figure 6. Calculating Back-EMF Using Known Motor Parameters and a First-Order Differential Equation

2.4 Control Methods: Trap, Sine, or FOC

Many Brushless-DC motor commutation methods can be used to satisfy specific system requirements. Commutation methods vary largely on the motor type, application, and solution needed for the system. TI motor drivers offer a wide portfolio of discrete and integrated solutions for trapezoidal, sinusoidal, and field-oriented control commutation.

Motor construction should be the main factor of choosing a control method. Brushless DC motors are wound trapezoidally or sinusoidally, determined by their Back-EMF (BEMF) waveform. To maximize torque and efficiency, the current driving the motor should match the shape of the Back-EMF waveform. Application type (torque, speed, or position) should also be considered when selecting a control method to optimize performance parameters.

A high-level overview of control method performance parameters are listed in Table 3.

Table 3. Comparison of Control Methods

	Trapezoidal	Sinusoidal	Field-oriented Control
Algorithm complexity	Low	Medium	High
Motor efficiency (MTPA)	Low	Medium	High
Maximum speed	High	Low	Medium (Standard FOC) High (Field Weakening)
MOSFET switching losses	Low	High	High
Torque ripple	High	Medium	Low
Audible noise	High	Low	Low

2.4.1 Trapezoidal

Trap, shortened for trapezoidal commutation, is the basic method of 3-phase Brushless-DC motor. This is accomplished by energizing the windings in a 6-step pattern every 60 electrical degrees so that one phase is always 100% ON, another phase is 100% OFF, and the last phase remains unconnected. This produces a 120° trapezoidal-shaped current waveform (Figure 7).

Trap can be sensored or sensorless to determine the position of the motor and commutate the motor effectively. It is a low-cost, simple solution to implement that can generate high amounts of torque and speed and minimal MOSFET switching losses. However, it is low resolution and results in torque ripple and audible noise due to a non-ideal current drive.

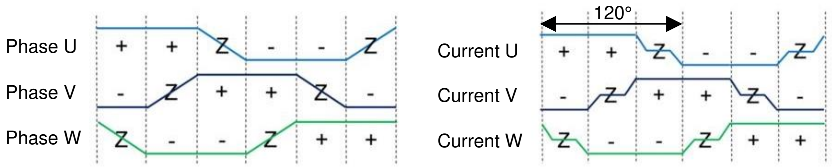


Figure 7. Trapezoidal Control (120°)

2.4.2 Sinusoidal

Sine, shortened for sinusoidal commutation, is another commutation method that drives current through all three phases at a time and the current waveforms in all three motor windings vary smoothly and sinusoidally for 180 electrical degrees (Figure 8). A sinusoidal magnetic flux from the stator attracts the rotor permanent magnets to smoothly spin the rotor. Motors with sinusoidal BEMF generate very low torque ripple because the motor current is also sinusoidal and the delivered torque is constant. This means that the motor is acoustically quiet with good power efficiency. However, in sinusoidal commutation, switching losses are high as the commutation occurs throughout 180 electrical degrees with no window for High-Z.

In sensored controls, commutation signals (varying PWM duty cycle waveform) are generated based on rotor position to drive the MOSFETS and generate smooth sinusoidal modulation of stator currents. In sensorless controls, a commutation look-up table is implemented. Based on BEMF estimation, commutation signals drive the MOSFETS to generate smooth sinusoidal modulation of stator currents.

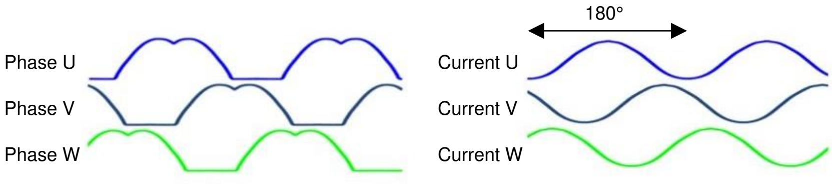


Figure 8. Sinusoidal Control (180°)

2.4.3 Field-Oriented Control

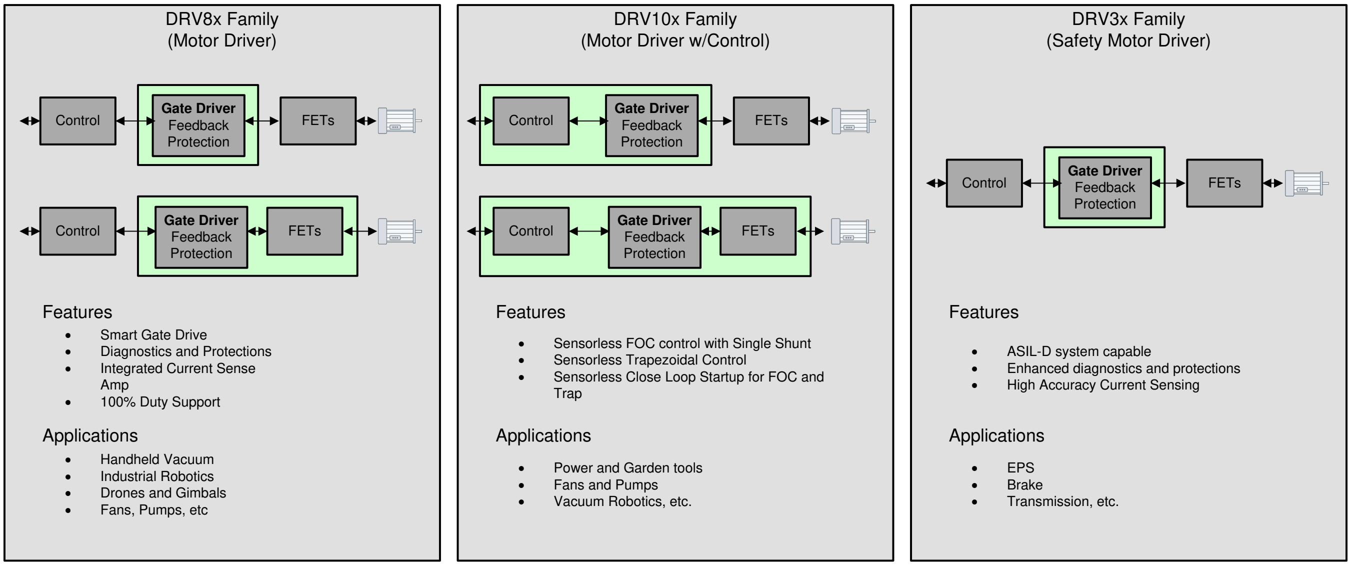
FOC, shortened for Field-oriented Control, is an efficient commutation technique used to precisely and efficiently control the speed and torque of the motor. As the name suggests, FOC techniques orient the stator field perpendicular to rotor flux to achieve maximum torque.

Implementation of FOC can be highly complicated as it requires complex software and processing power to handle mathematical transforms and computations, such as Clarke Park, inverse Clarke, and inverse Park transforms. If position and speed are estimated sensorlessly from phase stator currents and voltages, the microcontroller must be fast enough to estimate the angle and velocity as the motor spins. This may require the use of real-time Digital Signal Processors (DSPs) to pipeline these math calculations or implement large lookup tables while the rest of the transformations are simultaneously being calculated. High-precision encoders are needed for FOC applications that require high accuracy, such as actuators and robotic arms. Based on the resolution of the encoders, positions can be precisely controlled with minimum torque ripple.

TI provides sensored and sensorless FOC solutions through its InstaSPIN™ library. It allows users to be able to identify, tune, and fully control motor parameters through real-time 3-phase voltage and current monitoring. In addition, a user-tuned speed controller and field controller allows the motor to obtain optimal speeds than designed.

3 Texas Instruments' Brushless-DC Motor Drivers

TI’s Brushless DC Motor Driver portfolio supports various combinations of the architecture and use cases previously discussed. The portfolio is divided into three groups: the Gate Drivers DRV8x family, the Control DRV10x family, and the Safety DRV3x family. Section 3.1–Section 3.3 provide details about the key technologies that each family supports, and Figure 9 illustrates the topologies and features of each family. To learn more about the specific products in each family, visit ti.com/bldc.



DRV8x Family (Motor Driver)

Features

- Smart Gate Drive
- Diagnostics and Protections
- Integrated Current Sense Amp
- 100% Duty Support

Applications

- Handheld Vacuum
- Industrial Robotics
- Drones and Gimbals
- Fans, Pumps, etc

DRV10x Family (Motor Driver w/Control)

Features

- Sensorless FOC control with Single Shunt
- Sensorless Trapezoidal Control
- Sensorless Close Loop Startup for FOC and Trap

Applications

- Power and Garden tools
- Fans and Pumps
- Vacuum Robotics, etc.

DRV3x Family (Safety Motor Driver)

Features

- ASIL-D system capable
- Enhanced diagnostics and protections
- High Accuracy Current Sensing

Applications

- EPS
- Brake
- Transmission, etc.

Figure 9. Motor Driver Families and Topologies

3.1 Driver: DRV8x Family

TI’s DRV8x family of motor drivers includes gate drive solutions with protection, sensing, or power management solutions. Gate drivers include Smart Gate Drive technology, which provides a combination of protection features and gate-drive configurability. Further integrated features include power MOSFETs, buck converters, and current sense amplifiers (CSAs). These architectures eliminate the need for external components to create safe, simple, and robust motor drive applications. DRV8x devices range in voltages from 4.5 V to 102 V and are intended for up to 56-V systems.

Smart Gate Drive™ technology includes MOSFET slew rate adjustability, closed-loop dead time, integrated gate fault protection, and strong pulldowns to prevent accidental dv/dt turn-ons. These internal gate-drive circuits allow designers to quickly and easily optimize switching losses and EMI performance by configuring gate registers through SPI commands rather than redesigning a schematic. By integrating performance and protection circuitry into the chip, this not only reduces the system size and total cost but also provides enhanced flexibility, ease of use, and design simplicity when compared to discretely built or non-Smart-Gate-Drive drivers.

Some gate drivers of TI’s DRV8x family include integrated MOSFET solutions to further save board space and reduce overall system cost. Integrated MOSFET solutions provide efficient switching and current control to maximize output current capability from a single integrated circuit. To control MOSFET switching, many integrated and external MOSFET architectures utilize 1x, 3x, 6x, or independent PWM mode control schemes. These PWM modes allow the designer to support various commutation and control methods as well as free up I/O pins for the MCU.

TI’s Smart Gate Drivers and integrated FET drivers also include additional optional integration such as current sensing and power supply. For gate drivers with external MOSFET architectures, optional integrated current sense amplifiers can measure the phase currents of the low-side FETs through external sense resistors and send this information to the microcontroller as sense voltages. Select DRV8x devices offer optional integrated LDOs or buck regulators to supply power to microcontrollers or provide system voltage rails with exceptional efficiency and low input quiescent current, which further reduce system size, cost, and enable easier manufacturing sourcing.

3.2 Control: DRV10x Family

TI's DRV10x family of motor drivers includes gate drivers, integrated MOSFET, and integrated control functionality to spin a motor without an external microcontroller. DRV10x devices minimize noise and vibration with true and accurate 180° sinusoidal algorithms. Our motor drivers feature trap, sine, and FOC control variants for optimal efficiency in a variety of motors. Sensorless algorithms further reduce design complexity by removing Hall sensors.

The DRV10x family provides simple control of motor speed by applying a PWM input to control the magnitude of the drive voltage. This is accomplished by driving the PWM pin with an analog voltage or writing the speed command directly through the I2C serial port and monitoring the FG pin for speed feedback. An adjustable lead angle feature in DRV10x devices allows the user to optimize the driver efficiency by aligning the phase current and the phase Back-EMF. Lead angle adjustment achieves the best efficiency regardless of the motor parameters and load conditions. DRV10x devices deliver current to the motor with an input supply voltage ranging from 2.1 V to 30 V. In some devices, if the power supply voltage is higher than the maximum voltage threshold, the device stops driving the motor and protects the device circuitry. DRV10x devices feature an integrated step-down regulator to accurately step down the supply voltage to either 5 V or 3.3 V for powering both internal and external circuits. Devices are available in either a sleep mode or a standby mode version to conserve power when the motor is not running.

3.3 Safety: DRV3x Family

TI's DRV32xx family of 3-phase gate drivers is designed for customers developing Functional Safety automotive motor systems. TI's DRV32xx family includes devices tailored for 12-V automotive battery profiles. The devices are available in both AEC-Q100 Grade 1 (–40°C to 125°C ambient temperature) and Grade 0 (–40°C to 150°C ambient temperature) qualified packages. These devices are developed using an ISO-26262 certified workflow, and include additional diagnostic and monitoring features to enable system designers targeting ASIL ratings up to ASIL-D.

DRV32x gate drivers also come with additional supporting documentation to help enable system designers to achieve their targeted ASIL rating. The Safety Manual includes detailed explanations for the monitoring and diagnostic features assumed by the Safety Element Out of Context (SEOoC). The Safety Analysis Report includes a detailed Failure Mode Effect and Diagnostic Analysis (FMEDA) and FIT rate calculation for the device.

4 Conclusion

As using BLDC motors is becoming more common in applications today, understanding the architecture options and key considerations when choosing a specific BLDC motor driver is important to get the most out of a design, whether that be for size optimization, increasing thermal efficiency, lessening commutation complexity, or lowering total BOM cost. As discussed in this document, TI's BLDC motor driver portfolio supports various architectures and use cases to enable designers of all applications to get the most out of their BLDC systems. To learn more about BLDC's motor driver solutions, visit the products page at http://www.ti.com/motor-drivers/brushless-dc-bldc-drivers/products.html.

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