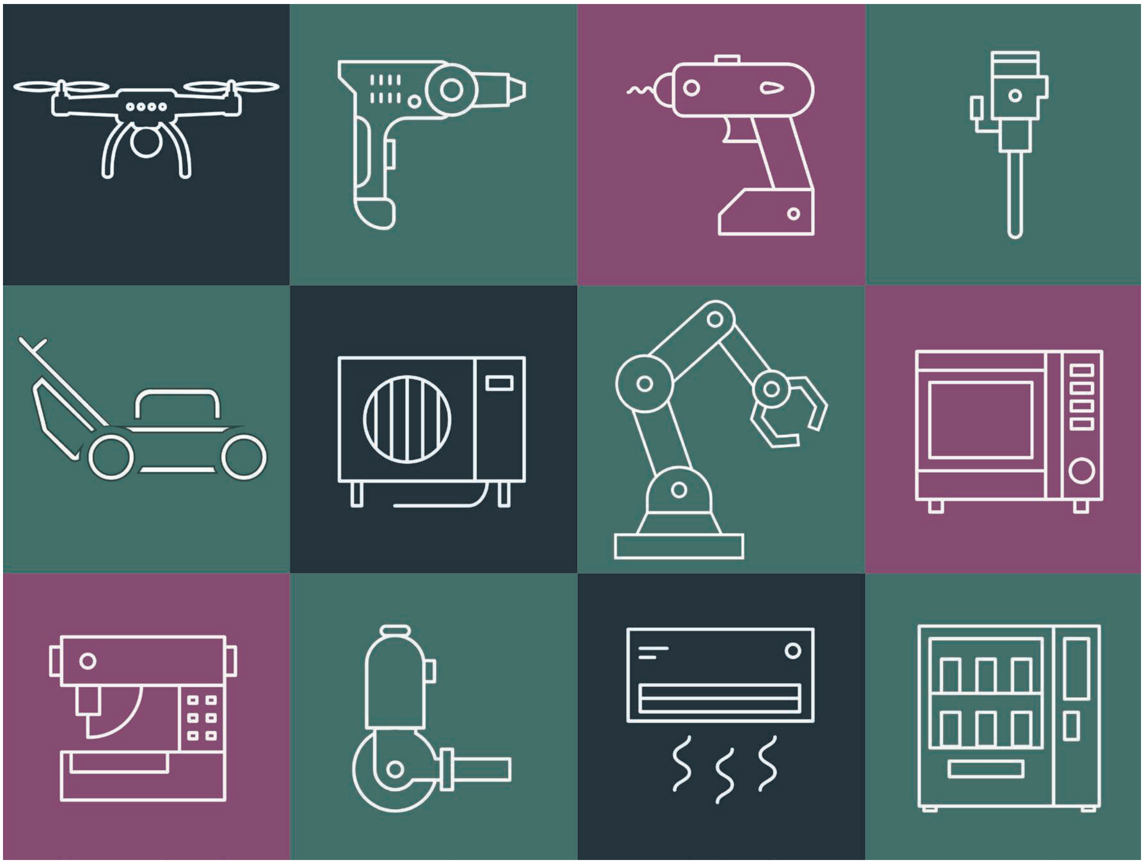

Hardware Engineer's Guide to a Brushless-DC Motor Controller

Design and challenges

by Prabhat Ranjan Tripathi

Brushless-dc (BLDC) motors have best-in-class torque to weight ratio, high efficiency, and effective control algorithms, which make them effective solutions in applications requiring high power density, such as cordless power and garden tools, unmanned aerial vehicles (UAV), robotics, and others. Improvements in semiconductor packaging technology, motor control algorithms, and power management integrated circuits (ICs) have increased the industrial uptake of BLDC motors. High-power battery-powered motor-drive solutions require power levels ranging from a few watts to hundreds or even thousands of watts. High wattage systems require high motor currents, resulting in design challenges of system losses and thermal management. A system designer's challenge is to accommodate all the functionalities of a motor controller in a compact form for the

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whole range operation. Typically, a motor controller uses an analog signal chain, analog power management, and digital components with both signal and power traces on the same board. A well-designed printed circuit board (PCB) is required for the system to operate efficiently. This article lays the guidelines for designing a BLDC motor drive PCB.

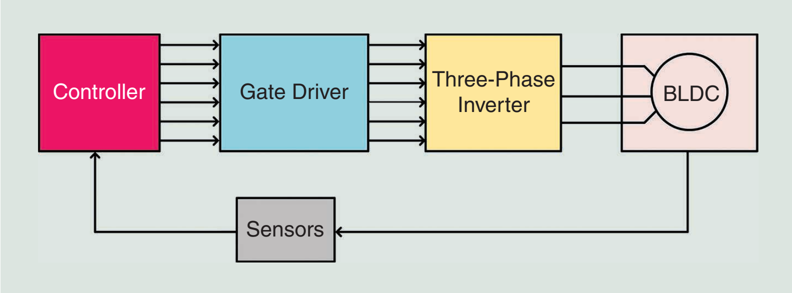

FIG 1 A typical BLDC motor driver block diagram.

Components of BLDC Motor Controller

BLDC motors are closer to us in our day-to-day lives than we think. They are integral to home appliances like washing machines, refrigerators, and fans. BLDC motors often replace brushed DC and induction motor drives because of their high power density, efficiency, and efficient control. In low voltage, high current applications BLDC motors provide significant system benefits. Technological advancements in semiconductor technology enable complex control algorithms for BLDC motors to perform speed control, position control, and torque control. However, there are several hardware design challenges, including gate driver selection, MOSFET selection, PCB layout, sensors placement, and control scheme. PCB design in this mixed-signal and the mixed-power domain is not trivial and has specific requirements.

The various components of a typical BLDC motor driver are shown in Figure 1 and are explained briefly in the following sub-sections.

Controller

The controller can be a microcontroller, digital signal processor (DSP), field-programmable gate array (FPGA), or any hardware-in-loop (HIL) simulation hardware. Its task is to provide the commutation signals to the inverter through gate drivers. Depending on the commutation type and control method, the controller assesses the motor parameters and input from the inverter through various sensors. The controller uses the motor parameters and end-user requirements to generate the control signals to drive the motor as desired.

Gate Driver

Various off-the-shelf gate drivers are available in different configurations. Based on the level of integration, these gate-drivers can be classified in various forms as outlined in the flow-chart in Figure 2.

Considering the many use cases for the BLDC motor in high power density, battery-powered low voltage high current applications like robotics, hand-held tools, and UAVs, this article presents a design guideline for the hardware development of motor controllers with medium-level integration gate drivers. The article focuses on three-phase integrated gate drivers with an external power stage.

3-Phase Inverter

The inverter is a combination of three half H-Bridges connected to a common DC rail with the midpoints of H-Bridge legs serving as motor connection points. These are also available in discrete switch, half H-Bridge, and three-phase module forms. The selection of the MOSFETs or modules to design the inverter depends on the design constraints and motor ratings.

Sensors

BLDC motors require different sensors to drive the motor properly. Speed control can be achieved with or without a speed sensor and implemented as sensored or sensorless control. The most common sensors associated with BLDC are hall-effect sensors, which provide the sectorial rotor position depending on the placement of hall-sensors. More accurate resolvers or encoders can be used when position control is required. The phase current and voltages are also required for more complex controls like field-oriented control (FOC), so external current sensors or integrated current sense amplifiers are used.

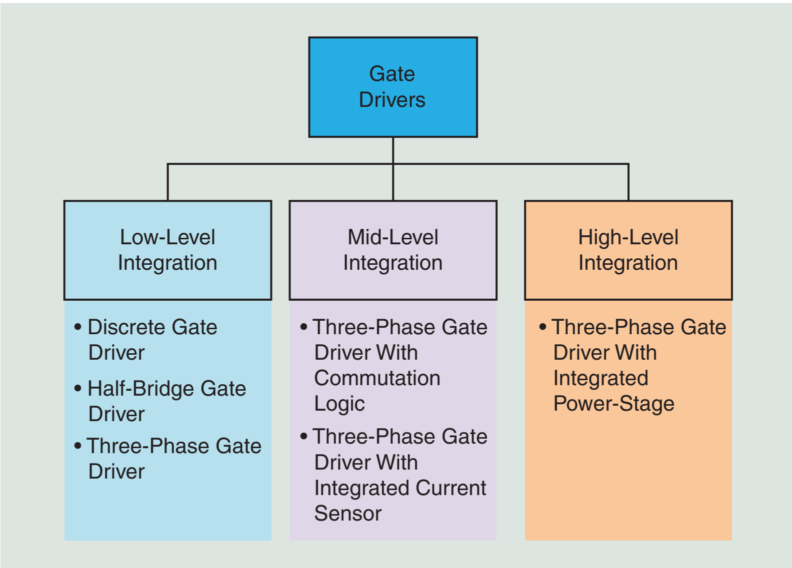

FIG 2 Different gate-drivers with varying levels of integration.

Why Integrated BLDC Motor Controller

End-use constraints are the first concern of a design engineer. In the case of BLDC motors, efficient operation and excellent dynamic response are required. There are many ways to spin a BLDC motor, for example, trapezoidal commutation, sinusoidal commutation, and FOC. The first two offer simple to control but lack the optimal speed and torque response. It has been established that the optimal and efficient speed control of the BLDC motor is achieved by the FOC method providing the best dynamic speed response and low-speed operation. However, for FOC implementation, the phase voltages and currents need to be measured accurately. The integrated gate drivers can help solve this challenge by providing in-built current sense amplifiers, which sense current from low-cost sense resistors connected to the ground side of three half H-Bridge legs.

The second major concern of the design engineer is the system cost. Discrete gate drivers give flexibility in power rating, but it comes at the cost of an increased bill of material (BOM) due to the many discrete components. Each discrete gate driver requires an external power supply for biasing and other passive components to work optimally. However, integrated gate drivers can include internal LDOs to power the device from the common voltage rail and not require an external power supply. Integrated drivers require minimal external passive components. With a reduced number of components, the footprint required on PCB to provide the solution can be minimized, helping the design engineer make the design compact. A comparative analysis showing the pros and cons of a motor controller designed with a discrete gate driver and integrated gate driver configuration is given in Table I.

As shown in Table I, discrete gate drivers give the designer flexibility to design the motor controller for a wide output power requirement and choose the optimal arrangement of other components. However, the design requires many discrete circuits and therefore is costly and complex. The motor controller design for a high voltage motor can only be achieved using discrete or half H-Bridge gate drivers. However, battery-operated hand-held portable tools or robotics applications utilize lower operational voltages. Cost and weight need to be minimized in these systems, so the integrated gate drivers are the best choice. There are hundreds of integrated gate drivers with different configurations available on the market. The system designer must make the design decisions to trade-off between cost, size, and complexity.

Table I. Design Differences with Discrete and Integrated Gate Driver.

Parameter	Discrete Gate Driver	Integrated Gate Driver
Operational Voltage Range	Up to 1200 Volts	Up to 600 Volts
Gate Source and Sink current	Typically, 2 to 6 Amps	Max 2.5 Amps
Functional Isolation	In the range of KV	Limited to Max operating voltage
PWM signals	Six (3-Phase Configuration)	May operate with Single, Three or Six PWMs
Isolated Power Supply	Required	Not required
Peripheral Passive Components	Very High	Low
Current Sensors	External	Can be Integrated
Bootstrap Circuit	Required	Not required (internal charge pump or bootstrap circuit)

Table II. BLDC Motor Specifications.

Parameter	Value
Motor Pole Pairs	8
Rated Voltage	24 Volts
Rated Motor Current	20 Amps
Max Current	30 Amps (10 sec)
Max Target Speed	6000 RPM

Table III. Switch Specifications.

Priority of Selection	Parameter	Value
1	Drain to Source Voltage (V_{DS})	$\geq 2 \times V_M$
2	Continuous Drain Current (I_D)	$\geq 2.5 \times I_M$
3	Threshold Gate Voltage ($V_{GS(th)}$)	Matched with gate driver
4	ON time resistance (R_{DSon})	As low as possible**
5	Total Gate Charge (Q_G)	As low as possible

* V_M is the max input voltage, and I_M is the maximum motor current.
** Although R_{DSon} should be as low as possible, it comes at the cost of a higher price tag for MOSFETs. Therefore, a trade-off between cost and R_{DSon} should be taken care of while selecting MOSFET.

Design Constraints and Component Selection

This article lays guidelines for designing PCB for a real-time application for a spindle motor drive utilizing a FOC algorithm. This system is designed for speed control and uses a low-side single-shunt current measurement to reconstruct phase currents and a voltage divider circuit at each phase output for phase voltage measurement. The design discussed here uses the BLDC motor with specifications given in Table II.

The ratings of the BLDC motor govern the design requirements of the motor controller hardware. This article does not list any particular manufacturer part number; instead, it gives the readers key specifications. The key components required for the complete solution and their key specs to be met are:

- **Gate Driver**—This component should be capable of driving six discrete MOSFETs, and as a rule of thumb, the voltage rating of the gate driver should be at least twice that of the rated motor voltage for a high-power system. If FOC control is required, the gate driver should have the capability to support a six-PWM mode interface. This design requires only one current measurement, and so we select a gate driver with at least one current sense amplifier. Gate drivers support a 3.3 V or 5 V logic level, and the device should be selected to support the target logic voltage; otherwise, a level shifter circuit will be required. Another critical design constraint is the gate driving current capability; a higher current gate driving capability allows a maximum switching frequency.

- **MOSFET—**Key specs to be considered while choosing the MOSFET are given in Table III.
- **Sense Resistor—**Selection of a sense resistor depends on the rating of the current sense amplifier (CSA). A proper design considers the trade-off between the highest voltage at the CSA input and the sense resistor's power loss (ohmic loss). This trade-off can be achieved by the optimal solution of equations (1) and (2).

$$V_{\mathrm{CSA}} = I_M \times \mathbf{A} \times \mathbf{R}_{\mathbf{sense}} \tag{1}$$

$$P_{\mathrm{loss}} = I_M^2 \times \mathbf{R}_{\mathbf{sense}} \tag{2}$$

Where A is the CSA gain and P_{loss} is ohmic power loss in the sense resistor.

- **Peripheral Passives—**A gate driver requires some passive components for a proper operation like gate drive resistors, charge pump capacitors, and decoupling capacitors which vary from part to part. The datasheet should be followed for the selection of such components.
- **Connectors—**The connectors should be carefully chosen for PCB mounting. Power connectors chosen should respect the current ratings of the BLDC motor and input supply. One key constraint is the mating cycle, which should be high for plug-and-play devices, while the solder pads work best with epoxy coatings for fixed connection use cases.

PCB Design Challenges and Mitigation

Integrated gate drivers are offered in compact packages that integrate analog signal chain components (sensors), digital signal control (PWM), and power management (battery and motor). The PCB design evolves around this central component, and therefore it poses a unique challenge in floor planning and layout of the PCB. A typical schematic of a motor controller with an integrated gate driver is shown in Figure 3.

Key PCB design constraints and the ways to mitigate them are discussed below:

- **Grounding—**The most crucial factor in designing a mixed-signal PCB is grounding. Every signal on the PCB requires a return path, and ideally, every signal must have the return path as short as possible to minimize the loop area. Every loop on the PCB can be an antenna that radiates electromagnetic emissions. However, it is not always possible to have the return path associated with every signal; in such cases, the ground plane provides the

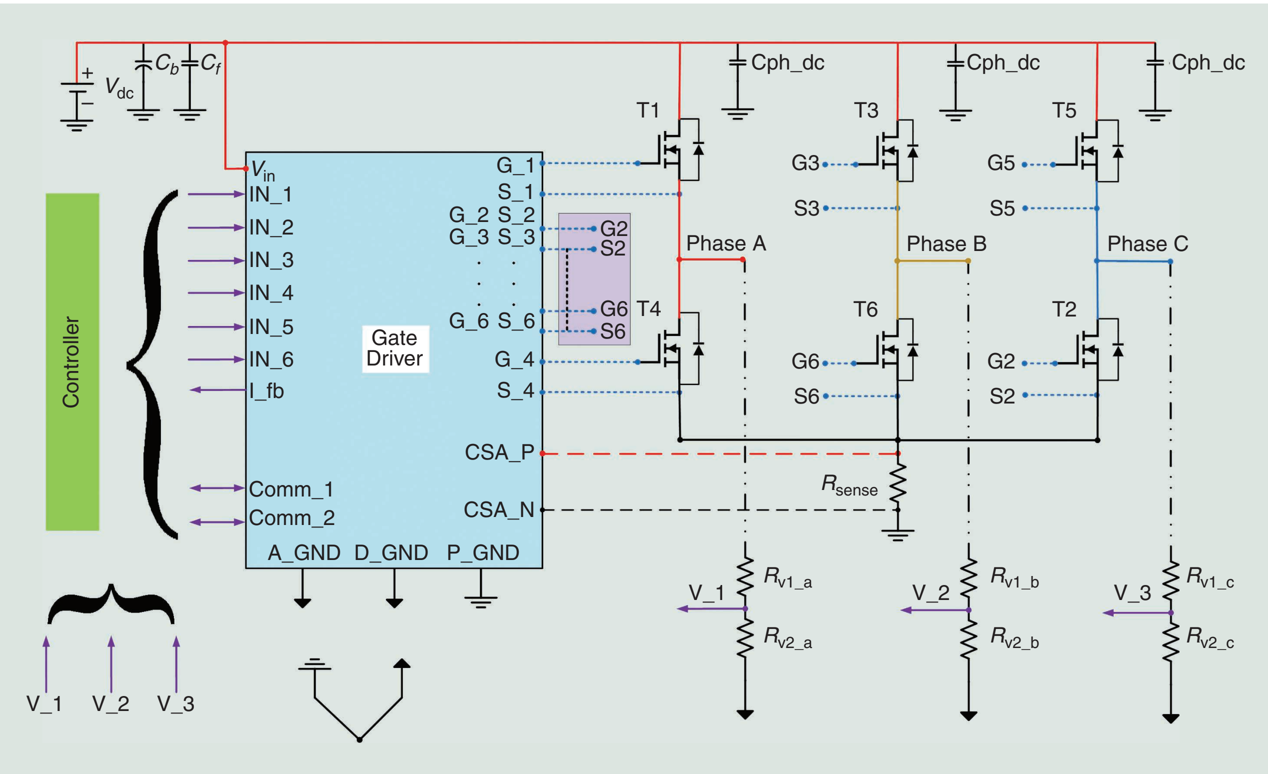

FIG 3 Sample schematic of a motor controller with integrated gate driver.

closest return path. The best way to ensure the minimal loop is to use a four-layer PCB with the dedicated ground plane. This setup ensures noise immunity in the signals; however, the two-layer PCB can also provide a gridded ground plane in cost-constrained designs.

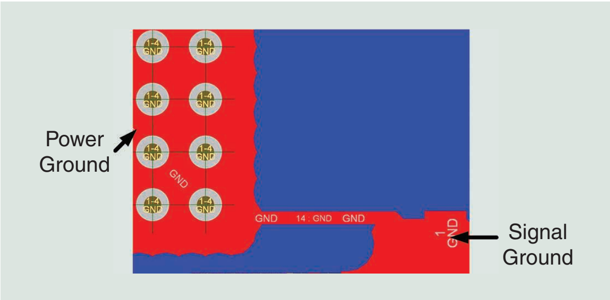

FIG 4 Proper grounding with separate signal and power ground connected at one point.

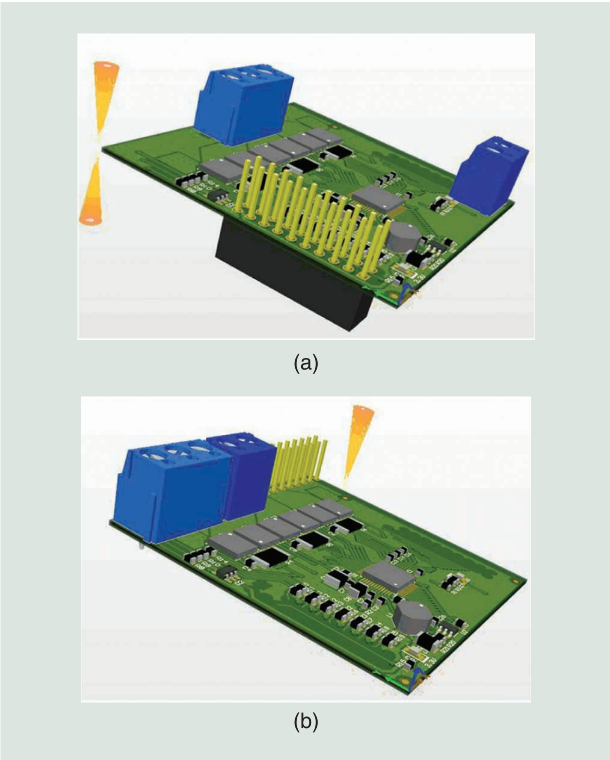

FIG 5 Connector placement. (a) Connectors Placed on Different Sides. (b) Connectors Placed on Same Sides.

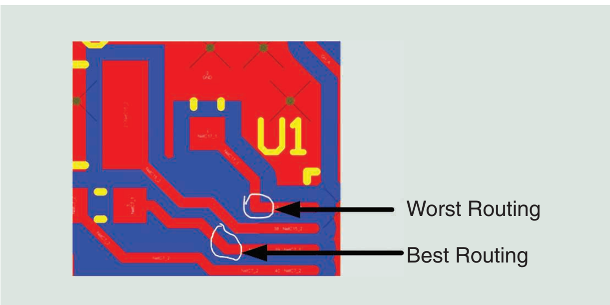

FIG 6 Routing techniques.

The signal ground and power ground should not be the same; these two planes should be connected with a small trace or net tie, as shown in the schematic (Figure 3). The signal ground analog (A_GND) and digital (D_GND) are separated from the power ground (P_GND) but connected with a small trace. This is also shown in the PCB layout in Figure 4.

- **Cable Radiated Emissions**—Connecting cables are the source of electromagnetic emissions and electromagnetic interference. The connecting cables can also act as radiating antennas and make the signals susceptible to noise. Therefore, connectors should be placed on only one side to mitigate these issues. The instances of connector placements are shown in Figure 5.
- **Gate Driving Loops**—For the best switching performance, the end goal is to minimize the current loop length for the high-side and low-side gate drivers. The high-side loop (Figure 3) is from the G_1 to the power MOSFET (T1) and returns through S_1. The low-side loop is from the G_4 to the power MOSFET (T4) and returns through S_4. It is recommended to use 15–20 mil wide traces to support higher gate driving currents and minimize gate drive inductance and impedance. Wide traces have less inductance, and shorter traces have lower impedance. Improperly designed gate drive traces add significant inductance and cause gate drive turn on/turn off issues and cause gate drive faults, worse EMI performance, and charge pump undervoltage.
- **Routing Switching Signals**—While routing a switching signal, right-angled traces should never be used as they form a radiation antenna. They should always be connected at obtuse angles. Examples of worst and best routing for a switching signal are shown in Figure 6.
- **Role of Decoupling and Bypass Capacitors**—The supply from the battery powers the motor; however, rapid motor transients are supplied by the on-board bulk capacitor C_b (shown in Figure 3). Bulk capacitors are generally electrolytic and should be placed at the input terminal; these capacitors mitigate the low-frequency ripples in the supply. Another set of filters C_f-generally ceramic capacitors—filters out the high-frequency ripple. These components can be seen in Figure 3. There are additional capacitors provided ($C_{\mathrm{ph\_dc}}$) near each leg. These capacitors also act as decoupling capacitors in addition to the bulk capacitor. These components should be placed near the top side of MOSFET as close as possible.
- **High Current Routing**—The traces from the battery to the MOSFET and the motor connection must conduct a very high current. For such high current applications, the thickness of copper chosen for PCB should be at least 2 oz. This provides higher current carrying capacity as well as better thermal management. Often for high current capability, polygon pours of copper are used instead of traces. Still, the polygon pours should be as short and wide as possible to minimize the inductive effect. Several vias can also

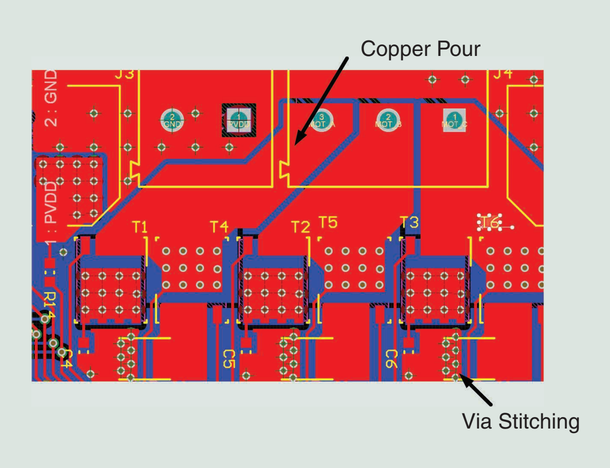

FIG 7 High current routing of power traces.

be added to stitch traces or polygon pours on multiple layers to conduct high current, as shown in Figure 7.

- **Thermal Management**—With high-level integration and high current capacity, these integrated gate drivers and MOSFETs dissipate power from ohmic loss (R_{DSon}). A design engineer takes every step to minimize these losses, but they cannot be eliminated. The best way to provide thermal management is to provide copper pours for the components with high power dissipation. Thermal vias also help in transferring heat from the power devices. As shown in Figure 7, we can see that MOSFETs T1 to T6 have solid copper beneath them with thermal vias to transfer heat away from the components. A combination of thermal vias with solid copper acts as a miniature heat sink and is the best ally of design engineers for thermal management.
- **Current Measurement**—FOC algorithms require accurate current sensing. Therefore, the sense resistor and the sense amplifier design are critical. A Kelvin connection ensures the accuracy of the current measurement by providing a four-wire connection, as shown in Figure 8.

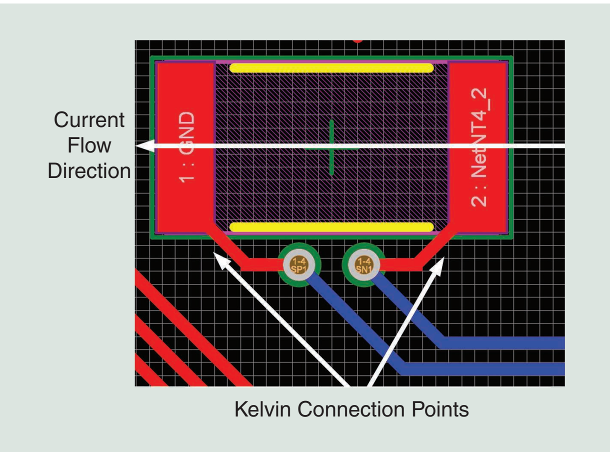

FIG 8 Kelvin connection for current measurement through the sense resistor.

The two points acting as signal points can also be routed as differential pairs for better accuracy and easy routing.

Summary

This article aims to provide a quick reference guide on designing BLDC motor controller hardware. A basic introduction of different motor controller components has been provided along with their function. Different types of integration levels available in off-the-shelf gate drivers have been highlighted. The use case for integrated gate driver in low voltage medium current application has been established with a comparative evaluation based on BOM and design complexity. Then a step-by-step guide to manufacturer-independent component selection for a BLDC motor controller prototype has been laid out to enable the end-user to design their hardware. This document also pointed out the main design challenges and constraints to consider when designing the PCB for the hardware. A list of references to enhance the knowledge in the domain has also been included for enthusiastic readers.

About the Author

Prabhat Ranjan Tripathi (iamprt@ieee.org) leads the Power Electronic System Design group at FleetRF Pvt. Ltd., New Delhi, India. He received his B. Tech from SRM University, Chennai, India in 2012, specializing in electrical and electronics engineering. He was a doctoral candidate in the electrical and electronics engineering department, Birla Institute of Technology, Mesra, Ranchi, India, till August 2021. He has been a visiting student at the center of research on microgrid (CROM), Aalborg University, Denmark [May-December 2020] and the Electrical Engineering Division at the University of Cambridge, UK [September 2017-March 2018]. He has hands-on experience in the hardware design of various DC-DC, DC-AC converters, motor controllers, and battery management systems. He is a senior member of IEEE (IES, IAS, PES, and PELS).

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