Inverter for Cordless Power Tool

Design Guide

RD252-DGUIDE-01

Toshiba Electronic Devices & Storage Corporation

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1. Introduction

This design guide (hereinafter referred to as "this guide") describes the reference design (hereinafter referred to as "this design") of the Inverter for Cordless Power Tool.

In recent years, the power tool market has grown significantly beyond the sales of hand tools. This growth is driven by expanding infrastructure in developing countries and the growing number of do-it-yourself (DIY) enthusiasts. In addition, in recent years, advances in battery technology have led to the cordless power tools with lighter weight, higher efficiency, and longer operating times on a single charge, leading to a shift from corded to cordless power supply, improving usability, portability, and safety. In addition, the number of motors used is increasing shifting from brushed motors to high-output-power and high-efficiency brushless DC motors (hereinafter referred to as BLDC motors). For these cordless power tools, it is important to design a motor drive circuit that efficiently converts the electrical energy of the battery into mechanical energy.

We have developed the reference design of the motor drive circuit for the cordless power tools that need to have small size and high efficiency with a limited battery capacity. In this design, two types of circuits are available: Type 1 for 18V Li-ion batteries and Type 2 for 36V Li-ion batteries. Therefore, this design also supports the models that increase the motor applied voltage (battery voltage) to achieve higher output.

Three-phase gate driver IC TB67Z833SFTG with various built-in protection functions and adjustable gate drive capability via SPI (Serial Peripheral Interface) communication drives six SOP Advance package (5mm × 6mm) power MOSFETs on a small 55mm x 55mm board. Type 1 circuit uses the 40V TPH1R204PB power MOSFETs, and Type 2 circuit uses the 80V TPH2R408QM power MOSFETs. These latest-generation power MOSFETs have low on-resistance and contributes to compactness and high efficiency. Current sensing is done using TB67Z833SFTG internal op-amp, and overcurrent detection is realized using the TC75W58FU comparators.

This design is configured to assume control by an external MCU. The motor current sensing is done by the 3-shunt method, which can also be used for sensorless control. In addition, it is possible to switch the solder jumper on the board to create the 1-shunt configuration. Please use this design with a control method and a current detection method suitable for actual application.

2. Specifications and Block Diagram

The main specifications of this design are shown in Table 2.1.

Table 2.1 Specifications of This Design

Board	Type1 For 18V Battery	Type2 For 36V Battery	
Item	Value		Unit
Output Power	200	400	W
Input Voltage	12 to 24	24 to 48	V
Average Current	±20	±20	A
Maximum Peak Current	±40	±40	A
Switching Frequency	20	20	kHz
Current Sensing Method	3-Shunt Method / 1-Shunt Method		
Board Size	55mm x 55mm		
Board Layer Composition	FR-4 2.0mm Thick, 2 Layer Configuration 105µm Copper Thickness		

The block diagram of this design is shown in Fig. 2.1.

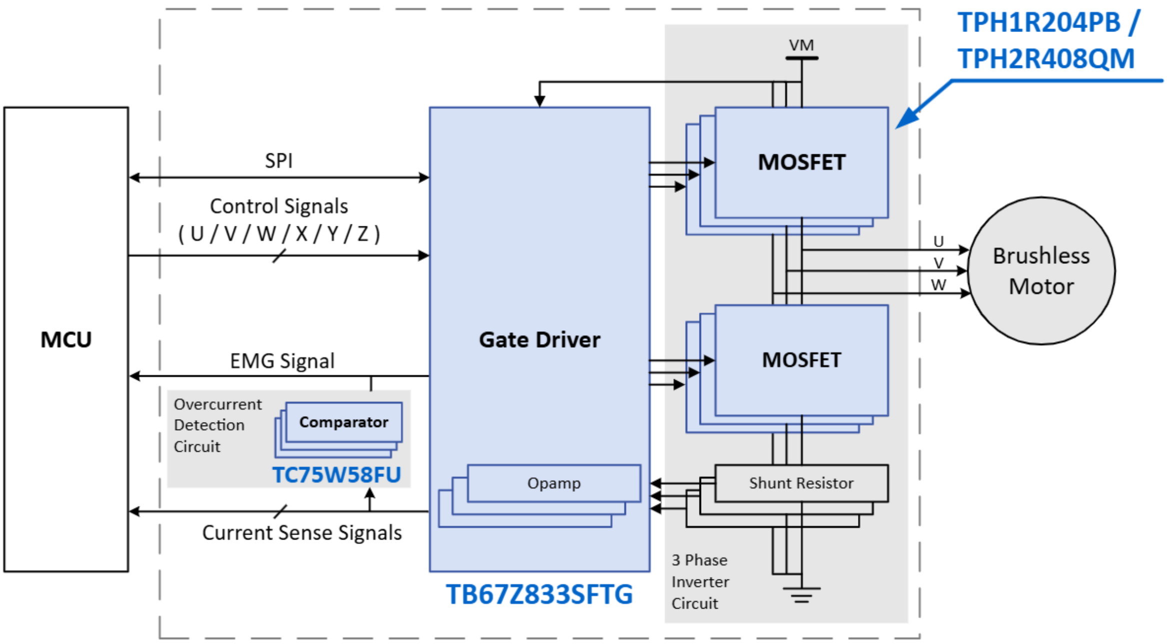


Fig. 2.1 Block Diagram of This Design

TB67Z833FTG receives control signals from an external MCU and drives a total of six MOSFETs arranged in the U, V, and W phases to control the brushless motor. When an error is detected, an EMG (Emergency) signal is sent to the external MCU.

3. Main Components Used

This chapter describes the main components used in this design.

3.1. Power MOSFET TPH1R204PB

40V N-channel MOSFETs TPH1R204PB are used in the motor-drive section of the Type1 circuit. The main features of TPH1R204PB are as follows.

- V_{DSS} = 40V, I_D = 150A
- High-speed switching
- Small gate charge: Q_{SW} = 21nC (Typ.)
- Small output charge: Q_{OSS} = 56nC (Typ.)
- Low drain-source on-resistance: $R_{DS(ON)}$ = 0.85mΩ (Typ.) (V_{GS} = 10V)
- Low leakage current: I_{DSS} = 10μA (Max.) (V_{DS} = 40V)
- Enhancement mode: V_{th} = 2.0 to 3.0V (V_{DS} = 10V, I_D = 0.5mA)

External View and Pin Layout

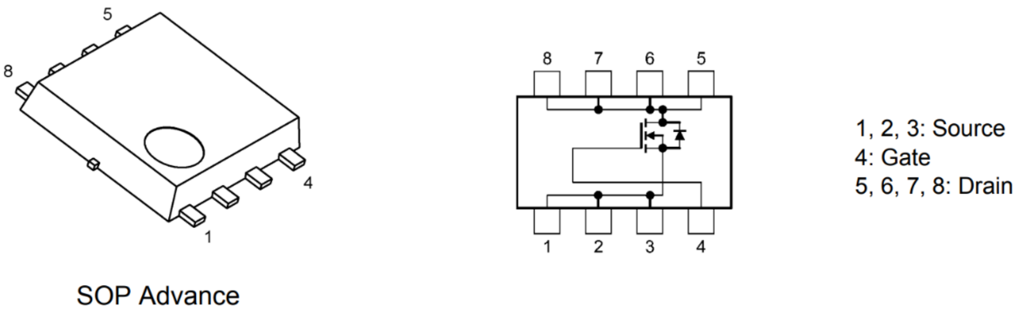


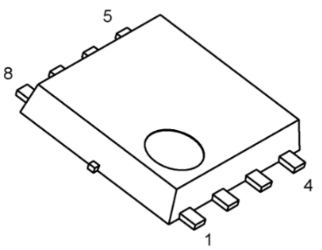
Fig. 3.1 External View and Pin Layout of TPH1R204PB

3.2. Power MOSFET TPH2R408QM

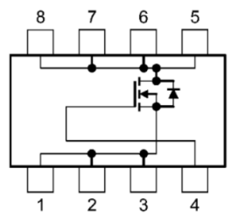
80V N-channel MOSFETs TPH2R408QM are used in the motor-drive section of Type2 circuit. The main features of TPH2R408QM are as follows.

- V_{DSS} = 80V, I_D = 120A
- High-speed switching
- Small gate charge: Q_{SW} = 28nC (Typ.)
- Small output charge: Q_{OSS} = 90nC (Typ.)
- Low drain-source on-resistance: $R_{DS(ON)}$ = 1.9mΩ (Typ.) (V_{GS} = 10V)
- Low leakage current: I_{DSS} = 10μA (Max.) (V_{DS} = 80V)
- Enhancement mode: V_{th} = 2.5 to 3.5V (V_{DS} = 10V, ID = 1.0mA)

External View and Pin Layout



SOP Advance



1, 2, 3: Source
4: Gate
5, 6, 7, 8: Drain

Fig. 3.2 External View and Pin Layout of TPH2R408QM

3.3. Three-Phase Gate Driver IC TB67Z833SFTG

The gate driver IC TB67Z833SFTG is used to drive six MOSFETs, which drive a three-phase brushless motor. The main features of TB67Z833SFTG are as follows.

- Gate driver for high-side and low-side N-channel MOSFET
- Adjustable gate drive capability
  Source current capability: 10mA to 1A (peak)
  Sink current capability: 20mA to 2A (peak)
- Operating voltage range: 8 to 75V
- Built-in voltage regulator
- Built-in 3-channel current sense amplifiers
- SPI and Hardware interface
- 6-PWM input mode, 3-PWM input mode, Hall input mode, and Independent PWM mode
- Standby mode (1μA @ VM = 24V)
- Built-in protection functions

External View

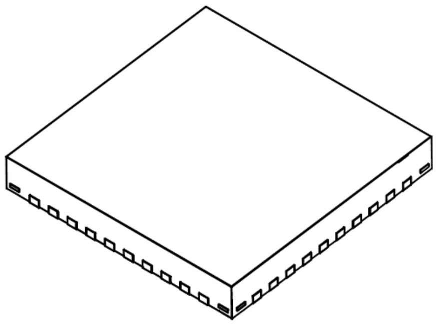


Fig. 3.3 External View of TB67Z833SFTG

3.4. Comparator TC75W58FU

CMOS dual-comparators TC75W58FU are used to detect overcurrent. The main features of TC75W58FU are as follows.

- Low supply current: I_{DD} = 20μA (Typ.)
- Single power supply operation
- Wide common mode input voltage range: V_{SS} to V_{DD}−0.9V
- Open drain output circuit
- Low input bias current

External View and Pin Layout

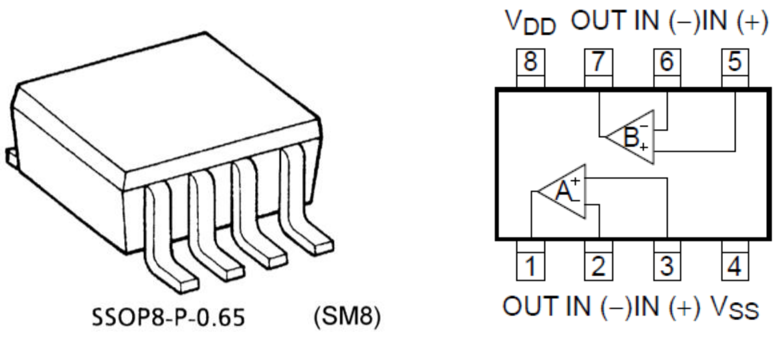


Fig. 3.4 External View and Pin Layout of TC75W58FU

4. Circuit Design

4.1. Motor Drive Circuit

There are two methods for driving a 3-phase BLDC motor: square wave drive and sine wave drive, the names indicate the wave form of the motor current. In both methods, the rotational force is obtained by detecting the rotational position of the motor and changing the direction in which the current flows accordingly.

Sine wave drive is excellent in terms of control accuracy, efficiency, and noise, but the system becomes complicated and expensive. On the other hand, square-wave drive is inferior to sine-wave drive in terms of control accuracy, efficiency, and noise, but the system is characterized by simple and inexpensive operation.

Both drive systems require rotor position detection to change the direction of the current flowing through the coil of the motor and can be divided into two methods: control with a position sensor and control without a position sensor.

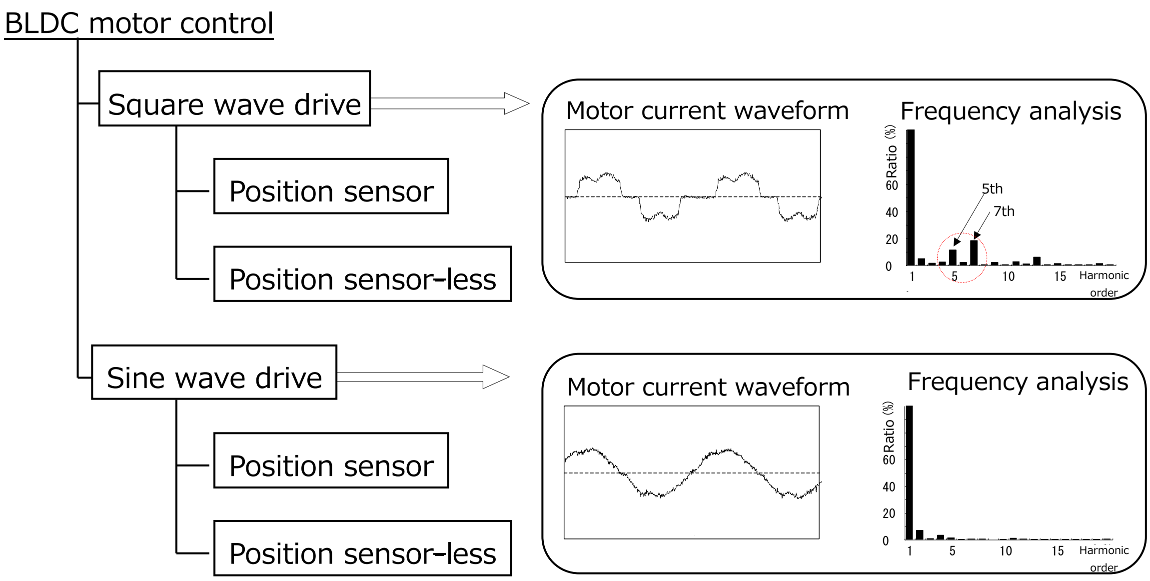


Fig. 4.1 BLDC Motor Control System

Control with position sensor uses sensors that detect the rotational speed and rotational position of the motor, and the rotor position can be accurately detected at startup, so torque can be output from low speed. However, it is necessary to consider the mounting position accuracy of sensors such as Hall sensors and encoders. Wiring of the sensor signal output from the motor is also required.

On the other hand, position sensor-less control is easy to cope with motors that cannot have sensors inside and motors that are exposed to poor environments, so the structure of the motor can be simplified, but there is a demerit that it is difficult to produce torque at low speeds because motor position detection cannot be performed during startup.

Fig. 4.2 shows a block diagram of this design again.

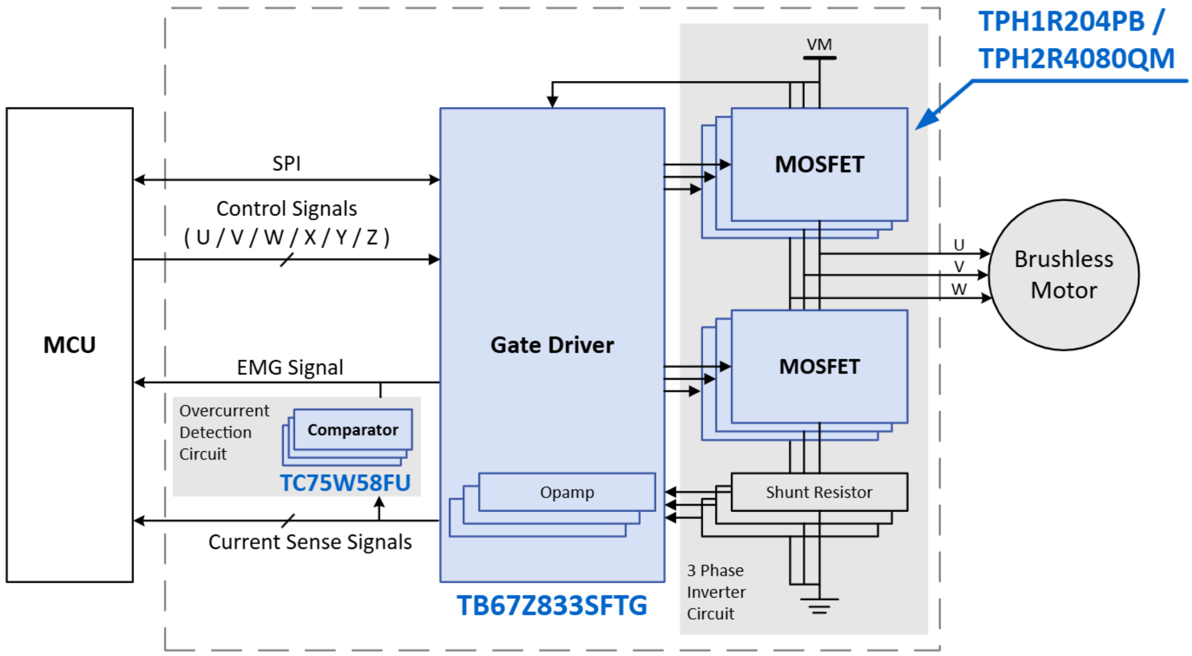


Fig. 4.2 Block Diagram of This Design

Assuming that this design will be applied to various power tools, this design contains only the inverter part and is configured to connect to external MCU for control.

A total of six MOSFETs (TPH1R204PB in Type1 circuit, TPH2R408QM in Type2 circuit) are used on the upper and lower sides of each phase as output elements for driving each phase (U, V, and W) of the motor. These MOSFETs are driven by a three-phase gate driver IC TB67Z833SFTG. TB67Z833SFTG supports the Hall input mode, which can easily realize square-wave drive, the 6-PWM input mode and the 3-PWM input mode allows switching between square-wave drive and sine-wave drive. The external MCU can be used to control the revolutions and torque, and to switch between drive modes.

As mentioned above, there are merits and demerits for square wave drive and sine wave drive. In this guide, we will explain each part assuming the operation with sine wave drive by 6-PWM input mode.

TB67Z833SFTG has three gain-adjustable amplifiers that can detect the shunt current of each phase separately and can also support sensorless control of rotational speed and torque.

4.2. Motor Current Sensing Circuit

In this design, the current sensing circuit is of 3-shunt type, in which a shunt resistor is externally connected to the source pin of the low-side MOSFET of each of the U, V, and W phases. The voltage generated at each shunt resistor by the motor current of each phase is amplified by the amplifier built into TB67Z833SFTG and can be used as a signal for controlling the motor speed and torque and for vector control.

Fig. 4.3 shows the circuit diagram of the 3-shunt method.

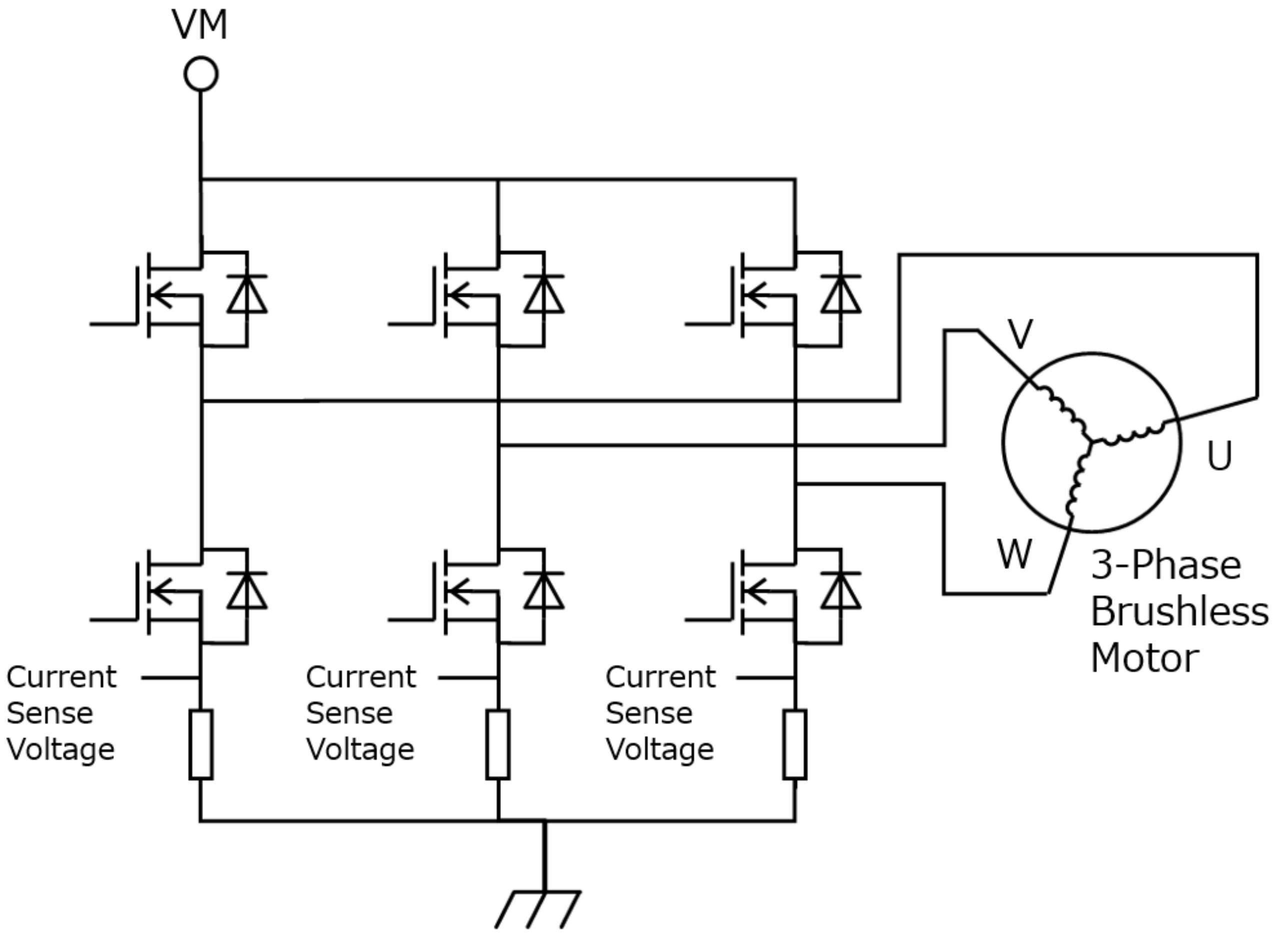


Fig. 4.3 Circuit Diagram of 3-Shunt Method

A shunt resistor is placed between the source pin of the low-side MOSFET of each phase and GND. Fig. 4.4 shows an example of the shunt resistor section of the circuit. The current of each phase is detected by the voltage generated across the shunt resistor (RSEN1, RSEN2, RSEN3) placed between the low-side MOSFET source pin of each phase and GND.

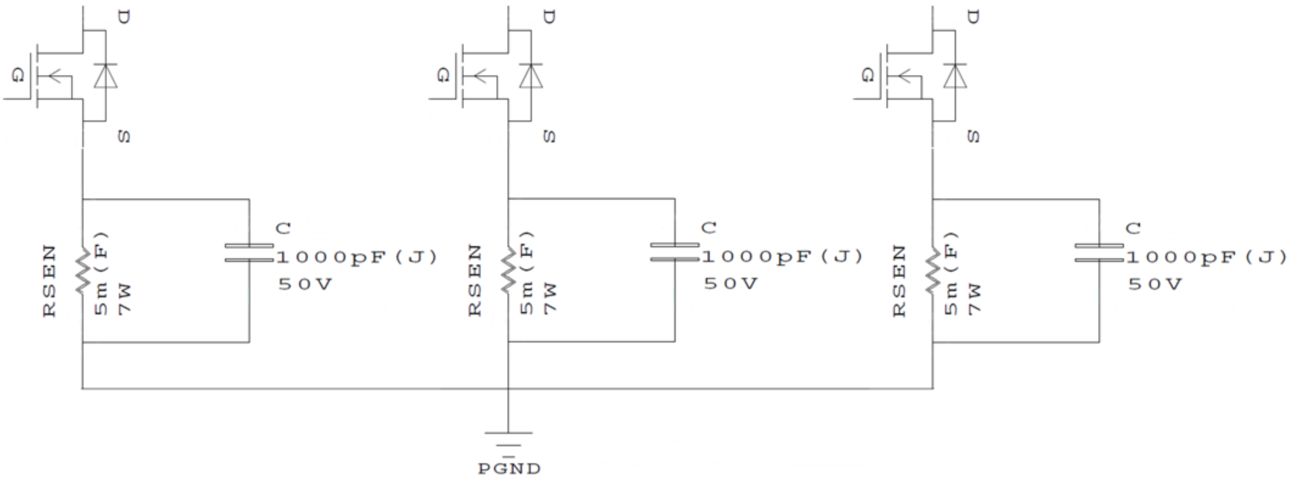


Fig. 4.4 Shunt Resistors in 3-Shunt Method

If the value of the shunt resistor is large, the level of the current sense voltage will also increase, allowing the current to be detected with high accuracy. On the other hand, since the generated power (I^2R) also increases, a resistor with a higher power rating that is, a larger resistor must be used. This may be unacceptable in applications that require miniaturization and space saving. On the contrary, when the value of the shunt resistor is decreased, the level of the current sense voltage decreases, so it is susceptible to errors and jumping noise caused by the parasitic resistance of the wiring of the printed circuit board. However, since the generated power is reduced, it is possible to use a resistor with low power rating and small size.

Considering the application for power tools, this design chooses a small value of resistance for the advantage of being able to miniaturize the system with the required sensing accuracy. The motor current is assumed to be ±20A in steady operation and max ±40A instantaneously, based on the size of the motor commonly used in power tools. Based on the current, power dissipation, and component size, the shunt resistor is chosen with the resistance value of 5mΩ and the power rating of 7W.

The voltage between both ends of the shunt resistor is very small (about ±200mV max. instantaneously), and thus the direct measurement with a MCU is difficult. Therefore, the signal-amplification by an op-amp, etc. is required. In addition, since the current flowing through each phase of the three-phase BLDC motor is bidirectional, both positive and negative voltages are generated across the shunt resistor. Since a positive voltage is required for the input to MCU, the output voltage of the op-amp must be shifted so that the bi-directional current can be detected.

Fig. 4.5 shows the current sensing circuit.

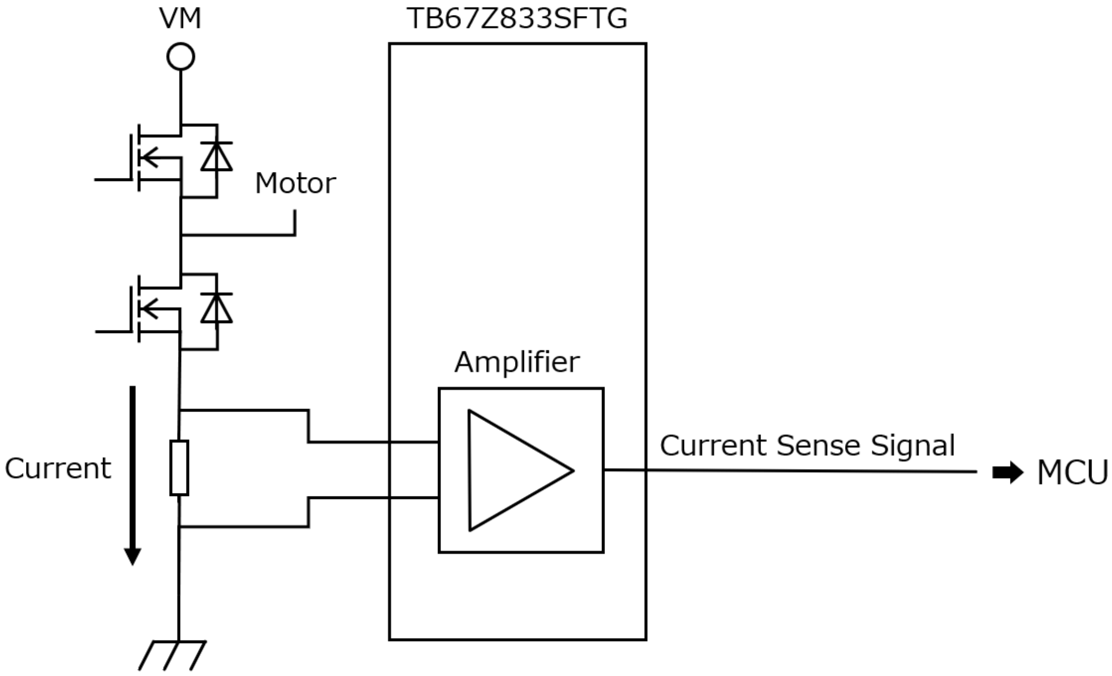


Fig. 4.5 Current Sensing Circuit

In this design, the built-in amplifier of TB67Z833SFTG amplify the input signal while also applying the bias voltage to shift the output voltage level. In TB67Z833SFTG, the gain of the built-in amplifier, the bias-voltage (V_{VREF} or $V_{VREF}/2$) to be applied, etc. are set by the SPI communication. The voltage generated by the shunt resistor because of the phase current flow is amplified and shifted in order to set the amplitude of the output signal to be within the linear output range of the built-in amplifier of TB67Z833SFTG. In this design, the maximum instantaneous current of the motor is ±40A and after adding margin it becomes ±45A. Therefore, in this design the amplifier is configured such that this ±45A is covered in the full linear output range of the amplifier.

In this design, the shunt resistor side connected to the MOSFET is input to the SNx pin (SNA, SNB, SNC) and the shunt resistor side connected to the GND is input to the SPx pin (SPA, SPB, SPC), therefore a current flow from MOSFET to GND will produce an higher voltage on SNx compared to SPx.

Assuming the use of a 5V MCU, ADC built-in the MCU will have an input range from 0 to 5V, the applied bias-voltage is set to $V_{VREF}/2$ (i.e. 2.5V) so that the signal is amplified around this half voltage (2.5V).

Also, since the built-in amplifier of TB67Z833SFTG has a linear output range of 0.25 to 4.75V, the gain is set to fit the maximum amplitude of the signal within this range. And because the shunt resistor is 5mΩ, a current of ±45A will generate ±225mV. Since the amplifier has a linear output range of 0.25 to 4.75 V with the center voltage of 2.5V and the maximum amplitude of ±2.25V as described above, dividing this maximum amplitude of the amplifier's linear output range by the maximum amplitude of the sense voltage yields the following values:

$$\frac{2.25}{225 \times 10^{-3}} \cong 10 \quad (times)$$

Therefore, the amplifier gain is set to 10 times (= 20dB).

Fig. 4.6 shows the relationship between the current flowing through the shunt resistor and the amplifier output voltage. The solid blue line shows the values within the linear output range of the amplifier, and the output voltage of the amplifier is proportional to the input current. The dotted blue line indicates values outside the linear output range, and the output voltage of the amplifier differs significantly from the calculated value.

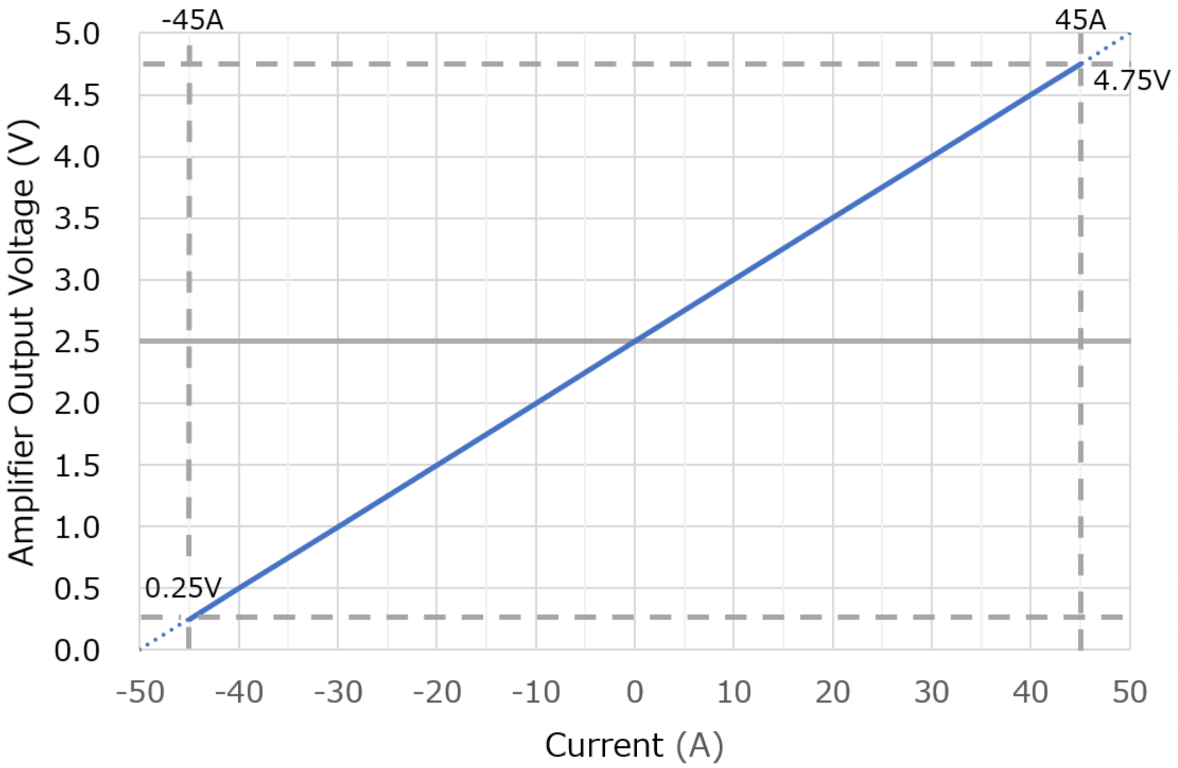


Fig. 4.6 Relationship Between the Current Flowing Through the Shunt Resistor and the Amplifier Output Voltage

(For Reference)

In this design, the source pin of each phase low-side MOSFET can be connected, and each phase current can be combined into one, making it less expensive to configure as a 1-shunt system. When the solder jumper SJ5, SJ6 on the board is opened and SJ3, SJ4 is short-circuited, a 1-shunt configuration is achieved.

Fig. 4.7 shows a circuit diagram of the 1-shunt method.

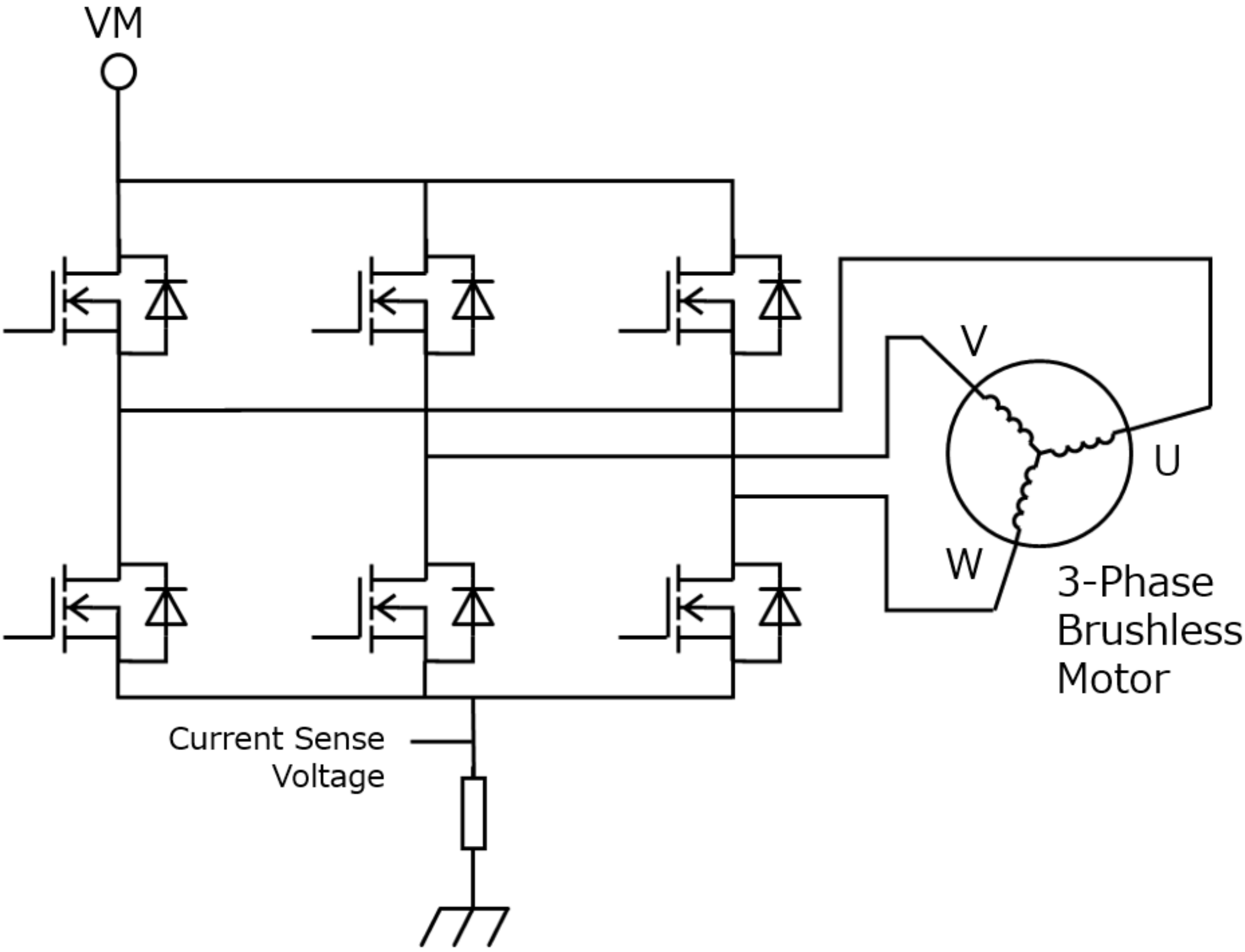


Fig. 4.7 Circuit Diagram of 1-Shunt Method

In this configuration a shunt resistor is placed between the low-side MOSFET source-pin and GND, and the voltage across it is measured. And similar to the 3-shunt method, this voltage is amplified and shifted by the amplifier, and then input to the MCU.

Note: This design is intended to be used with the 3-shunt method, so operation may differ with the 1-shunt method.

4.3. Overcurrent Detection Circuit

In this design, the EMG (emergency) is output to the MCU so that it shuts off the output and the protective operation can be performed when a circuit/operation error occurs. This EMG signal is connected to TB67Z833SFTG flag output pin (nFAULT) and is also connected to the overcurrent detector. When an error is detected, EMG signal goes low.

※: EMG signal is also connected to the nCS pin in addition to the nFAULT pin of TB67Z833SFTG. Before connecting to an MCU, please refer to the reference guide of this design for details.

Fig. 4.8 shows the overcurrent detection circuit.

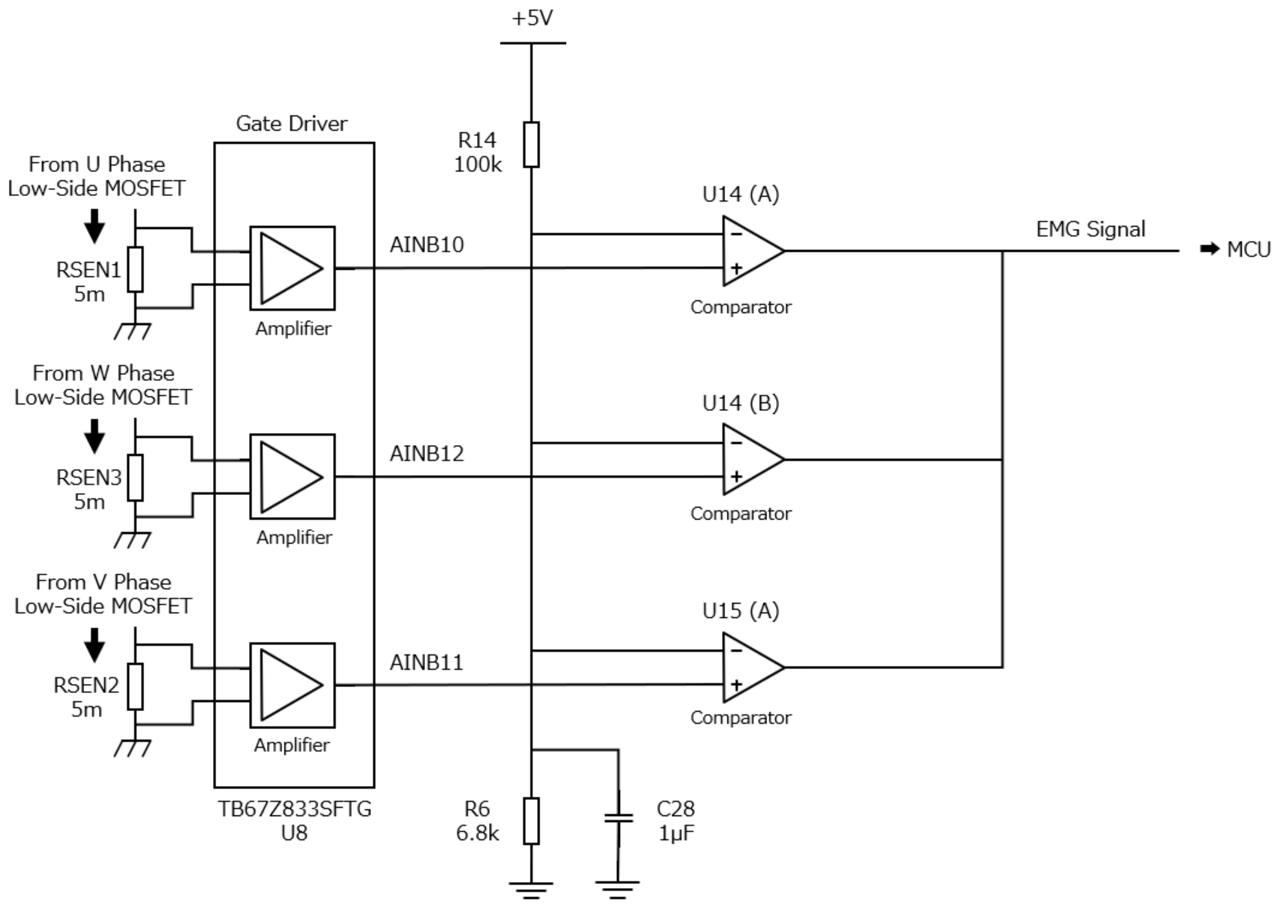


Fig. 4.8 Overcurrent Detection Circuit

The current sense voltage of each phase is amplified by the built-in amplifier of TB67Z833SFTG and then inputted to the comparator (TC75W58FU) on the overcurrent detection circuit and then is compared with the reference voltage (V_{OC}). If any of the current sense signals fall below the reference voltage, it is judged as overcurrent, and the EMG signal is output to the MCU.

In this design, in order to judge the current more than 43A as overcurrent, the V_{OC} threshold voltage must be set lower than the V_{OC}' threshold value calculated for 43A using the following equation.

$$V_{OC}' = \frac{V_{ref}}{2} - I_{SENSE} \times R_{SENSE} \times G_{CSA} = \frac{5.0\ (V)}{2} - 43\ (A) \times 5\ (\text{m}\Omega) \times 10 \cong 350\ (mV)$$

According to the circuit configuration of this design, the V_{OC} is calculated by dividing the power supply voltage (5V) using the resistors R6 (6.8kΩ) and R14 (100kΩ) as shown below and input to the IN(-) pin of the TC75W58FU. And therefore, the overcurrent detection current (I_{OC}) value of this circuit becomes -43.64A as shown below.

$$V_{OC} = \frac{R6}{R6 + R14} \times 5\ (V) = \frac{6.8 \times 10^3}{6.8 \times 10^3 + 100 \times 10^3} \times 5\ (V) \cong 318\ (mV)$$

$$I_{OC} = \frac{\frac{V_{ref}}{2} - V_{OC}}{R_{SENSE} \times G_{CSA}} = \frac{\frac{5.0\ (V)}{2} - 318 (mV)}{5\ (\text{m}\Omega) \times 10} \cong -43.64\ (A)$$

Fig. 4.9 shows the overcurrent detection area of this design.

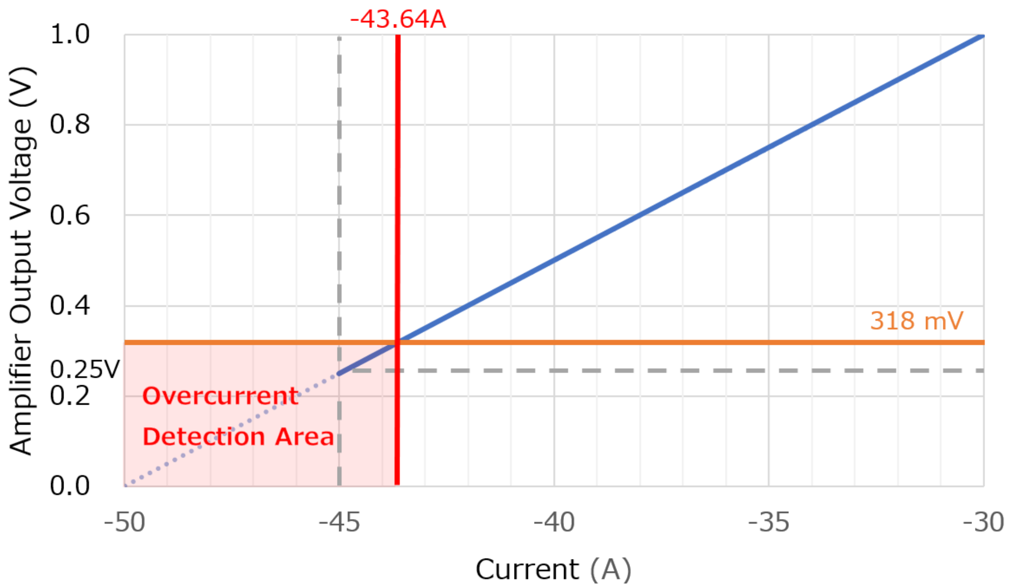


Fig. 4.9 Overcurrent Detection Area

4.4. Adjusting MOSFET Drive Capability

The MOSFET drive capability can be set in TB67Z833SFTG by SPI communication (Source: 10 to 1000mA, Sink: 20 to 2000mA). The drive capability can be adjusted according to the motor to be driven, and various requirements required for actual application such as loss and noise.

4.5. Notes on Circuit Design

- The absolute maximum rating is a standard that must not be exceed for any one of the multiple ratings even instantaneously. It cannot be exceeded for any of the multiple ratings. Even during operation, care must be taken to ensure derating so as not to exceed the absolute maximum ratings.

- The capacitance of the by-pass capacitor (C10) of the power supply is a capacitor value that is adequate for the board in this design. However, the required capacitance varies depending on the type of power supply, the wire inductance of the power supply and the motor drive circuit, the allowable supply voltage ripple, and the type of motor. In general, the capacitor capacitance is set with a margin, but since the size of the component is also large, there is a disadvantage of an increase in cost and an increase in the occupied area of the circuit board. Select the most suitable capacitor capacitance according to the actual circuit and target environment.

5. Board Design

5.1. Notes on PCB Pattern Design

This section describes precautions when designing board patterns.

- The most important precaution is to prevent errors caused by the resistance of the PCB pattern wiring from entering the voltage drop of the shunt resistor used for current sensing. For this reason, the wiring to the shunt resistor used to sense voltage drop across the land pattern of the resistor should be completely separated from the wiring that runs current so that the voltage drop caused by the wiring resistor does not enter the sensed voltage. This enables accurate sensing of the current, enabling high-precision motor control.
  This kind of wiring method is called Kelvin connection. Fig. 5.1 shows an image of a Kelvin connection wiring pattern.

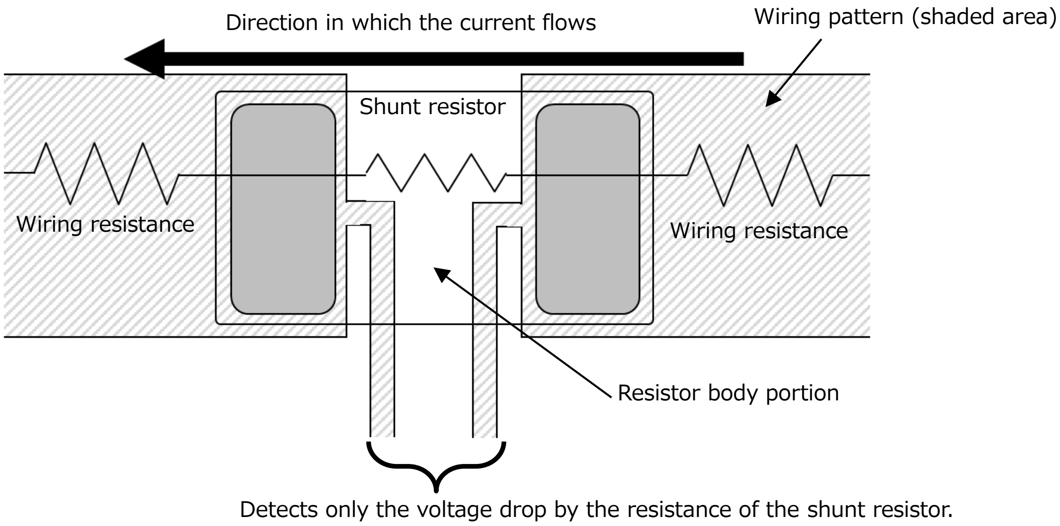


Fig. 5.1 Image of Kelvin Connection Wiring Pattern

- The wiring of the power supply, GND, and output of each phase around the motor should be routed thickly with as wide a wiring area as possible to reduce wiring resistance. In addition, there is a risk of picking up noise, so be careful not to route the power supply and GND patterns in a loop.

- GND of this design is divided into GND, PGND, AGND, etc. These GND divide the wires for each GND at the base of the grounded part of the power supply by-pass capacitor (C10) on the BOARD, and minimize the common-impedance components as much as possible.

- In this design, a by-pass capacitor is also placed at the power supply pin of each IC, such as the gate driver TB67Z833SFTG, and at the drain of the upper power MOSFET of each phase output. Place these capacitors as close to the pins as possible, and use a capacitor with good high-frequency characteristics. Also, place a capacitor connected in parallel to the shunt resistor as close as possible to the shunt resistor so that the resistance component that enters the capacitor in series is as small as possible.

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