

**Motor Driving Circuit  
for Automotive Body Electronics  
Using SmartMCD™  
Design Guide**

**RD228-DGUIDE-01**

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**Toshiba Electronic Devices & Storage Corporation**

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## 1. Introduction

This design guide document describes the design methodology of the Motor Driving Circuit for Automotive Body Electronics Using SmartMCD™ (hereinafter referred to as this design).

We have developed the brushless motor control circuit required for automotive body systems using Toshiba's gate driver IC SmartMCD [TB9M003FG](#) with an in-built microcontroller. The sensorless vector control process required for motor control is performed by SmartMCD, and the gate drivers required for driving MOSFETs of the inverter are also incorporated in SmartMCD, so that MOSFETs constituting the inverter can be directly connected and a simple configuration can be used to realize an automotive body motor control.

This design has a 130 mm X 73 mm board with circuit required for controlling the body motors, as well as switches and potentiometers required for checking operation. We have also prepared an external inverter board that is the same size as the main board and can drive a large-current motor. The on-board inverter on the main board uses the small package MOSFETs [SSM6K804R](#), and the external inverter board uses power MOSFETs [TK1R4S04PB](#), [XPH2R404PS](#), [TPW1R104PB](#), [XPN3R804NC](#).

## 2. Main Components

### 2.1. Gate Driver IC SmartMCD™ TB9M003FG With a Built-in Microcontroller

This design uses the gate driver IC SmartMCD™ [TB9M003FG](#) with an integrated microcontroller to control the motors. The main features of TB9M003FG are as follows.

- 32-bit Arm® Cortex®-M0 core
- Operating frequency: Max. 40 MHz, Operating voltage: 6.0 V to 18 V
- 64KB Code Flash (Including ECC SEC/DED)
- HTQFP48 package
- Equipped with our original Vector Engine (VE) for vector control

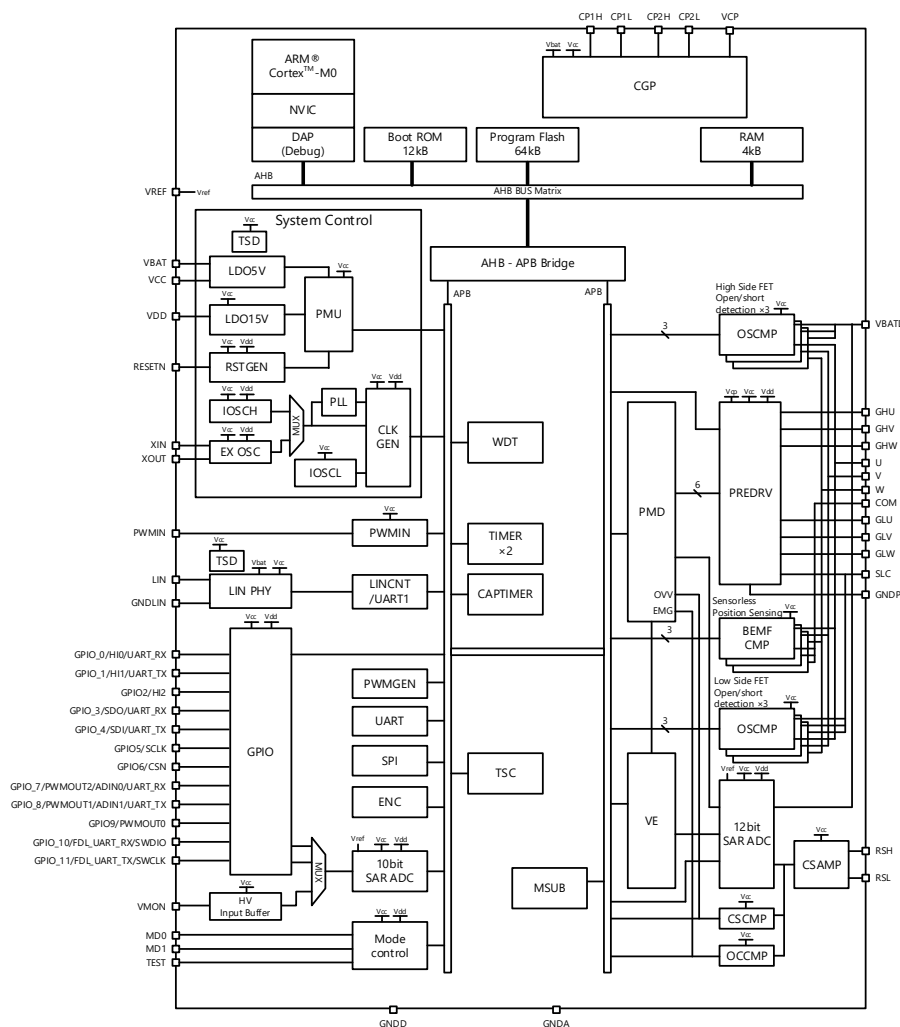
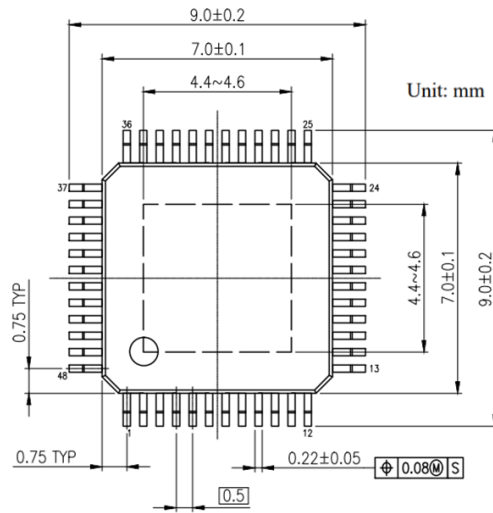


Fig. 2.1 TB9M003FG Internal Block Diagram

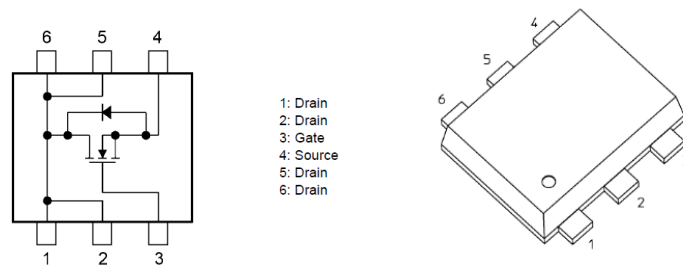


**Fig. 2.2 TB9M003FG Package**  
(HTQFP48, 7 mm x 7 mm, 0.5 mm Pitch)

**2.2. Small Package MOSFET SSM6K804R**

This design uses the small package MOSFET [SSM6K804R](#) as the switching device for the inverter circuit on the main board. The main features of SSM6K804R are as follows.

- AEC-Q101 qualified
- Low on-resistance:  $R_{DS(ON)} = 9 \text{ m}\Omega$  (Typ.) (@ $V_{GS} = 10 \text{ V}$ )
- Easy-to-use enhancement type:  $V_{th} = 1.4 \text{ to } 2.4 \text{ V}$  ( $V_{DS} = 10 \text{ V}$ ,  $I_D = 0.1 \text{ mA}$ )

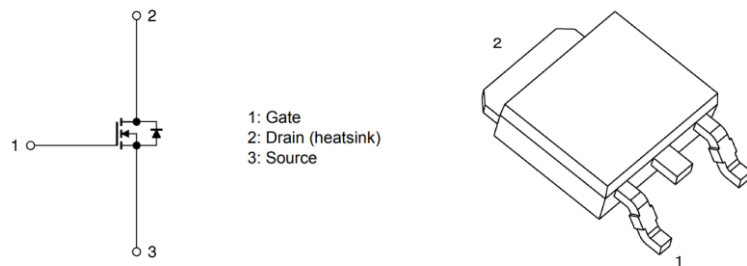


**Fig. 2.3 SSM6K804R Internal Configuration and Package (TSOP6F)**

### 2.3. Power MOSFET TK1R4S04PB

This design uses the power MOSFET [TK1R4S04PB](#) as the switching device in the inverter circuit of an external inverter board. The main features of TK1R4S04PB are as follows.

- AEC-Q101 qualified
- Low on-resistance:  $R_{DS(ON)} = 1.1 \text{ m}\Omega$  (Typ.)
- Low leakage current:  $I_{DSS} = 10 \text{ }\mu\text{A}$  (Max.) ( $V_{DS} = 40 \text{ V}$ )
- Easy-to-use enhancement type:  $V_{th} = 2.0 \text{ to } 3.0 \text{ V}$  ( $V_{DS} = 10 \text{ V}$ ,  $I_D = 0.5 \text{ mA}$ )

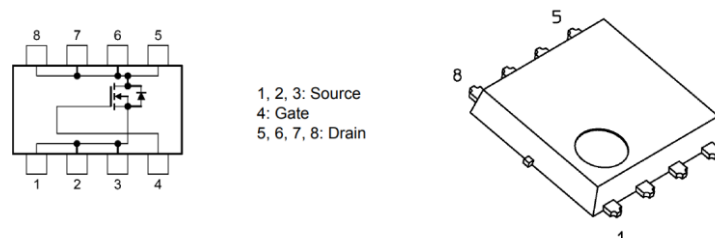


**Fig. 2.4 TK1R4S04PB Internal Configuration and Package (DPAK +)**

### 2.4. Power MOSFET XPH2R404PS

This design uses the power MOSFET [XPH2R404PS](#) as the switching device in the inverter circuit of an external inverter board. The main features of XPH2R404PS are as follows.

- AEC-Q101 qualified
- Small, thin, small mounting area
- Low on-resistance:  $R_{DS(ON)} = 1.8 \text{ m}\Omega$  (Typ.) ( $V_{GS} = 10 \text{ V}$ )
- Low leakage current:  $I_{DSS} = 10 \text{ }\mu\text{A}$  (Max.) ( $V_{DS} = 40 \text{ V}$ )
- Easy-to-use enhancement type:  $V_{th} = 2.0 \text{ to } 3.0 \text{ V}$  ( $V_{DS} = 10 \text{ V}$ ,  $I_D = 0.3 \text{ mA}$ )

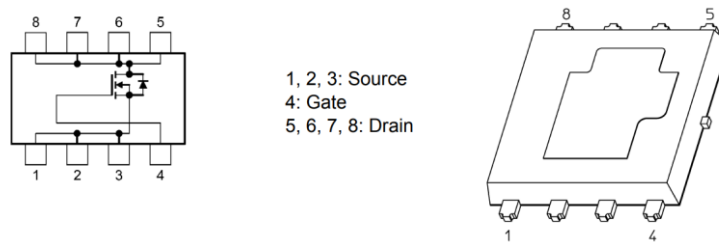


**Fig. 2.5 XPH2R404PS Internal Configuration and Package (SOP Advance(WF))**

### 2.5. Power MOSFET TPW1R104PB

This design uses the power MOSFET [TPW1R104PB](#) as the switching device in the inverter circuit of an external inverter board. The main features of TPW1R104PB are as follows.

- AEC-Q101 qualified
- Small, thin, small mounting area
- Low on-resistance:  $R_{DS(ON)} = 0.95 \text{ m}\Omega$  (Typ.) ( $V_{GS} = 10 \text{ V}$ )
- Low leakage current:  $I_{DSS} = 10 \text{ }\mu\text{A}$  (Max.) ( $V_{DS} = 40 \text{ V}$ )
- Easy-to-use enhancement type:  $V_{th} = 2.0 \text{ to } 3.0 \text{ V}$  ( $V_{DS} = 10 \text{ V}$ ,  $I_D = 0.5 \text{ mA}$ )

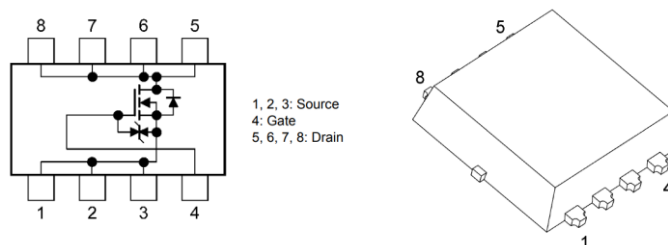


**Fig. 2.6 TPW1R104PB Internal Configuration and Package (DSOP Advance(WF)M)**

### 2.6. Power MOSFET XPN3R804NC

This design uses the power MOSFET [XPN3R804NC](#) as the switching device in the inverter circuit of an external inverter board. The main features of XPN3R804NC are as follows.

- AEC-Q101 qualified
- Small, thin, small mounting area
- Low on-resistance:  $R_{DS(ON)} = 3.0 \text{ m}\Omega$  (Typ.) ( $V_{GS} = 10 \text{ V}$ )
- Low leakage current:  $I_{DSS} = 10 \text{ }\mu\text{A}$  (Max.) ( $V_{DS} = 40 \text{ V}$ )
- Easy-to-use enhancement type:  $V_{th} = 1.5 \text{ to } 2.5 \text{ V}$  ( $V_{DS} = 10 \text{ V}$ ,  $I_D = 0.3 \text{ mA}$ )



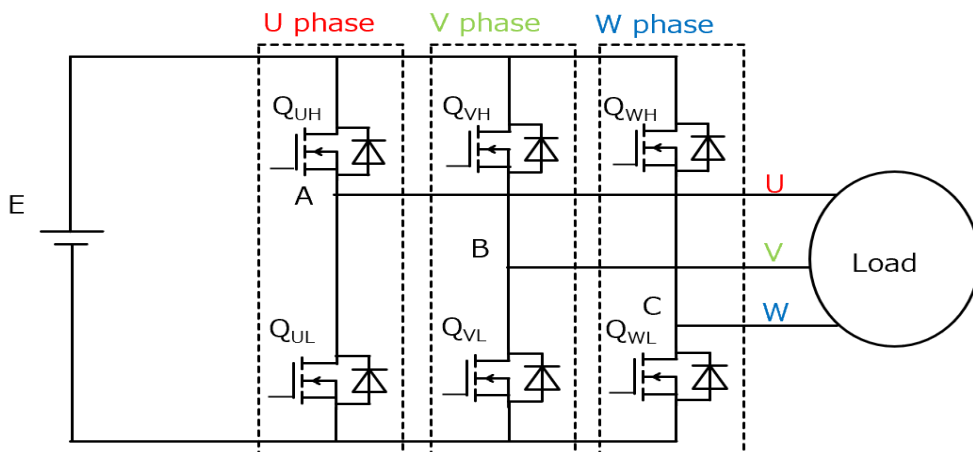
**Fig. 2.7 XPN3R804NC Internal Configuration and Package (TSOP Advance(WF))**

### 3. Outline of Operation

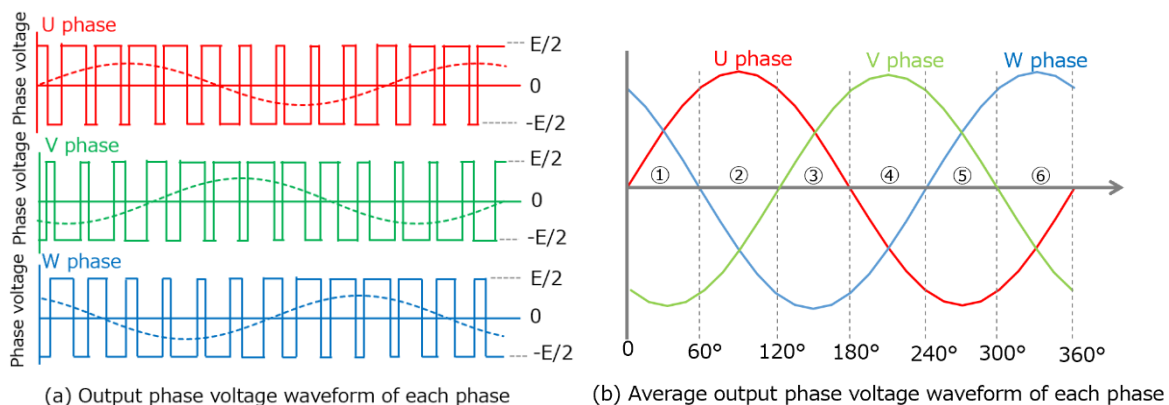
#### 3.1. 3-Phase Inverter Operation

Fig. 3.1 shows a three-phase inverter circuit. Three-phase inverters convert direct current into three-phase alternating current, and are used in many automotive body brushless motor drives. Three-phase inverters produce three-phase alternating current from direct current, enabling control of output voltage and output frequency. The energization method used to drive the motor with a three-phase inverter includes square-wave drive (120° energization) and sine-wave drive (180° energization). The square-wave drive switches only 120° out of the half-wave 180° interval at the electrical rotation angle, so the switching loss becomes smaller than the sine-wave drive, but the output current becomes a square-wave shape and the motor efficiency is lower than the sine-wave drive. The sine wave drive uses a sine wave to energize, which results in smooth rotation and low noise.

Fig. 3.2 shows an example of the phase voltage waveform of a 3-phase inverter. Sine-wave drive (180° energized) generates three-phase AC voltage with phase difference of 120° output by PWM controlling the upper and lower arm elements of each phase. This three-phase alternating current drives brushless motors in automotive body system.



**Fig. 3.1 3-Phase Inverter Circuit**

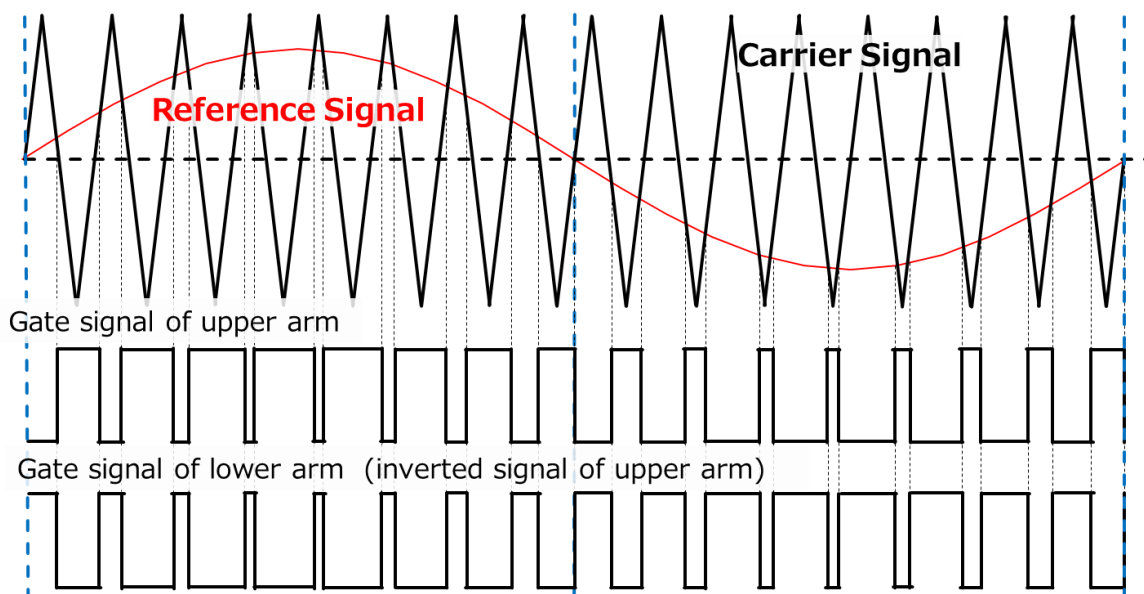


**Fig. 3.2 3-Phase Inverter Phase Voltage Waveform Example**



PWM (Pulse Width Modulation with sinusoidal drive) MOSFET of the upper and lower arms of each phase are complementarily switched. PWM control is controlled by changing the duty of the pulse-width of the input signal. The period is constant. The voltage and frequency of the output can be controlled by changing the duty of the pulse width. When the duty of the pulse width of the switching element is large, the output voltage and output current become large.

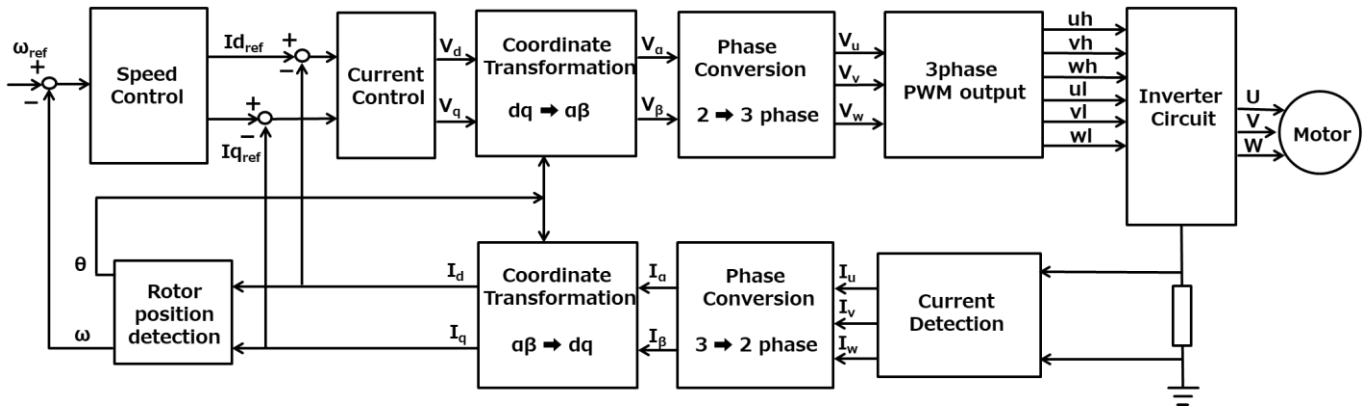
Fig. 3.3 shows an example of sine wave PWM generation. The voltage of the sinusoidal signal wave shown by the red line is compared with the voltage of the triangular carrier signal. When the sinusoidal signal voltage is higher than the carrier signal voltage, PWM control signal output becomes 1 and the inverter switch element is turned on. Otherwise, PWM control signal output becomes 0 and the inverter switch element is turned off. PWM control signal of the switching element of the lower arm uses a signal obtained by inverting PWM control signal of the switching element of the upper arm.



**Fig. 3.3 Sine-Wave PWM Generation**

### 3.2. Sensorless Vector Control

Fig. 3.4 shows an example of sensorless vector control block diagram. Vector control, which can efficiently process motor rotation control from low speed to high speed, has become widely used in motor control in recent years. Motor rotation angle detection is required for vector control. Previously, hall sensors and encoders were used for this rotation angle detection, however recently the sensorless method that estimates the rotation angle by detecting the motor current without using these external elements is also being used.



**Fig. 3.4 Example of Sensorless Vector Control Block Diagram**

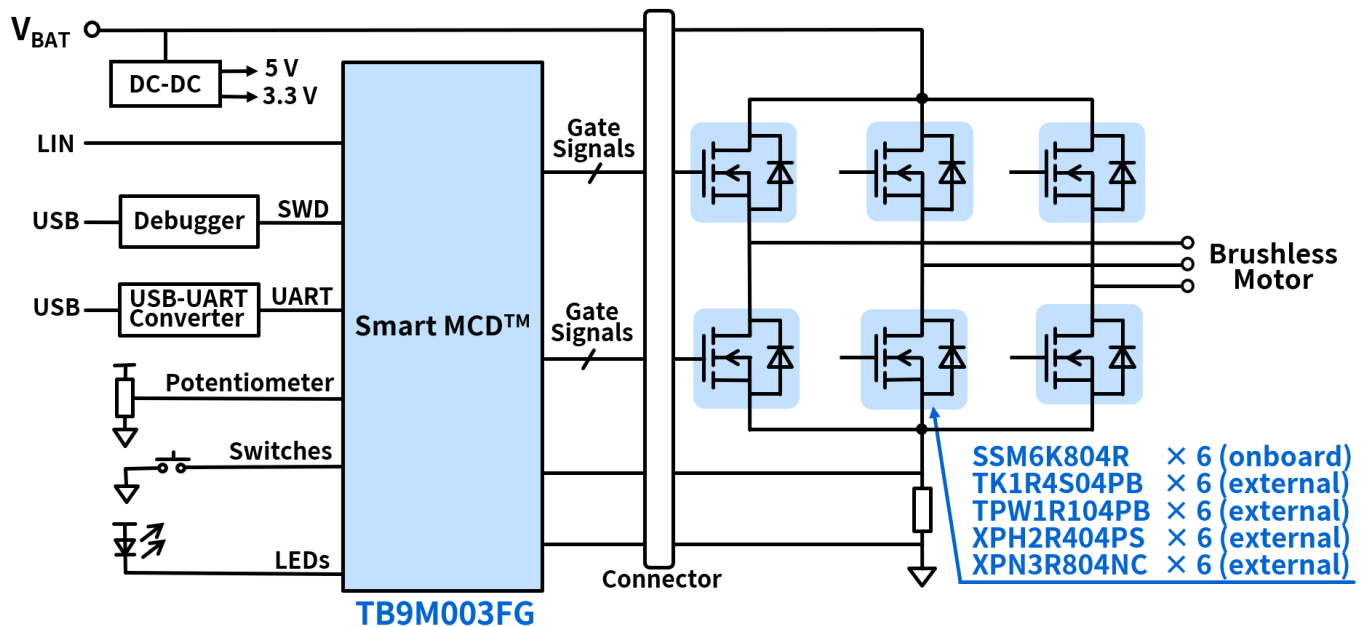
SmartMCD [TB9M003FG](#) is equipped with the dedicated hardware (VE, PMD, ADC) that supports sensorless vector control. It uses an easy to configure 1-shunt method for motor-current detection.

## 4. Circuit Design

### 4.1. Main PCB

#### 4.1.1. Overall Block Diagram

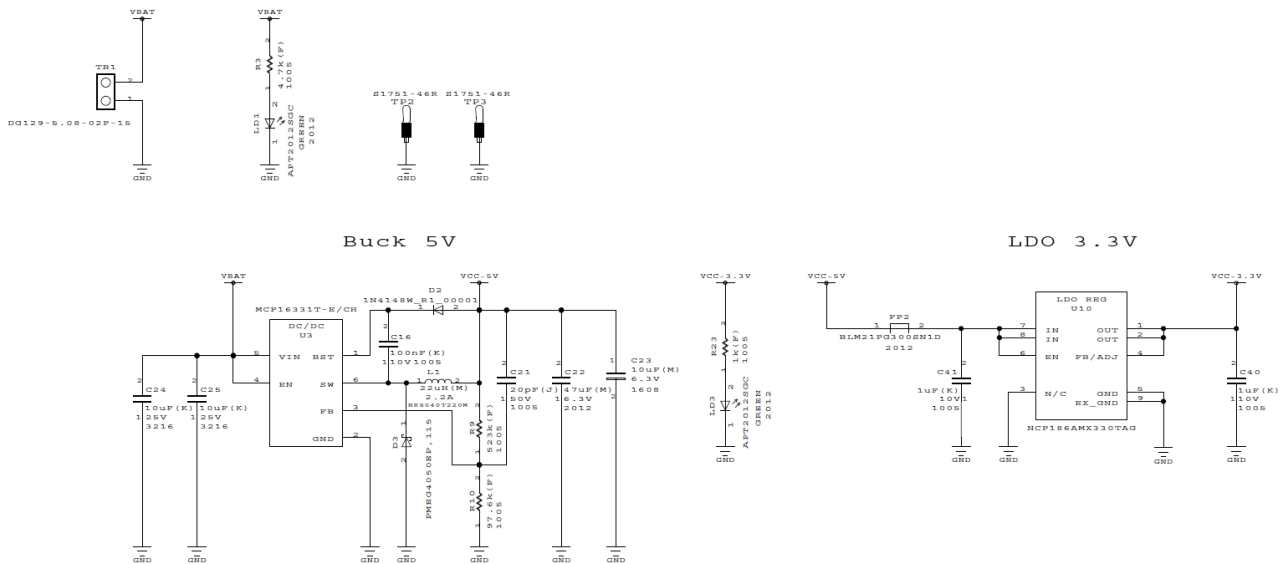
Fig. 4.1 shows the block diagram of the main board. SmartMCD TB9M003FG is a gate driver IC with a built-in microcontroller developed by Toshiba, that enables control of a 3-phase inverter circuit used for brushless motor control and overcurrent detection. It operates with the input power supply  $V_{BAT}$ .



**Fig. 4.1 Overall Block Diagram of Motor Driving Circuit for Automotive Body Electronics Using SmartMCD**

### 4.1.2. Power Supply Circuit

Fig. 4.2 shows the power supply circuit.



**Fig. 4.2 Power Supply Circuit**

The incoming power ( $V_{BAT}$ ) is supplied to the SmartMCD (U1), the inverter circuit, and the step-down DC-DC converter (U3). The step-down DC-DC converter (U3) used to generate 5 V power supply (VCC-5V) for ICs and components around SmartMCD (U1). In addition, 5 V power supply (VCC-5V) is also used to generate 3.3V power supply (VCC-3.3V) using LDO regulator (U10) and is supplied primarily to CMSIS-DAP (U2).

In order to output 5.0 V to the 5 V power supply (VCC-5V), the FB (3-pin) voltage of DC-DC converter (U3) is set to 0.8 V using the voltage divider made-up of the resistors (R9, R10).

### 4.1.3. SmartMCD Related Circuit

Fig. 4.3 shows the circuit related to SmartMCD.

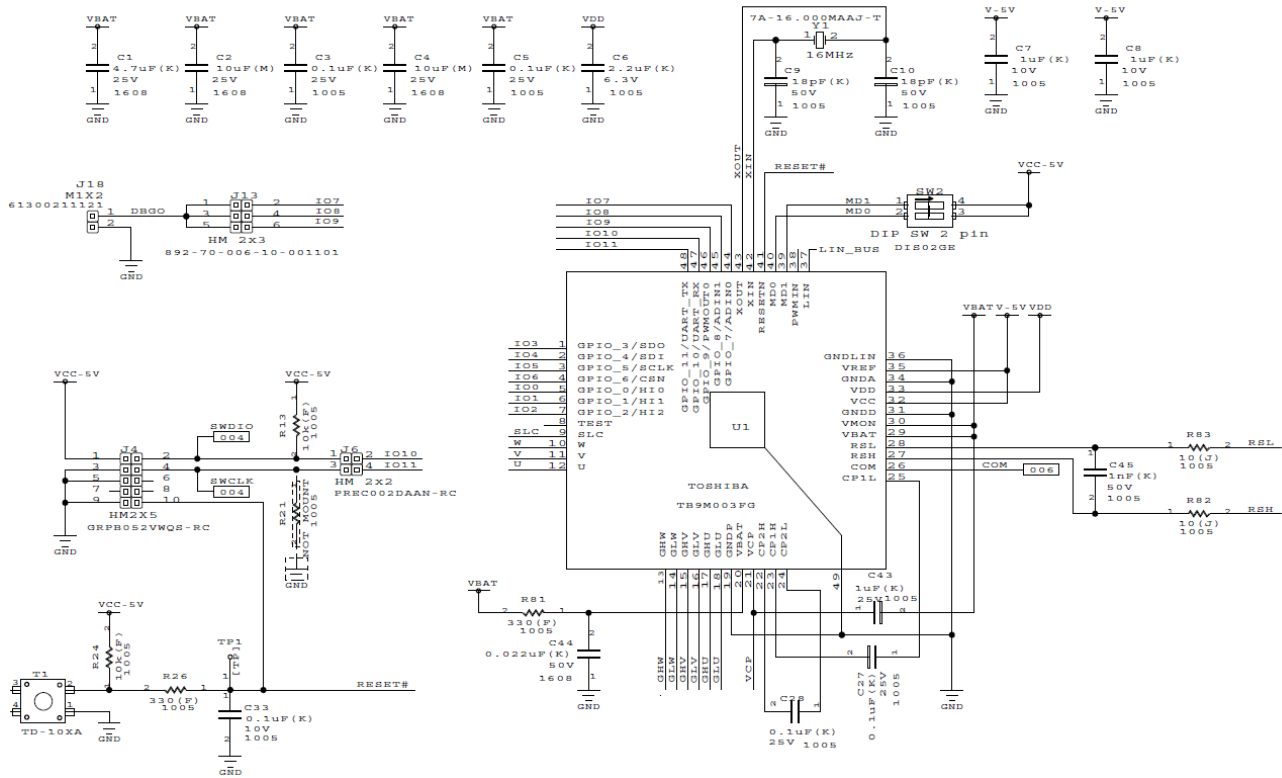


Fig. 4.3 SmartMCD Related Circuit

The gate driver IC SmartMCD [TB9M003FG](#) (U1) used in this design has a built-in 32 bit Arm<sup>®</sup> Cortex<sup>®</sup>-M0 core processor, enabling operation at the maximum frequency of 40 MHz.

SmartMCD (U1) can be powered using the voltage from 6 V to 18 V. By-pass capacitors (C1 to C5) are connected near VBAT pin (pin 29) which is the power supply input. A crystal resonator (Y1) of 16 MHz frequency and two 18 pF capacitors (C9, C10) are used for generating clock. The reset circuit consisting of a switch (T1), resistors (R24, R26) and a capacitor (C22) is used to generate a reset signal for SmartMCD (U1). This reset circuit also eliminates bouncing noise produced when the reset switch (T1) is used.

The charge pump boost circuit that generates the pre-driver power supply required to drive the inverter circuit MOSFETs requires the external capacitors C<sub>CP1</sub> (C27), C<sub>CP2</sub> (C28) and C<sub>VCP</sub> (C42).

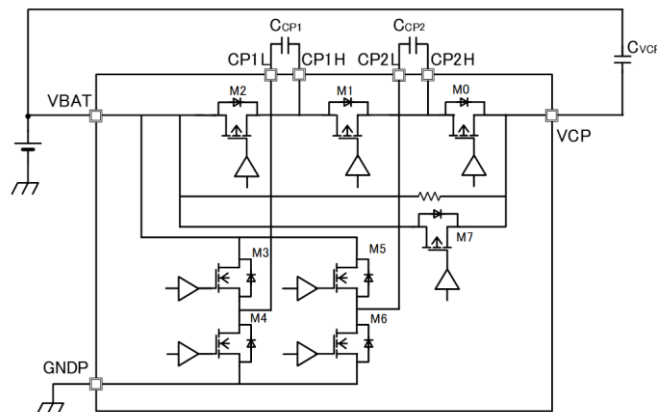


Fig. 4.4 Charge Pump Block Diagram

The start mode selection switch (SW2) is used to select the activation mode. When the reset is canceled, Normal mode, Flash Download mode, or Debug mode is selected according to the MD0, MD1 setting.

**Table 4.1 Start Mode Selection**

MD1	MD0	Mode
OFF	OFF	Normal
ON	OFF	Flash Download
OFF	ON	Debug

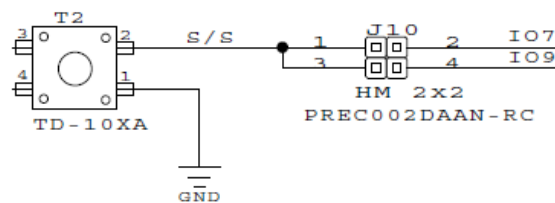
Some of the pins on SmartMCD (U1) are multiplexed, and the post-startup software configuration determines the pin assignment.

DBGO signal output connector (J18) is used to externally monitor the debug output signal (DBGO) of SmartMCD (U1) and can be connected to IO7, IO8, or IO9 of SmartMCD (U1) by using the DBGO Signal Jumper Pin Connector (J13).

SWD connector (J4) is used for connecting the external SWD interface to SmartMCD (U1). For it to work, the jumpers must be connected to SWD Signal Jumper Pin Connector (J6) to connect SWDIO to IO10 and SWCLK to IO11 of SmartMCD (U1).

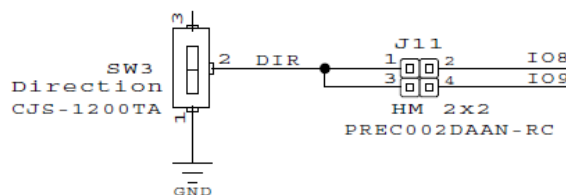
**4.1.4. Peripheral Switches, Connectors**

The push switch (T2) can be connected to IO7 or IO9 of SmartMCD (U1) by connecting the corresponding jumper on the Push Switch Jumper Pin Connector (J10). It is used by the software to Start/Stop the motor, etc..



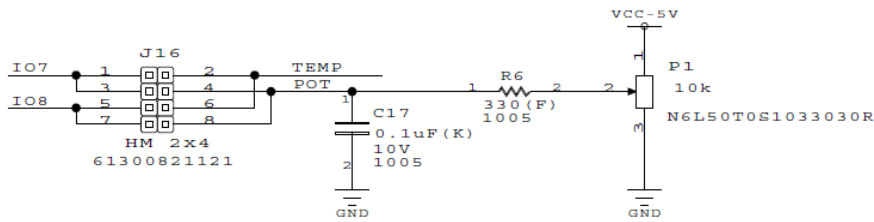
**Fig. 4.5 Push Switch (T2)**

The slide switch (SW3) can be connected to IO8 or IO9 of SmartMCD (U1) by connecting the corresponding jumper on the the Slide Switch Jumper Pin Connector (J11). It is used by the software to change the motor rotation direction, etc.



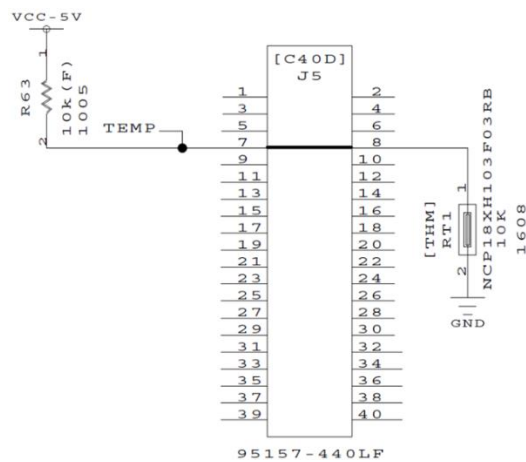
**Fig. 4.6 Slide Switch (SW3)**

The potentiometer (P1) can be connected to IO7 or IO8 of SmartMCD (U1) by connecting the corresponding jumper on the TEMP-POT Signal Jumper Pin Connector (J16). It is used by the software to change the motor rotational speed, etc.



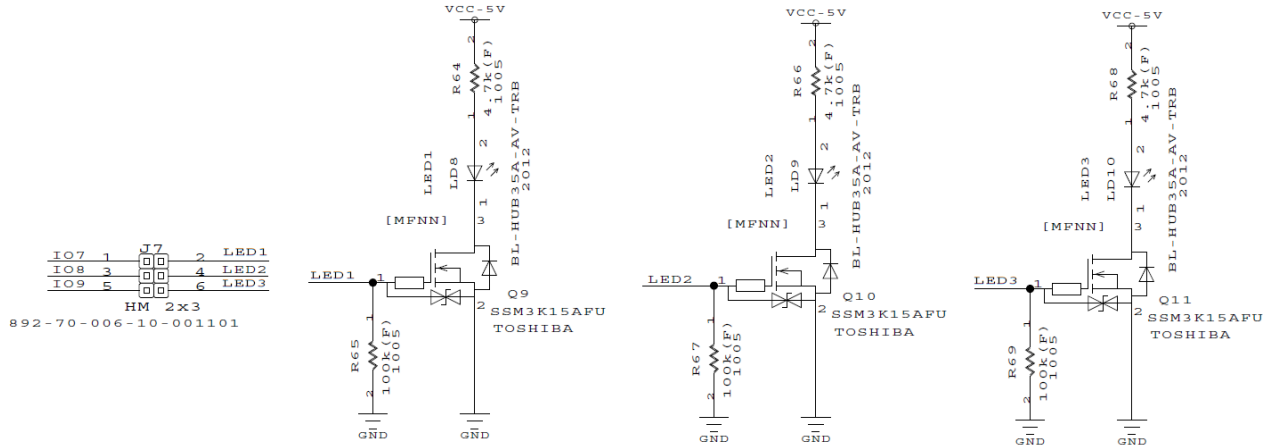
**Fig. 4.7 Potentiometer (P1)**

NTC thermistor (RT1) located near the inverter is connected in a voltage divider configuration with the resistor (R63). And the output signal (TEMP) of this voltage divider can be connected to IO7 or IO8 of SmartMCD (U1) by connecting the corresponding jumper on the TEMP-POT Signal Jumper Pin Connector (J16). It is possible to use this signal (TEMP) by the software for monitoring temperature to detect abnormal heat generation.



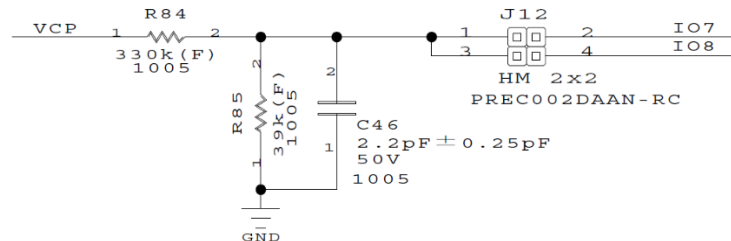
**Fig. 4.8 Temperature Monitoring Using NTC Thermistor (RT1)**

LED1 (LD8), LED2 (LD9), and LED3 (LD10) can be controlled by the software. When LED signal (LED1, LED2, LED3) of any LED becomes H, the corresponding MOSFET SSM3K15AFU (Q9, Q10, Q11) operating as a low-side switch is activated and LED lights-up. These LEDs can be connected to the IO7, IO8, IO9 of SmartMCD (U1) by connecting the corresponding jumpers on the LED Jumper Pin Connector (J7).



**Fig. 4.9 LED (LED1, LED2, LED3) Circuit**

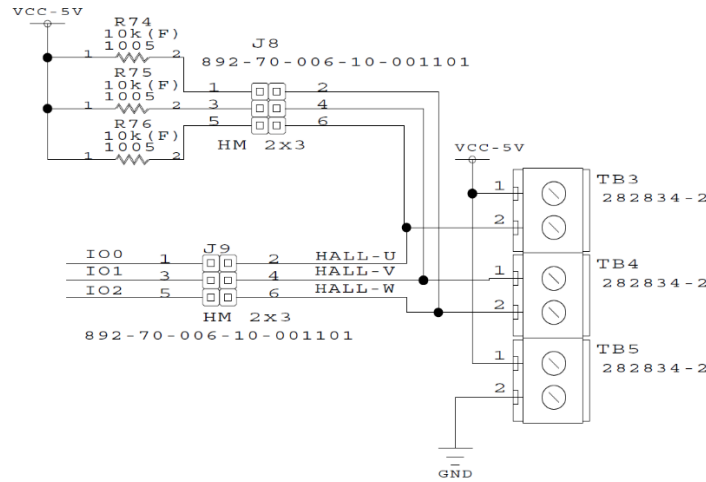
VCP (21 pin) provides the voltage output of the charge pump circuit of SmartMCD (U1). This output voltage is divided using the resistors (R84, R85) and this can be connected to IO7 or IO8 of the SmartMCD (U1) by connecting the corresponding jumper on the VCP Jumper Pin Connector (J12). Therefore it is possible for the software to monitor the charge pump voltage.



**Fig. 4.10 VCP Monitoring Circuit**

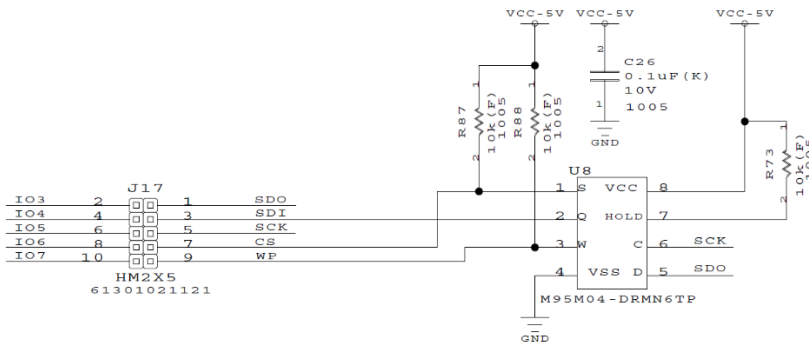


The external hall sensor signals (HALL-U, HALL-V, HALL-W) can be connected to the SmartMCD by connecting the corresponding jumpers on the Hall Sensor Connector Jumper Pin Connector (J9). HALL-U (TB3), HALL-V (TB4), and HALL-W (TB4) can be connected to IO0, IO1, and IO2 of SmartMCD respectively. 5 V pull-up can also be configured by connecting the corresponding jumpers on the Hall Sensor Connector Jumper Pin Connector (J8).



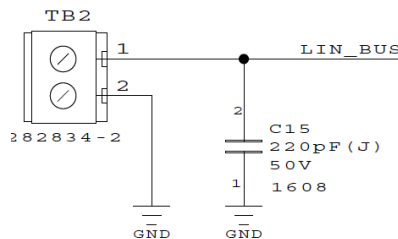
**Fig. 4.11 Hall Sensor Connection Circuit**

The external EEPROM (U8) can be connected to SmartMCD via EEPROM Connection Jumper Pin Connector (J17). SDO, SDI, SCK, CS, and WP of EEPROM can be connected to IO3, IO4, IO5, IO6, and IO7 of SmartMCD respectively by connecting the jumpers on J17.



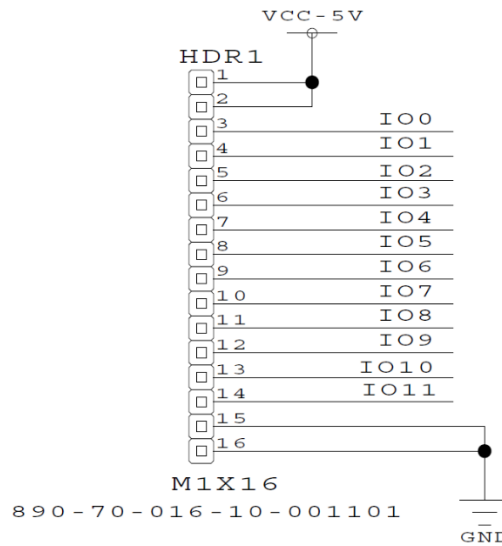
**Fig. 4.12 EEPROM (U8)**

LIN communication is performed via LIN Input/Output pin (TB2). The by-pass capacitor (C15) is used to reduce the amount of generated noise.



**Fig. 4.13 LIN Input/Output Terminal (TB2)**

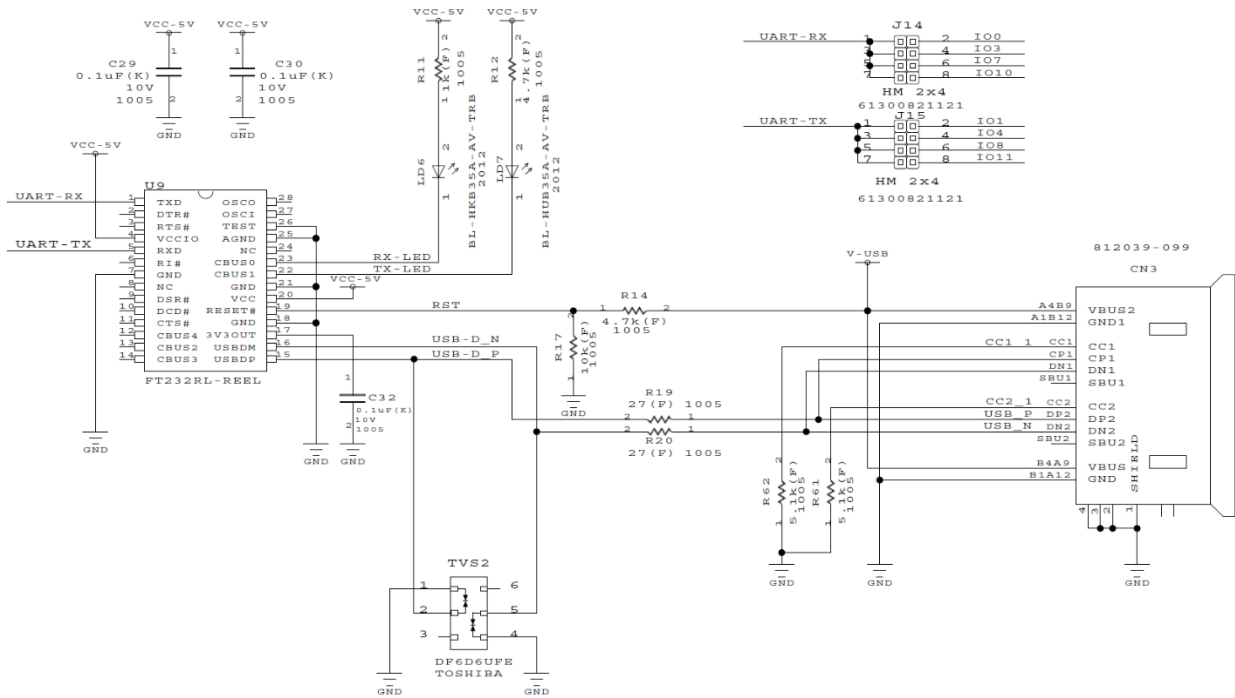
Pin Header for Testing (HDR1) can be used to connected to IO0 to IO11 pins of the SmartMCD (U1), 5 V power supply, and GND for testing.



**Fig. 4.14 Pin Header for Testing (HDR1)**

**4.1.5. USB-UART Circuit**

Fig. 4.15 shows the USB-UART circuit.



**Fig. 4.15 USB-UART Circuit**

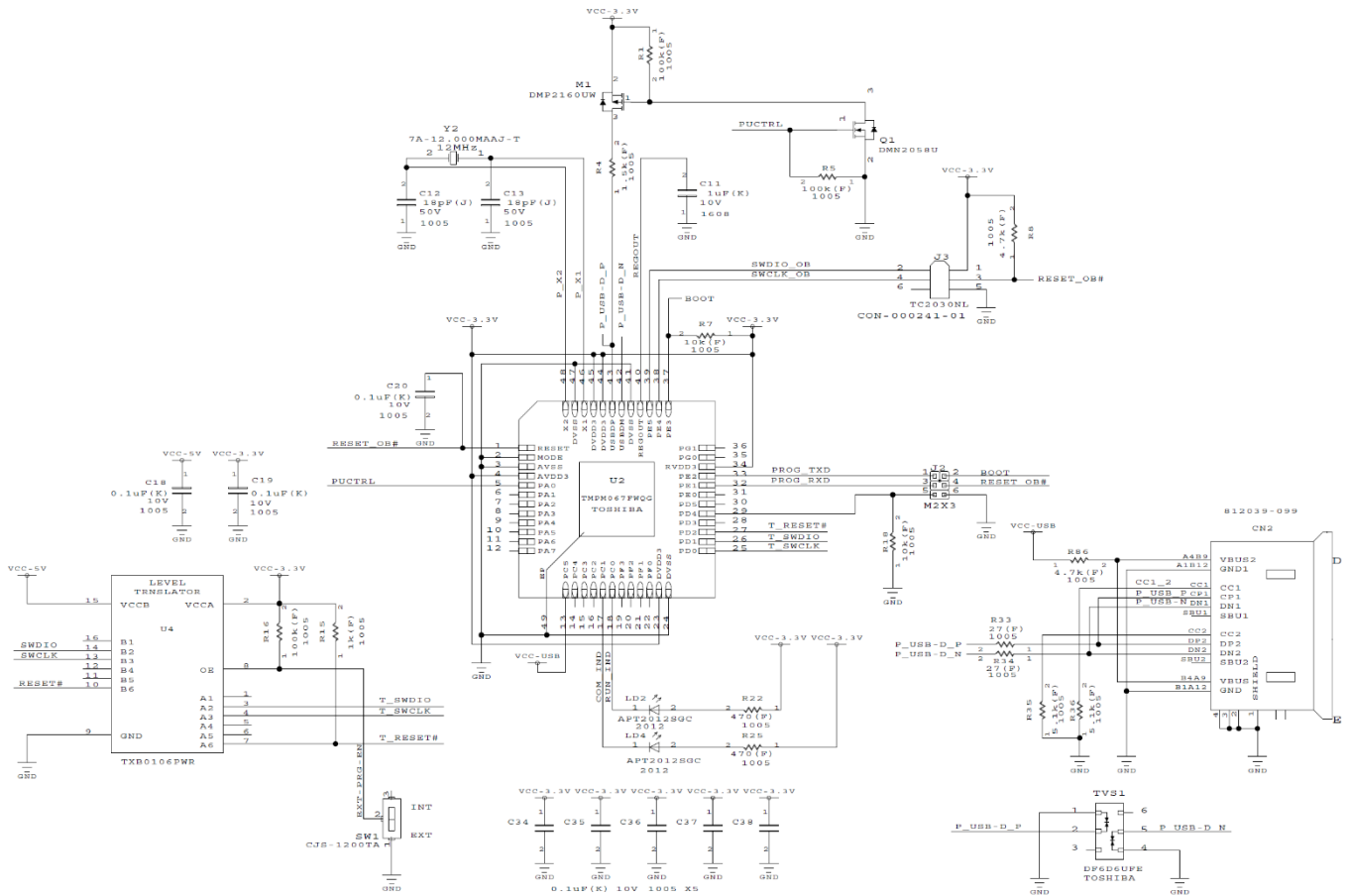
Serial communication with SmartMCD (U1) is available by connecting an external USB hosting device to USB Type-C® connector (CN3). USB signals (USB-D\_P, USB-D\_N) are converted to UART serial data signals (UART-TX, UART-RX) by USB-UART converter (U9) and it communicates serially with SmartMCD (U1). USB (USB-D\_P, USB-D\_N) signals are electrostatically protected by an ESD protection-diode IC (TVS2).

The transmit serial data (UART-TX) of USB-UART converter (U9) can be connected to IO1, IO4, IO8, or IO11 of SmartMCD (U1) by connecting the corresponding jumper on the UART-TX Signal Jumper Pin Connector (J15). TX LED (LD7) lights-up when the serial data is transmitted.

The receive serial data (UART-RX) of USB-UART converter (U9) can be connected to IO0, IO3, IO7, or IO10 of SmartMCD (U1) by connecting the corresponding jumper on the UART-RX Signal Jumper Pin Connector (J14). RX LED (LD6) lights-up when the serial data is received.

**4.1.6. CMSIS-DAP Circuit**

Fig. 4.16 shows CMSIS-DAP circuit.



**Fig. 4.16 CMSIS-DAP Circuit**

By connecting an external debugger to USB Type-C® connector (CN2), the SmartMCD (U1) can be programmed/debugged using CMSIS-DAP (U2). USB Source (P\_USB-D\_P, P\_USB-D\_N) is protected from static electricity by ESD Protection Diode IC (TVS1). RUN LED (LD2) And COM LED (LD4) indicate the operation status of CMSIS-DAP (U2).

The power supply voltage of CMSIS-DAP (U2) is 3.3 V and the power supply voltage SmartMCD (U1) is 5 V, therefore SWD interface signal and the reset signal between them are converted using the level shift IC (U4).

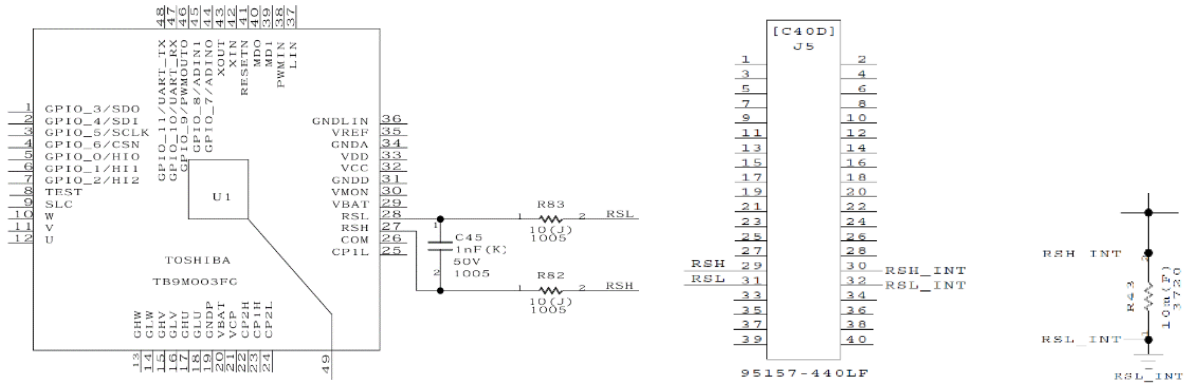
The program/debug switch (SW1) is used for selecting that from where to program/debug SmartMCD (U1), and can be selected as shown in the following table.

**Table 4.2 Program/Debug Switch (SW1) Specifications**

Selector Switch	State
INT	Programming/Debugging from CMSIS-DAP (U2)
EXT	Programming/Debugging from SWD connector (J4)

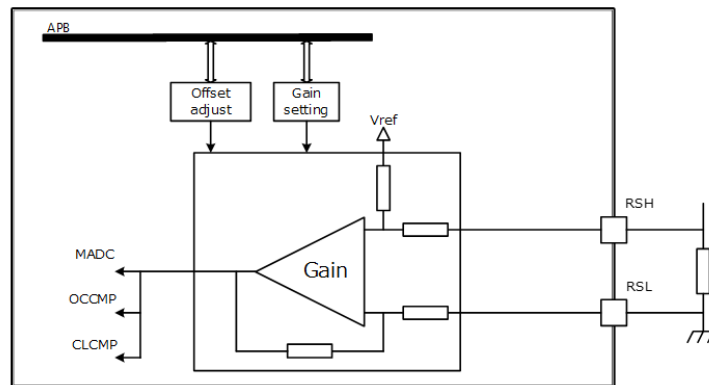
**4.1.7. Bus Current Sensor Circuit and Overcurrent Detection Circuit**

Fig. 4.17 shows the bus current sensor circuit of the inverter.



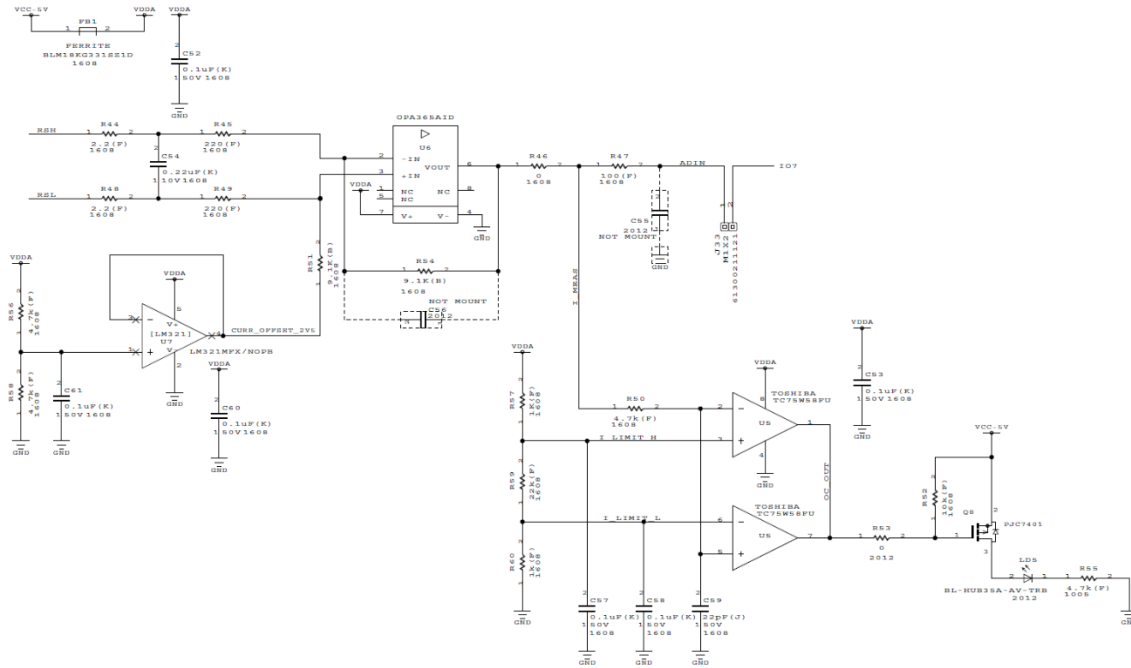
**Fig. 4.17 Bus Current Sensor Circuit**

Both sides of the inverter shunt resistor (R43 for an on-board inverter) are connected to the RSH pin (pin 27) and RSL pin (pin 28) of SmartMCD (U1). The voltage generated by the shunt resistor is amplified by the current-sensing amplifier built into SmartMCD (U1), and is then output to the Overcurrent Detection Comparator (OCCMP) and Current Clamp Comparator (CLCMP).



**Fig. 4.18 Current Detection Amplifier in SmartMCD**

Fig. 4.19 shows the overcurrent detection circuit.



**Fig. 4.19 Overcurrent Detection Circuit**

Overcurrent is detected by monitoring the inverter bus current flowing through a 10 mΩ shunt resistor (R43).

The relation between the bus current *i* flowing through the shunt resistor and ADIN voltage (pin 1 of Jumper Pin Connector (J33)) is:

$$ADIN \text{ voltage} = 2.5 \text{ V} - \frac{9.1 \text{ k}\Omega}{220 \Omega + 2.2 \Omega} \times 0.01 (\Omega) \times i (A)$$

For

$$ADIN \text{ voltage} \cong 2.5 - 0.41 \times i (A)$$

This ADIN voltage can be connected to IO7 of SmartMCD (U1) by connecting jumper to the jumper pin connector (J33). Bus current can be monitored by software.

In addition, the upper and lower limits of ADIN are monitored. If the upper and lower limits are crossed, the comparator (U5) goes to the L-level and Pch-MOSFET (Q8) turns ON, and the overcurrent detection LED FLT-LED (LD5) lights-up.

The overcurrent detection LED FLT-LED (LD5) lights-up in following cases:

$$2.5 (V) - \frac{9.1 \text{ k}\Omega}{220 \Omega + 2.2 \Omega} \times 0.01 (\Omega) \times i (A) > \frac{1 \text{ k}\Omega + 22 \text{ k}\Omega}{1 \text{ k}\Omega + 22 \text{ k}\Omega + 1 \text{ k}\Omega} \times 5 (V)$$

Or

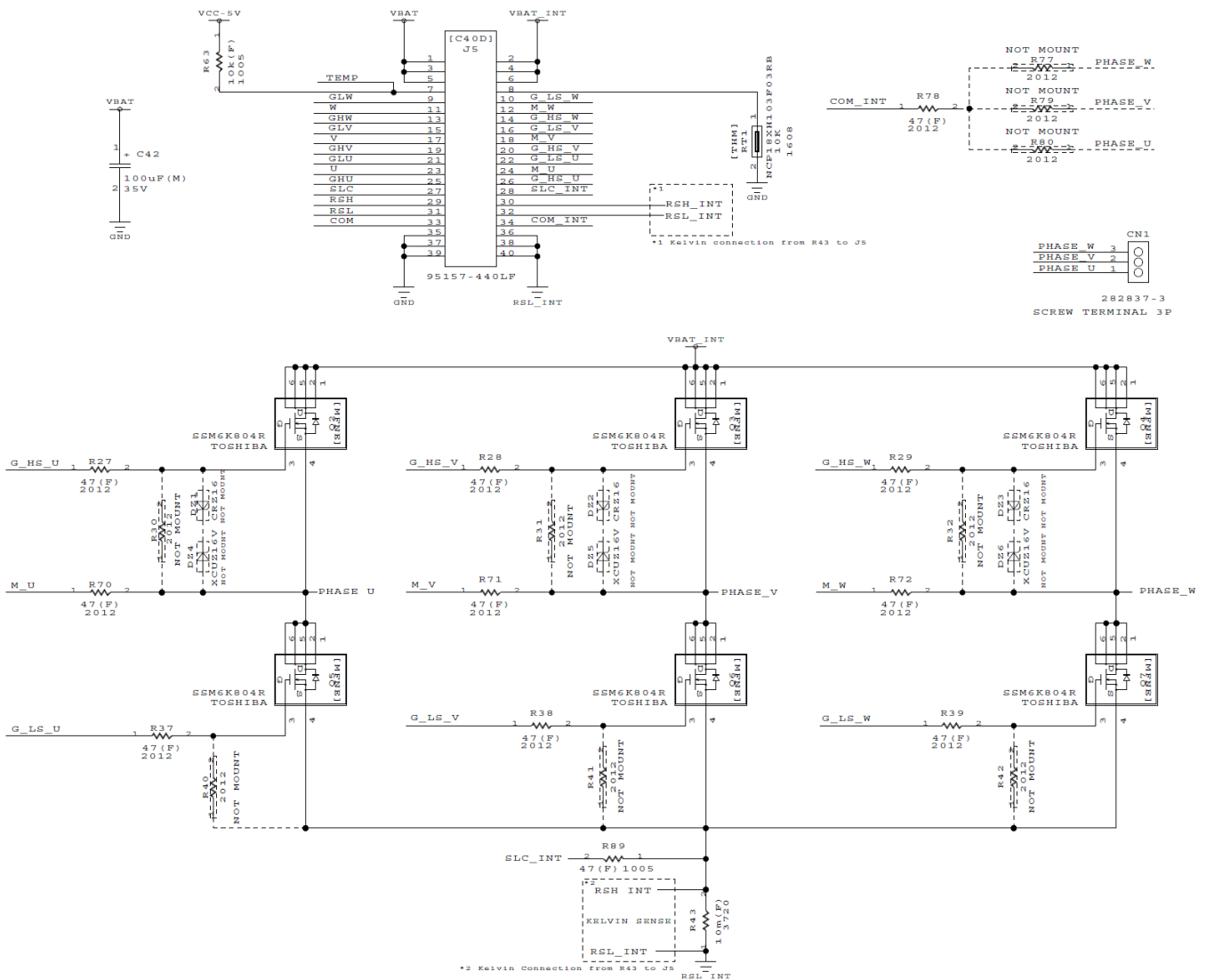
$$2.5 \text{ V} - \frac{9.1 \text{ k}\Omega}{220 \Omega + 2.2 \Omega} \times 0.01 (\Omega) \times i (A) < \frac{1 \text{ k}\Omega}{1 \text{ k}\Omega + 22 \text{ k}\Omega + 1 \text{ k}\Omega} \times 5 (V)$$

Therefore FLT-LED (LD5) lights-up when:

$$\text{Bus current} < -5.6 \text{ A or bus current} > 5.6 \text{ A}$$

### 4.2. On-board Inverter Circuit

Fig. 4.20 shows the on-board inverter circuit. The on-board inverter circuit is used by connecting all the jumpers on the Inverter Circuit Jumper Pin Connector (J5).



**Fig. 4.20 On-board Inverter Circuit**

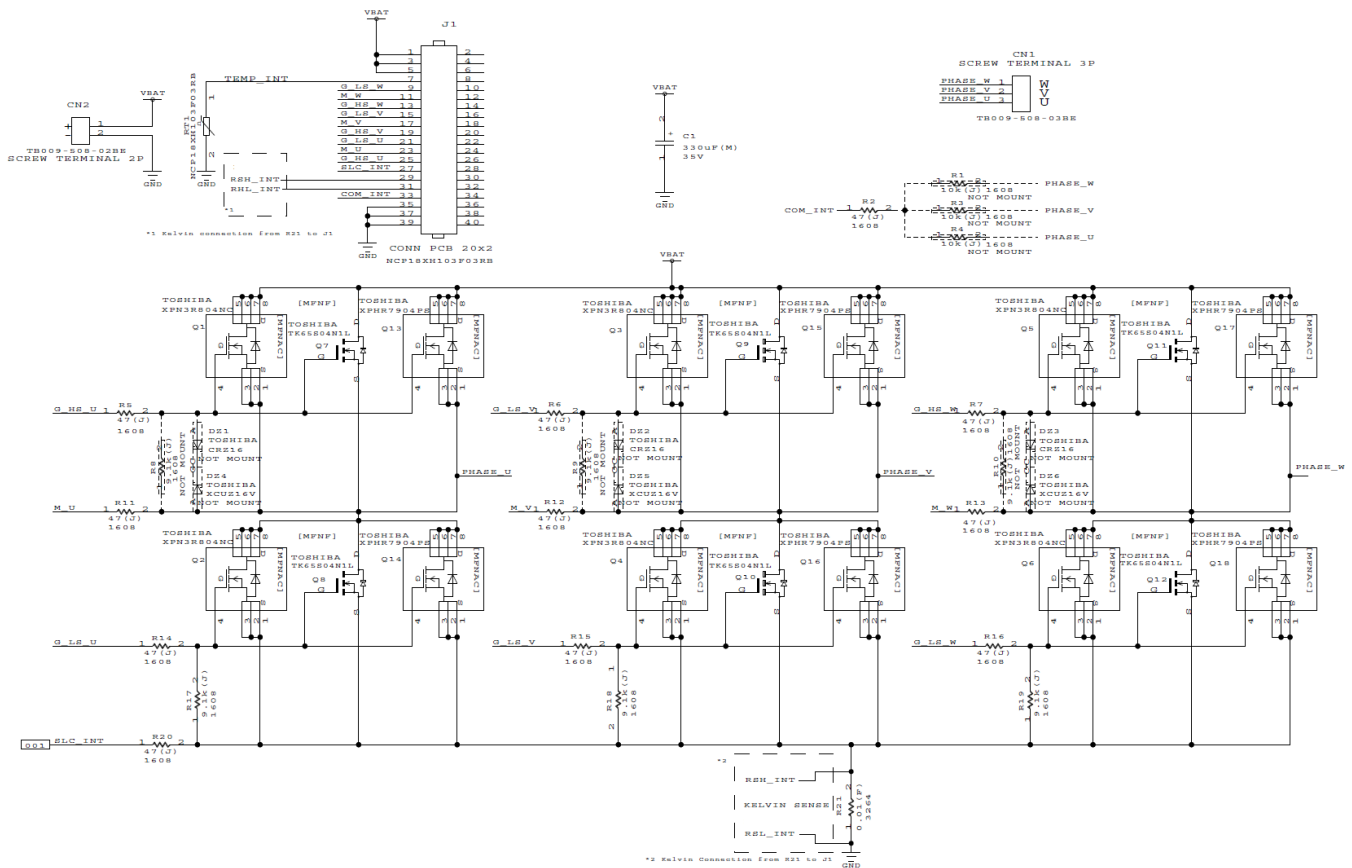
The on-board inverter consists of six [SSM6K804R](#) MOSFETs (Q2 to Q7), which are driven by the gate-signal output from SmartMCD (U1). The output of this inverter are U, V, and W phases, and these are used to drive a brushless motor which is connected to the 3-Phase Brushless Motor Terminal (CN1).

## 4.2.1. External Inverter Circuit (External Inverter Board)

Fig. 4.21 shows the external inverter circuit.

The external inverter circuit can be operated by stacking the Main Board Connector (J1) of the external inverter board on the Inverter Circuit Jumper Pin Connector (J5) of the main board. The circuit configuration is the same as the on-board inverter circuit, but uses MOSFETs (TK1R4S04PB, XPH2R404PS, TPW1R104PB, or XPN3R804NC) which support larger current.

The external inverter board is designed in a way so that any of the above MOSFETs could be mounted. Therefore a MOSFET could be selected according to the objective and mounted on the board.



**Fig. 4.21 External Inverter Circuit**

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