3-Phase Inverter Using SiC MOSFET

Design guide

RD220-DGUIDE-02

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

This Reference Guide (hereafter referred to as this Guide) describes the specifications and operation procedure of the 3-Phase Inverter (hereafter referred to as this Inverter) Using SiC MOSFET.

3-phase inverters are used to drive induction and synchronous motors used in industrial applications. At AC 400 V output, it is common to use an IGBT having a withstand voltage of 1200 V as a conventional switching device. However, SiC (silicon carbide) based SiC MOSFET developed in recent years, can reduce on-resistance while maintaining higher breakdown voltage compared to conventional Si (silicon) MOSFET. For the purpose of improving the inverter efficiency 1200 V SiC MOSFETs have been adopted and studied as switching elements to replace 1200 V IGBTs.

In this inverter, SiC MOSFET TW045Z120C (TO-247-4L(X) package) or TW045N120C (TO-247 package) is used to achieve higher efficiency for driving AC 440 V motors. TLP5774H is used as a gate driver to realize a high-speed isolated gate drive. And, the isolation amplifier TLP7820 is used to realizes isolated sensors such as motor phase current sensor and bus voltage sensor.

2. Main Components Used

This section introduces the components used in this inverter. Toshiba has a wide lineup of devices, including power semiconductors, driver couplers, and small-signal ICs.

2.1. SiC MOSFET TW045Z120C/TW045N120C

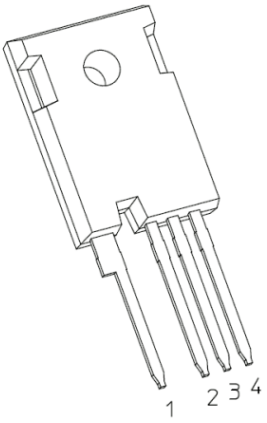
This inverter uses TW045Z120C / TW045N120C for the switching elements of the inverter.

Features

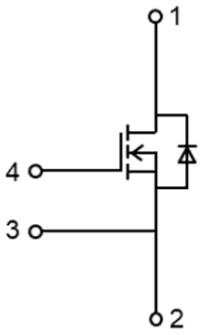
- Chip design of 3rd generation (Built-in SiC Schottky barrier diode)
- Low diode forward voltage: V_{DSF} = -1.35 V (Typ.)
- High voltage: V_{DSS} = 1200 V
- Low drain-source on-resistance: $R_{DS(ON)}$ = 45 mΩ (Typ.)
- Less susceptible to malfunction due to high threshold voltage: V_{th} = 3.0 to 5.0 V (V_{DS} = 10 V, I_D = 6.7 mA)
- Enhancement mode

Appearance and Pin Layout

TW045Z120C



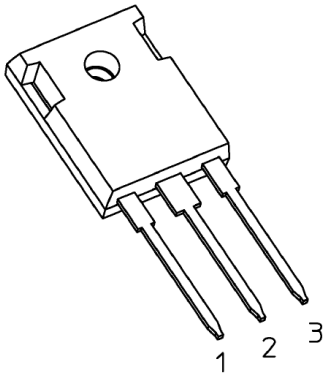
TO-247-4L(X)



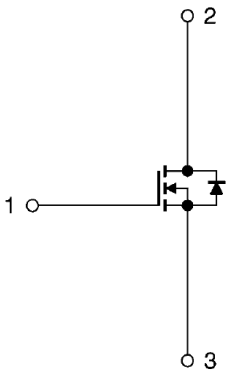
1. Drain (heatsink)
2. Source 1
3. Source 2
4. Gate

Notice: Only use source 2 pin for gate input signal return. Please make sure that the main current flows into the source 1 pin.

TW045N120C



TO-247



1: Gate
2: Drain (heatsink)
3: Source

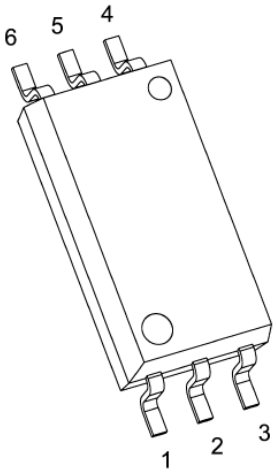
2.2. Driver Coupler TLP5774H

This inverter uses TLP5774H for the gate driver of SiC MOSFETs used in the inverter circuit.

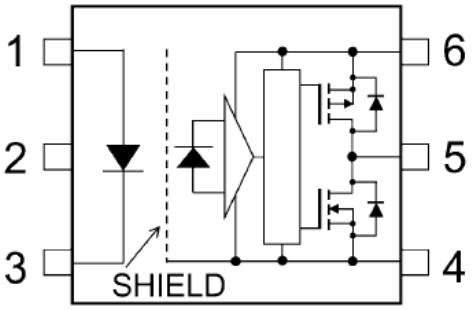
Features

- Buffer logic type (totem pole output)
- Output peak current: ±4.0 A (Max.)
- Operating temperature: -40 to 125 °C
- Supply current: 3 mA (Max.)
- Supply voltage: 10 to 30 V
- Threshold input current: 2 mA (Max.)
- Propagation delay time: 150 ns (Max.)
- Common-mode transient immunity: ±35 kV/μs (Min.)
- Isolation voltage: 5000 Vrms (Min.)
- Complies with safety standards

Appearance and Pin Layout



11-4N1A



1: Anode
2: N.C.
3: Cathode
4: GND
5: V_O (Output)
6: V_{CC}

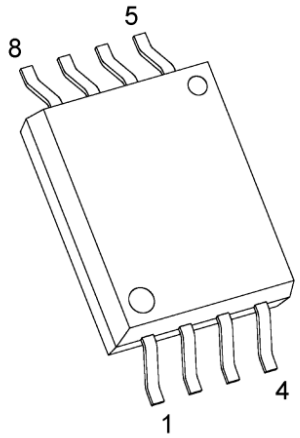
2.3. Isolation Amplifier TLP7820

This inverter uses TLP7820 for the isolated sensing using current sensors and voltage sensors.

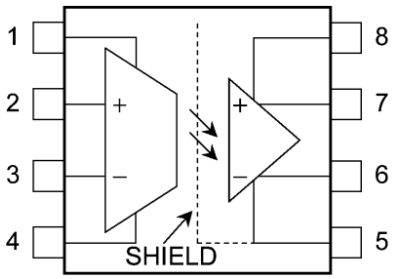
Features

- Gain accuracy: ±0.5 % (Gain rank B)
- Gain drift: 0.00012 V/V/°C (Typ.)
- Nonlinearity (V_{IN} = ±200 mV): 0.02 % (Typ.)
- Input offset voltage: 0.9 mV (Typ.)
- V_{OUT} bandwidth (-3 dB): 230 kHz (Typ.)
- Operating temperature range: -40 to 105 °C
- Common-mode transient immunity: 15 kV/μs (Min.)
- Complies with safety standards

Appearance and Pin Layout



11-6B1A



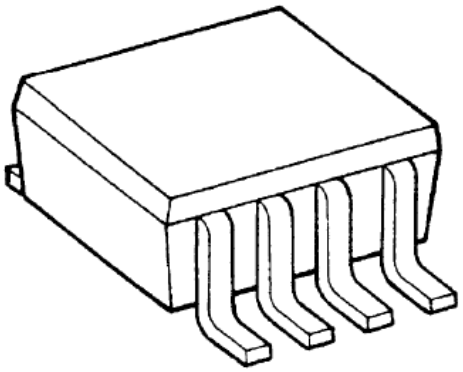
2.4. Comparator TC75W59FU

This inverter uses a TC75W59FU as a comparator for detecting errors.

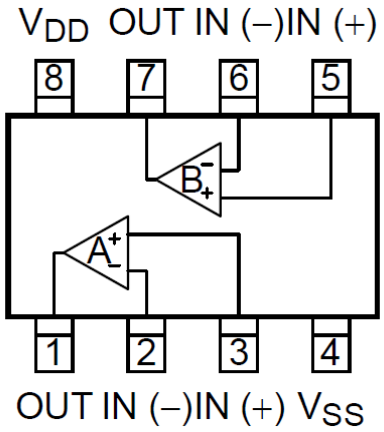
Features

- Low-voltage operation is possible compared with bipolar type general-purpose op-amps.
  V_{DD} = ±0.9 to 3.5 V or 1.8 to 7 V
- Low-current consumption compared to bipolar type general-purpose op-amps
  I_{DD} (V_{DD} = 3 V = 20 μA (Typ.)
- Internal phase compensation type, no external element required
- Small package

Appearance and Pin Layout



SSOP8-P-0.65 (SM8)



3. What is an Inverter?

3.1. Inverter Operation

An example of a half-bridge circuit that is a component of a typical inverter (two-level inverter) is shown in Fig. 3.1. As shown in the figure, a MOSFET Q1 is used in the upper arm and a MOSFET Q2 is used in the lower arm as switching elements. Bus voltage E is supplied. As shown in Fig. 3.2, two levels of voltage (E (bus voltage) or 0 (GND voltage)) appear on the inverter-output Vout when Q1, Q2 are turned on/off.

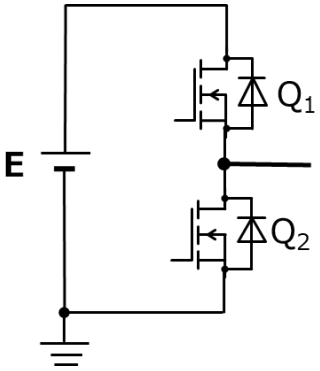


Fig. 3.1 Half-Bridge Circuit Example

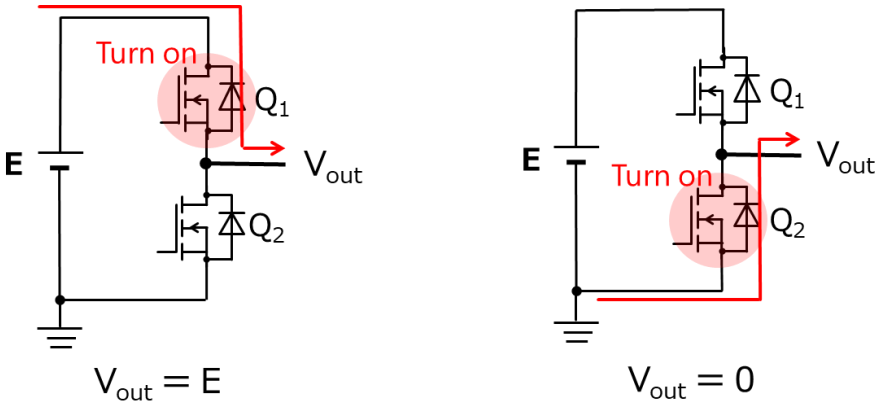


Fig. 3.2 Switching Operation of the Inverter

Output voltage is controlled by the PWM control of these switching devices. Fig. 3.3 shows an example of the sine wave commutation phase voltage output.

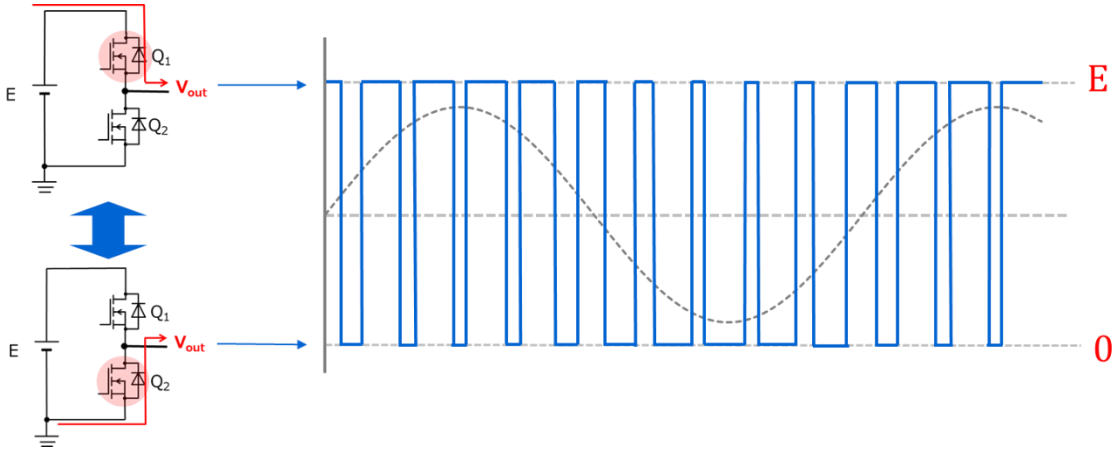


Fig. 3.3 Example of Sine Wave Commutation Phase Voltage Output of the Inverter

Fig. 3.4 shows the configuration of a 3-phase inverter. The 3-phase inverter has a 3-phase full-bridge configuration with three half-bridge circuits. By using PWM control switching of each phase, 3-phase alternating current with a 120° phase difference between each phase is output. Fig. 3.5 shows an example of sine wave commutation phase voltage output of a 3-phase inverter. (A half-bridge circuit, such as Q1 and Q2, is called a leg.)

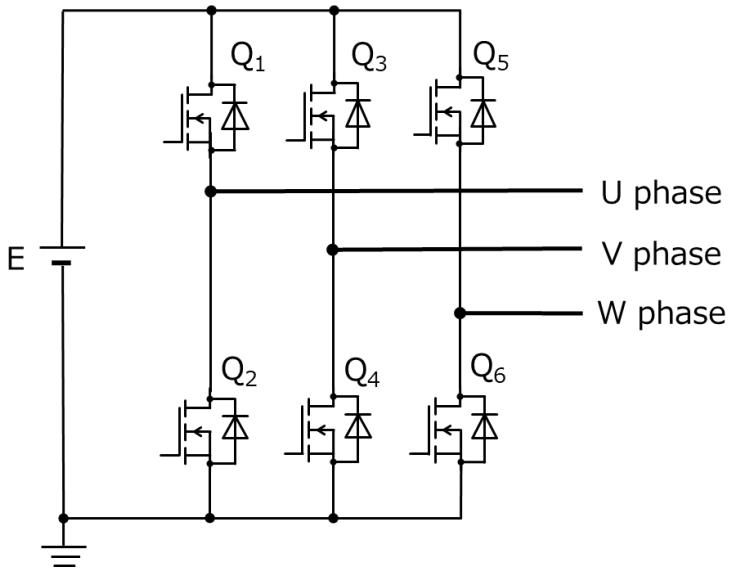


Fig. 3.4 Configuration of 3-Phase Inverter

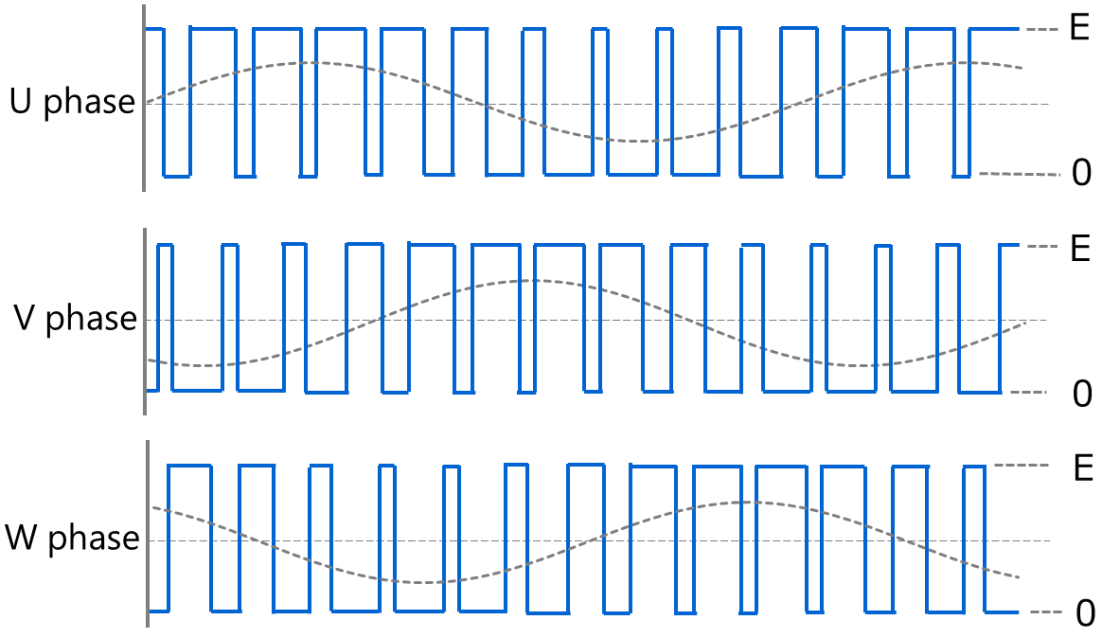


Fig. 3.5 Example of Sine Wave Commutation Phase Voltage Output of the 3-Phase Inverter

4. Circuit Design

This section describes the gist of the circuit design. Refer to RD220-SCHEMATIC1 (AC-DC board) and RD220-SCHEMATIC2 (inverter board) for schematic diagrams, and to RD220-BOM1 (AC-DC board) and RD220-BOM2 (inverter board) for bill of materials. Fig. 4.1 shows the block diagram of the inverter board of this inverter.

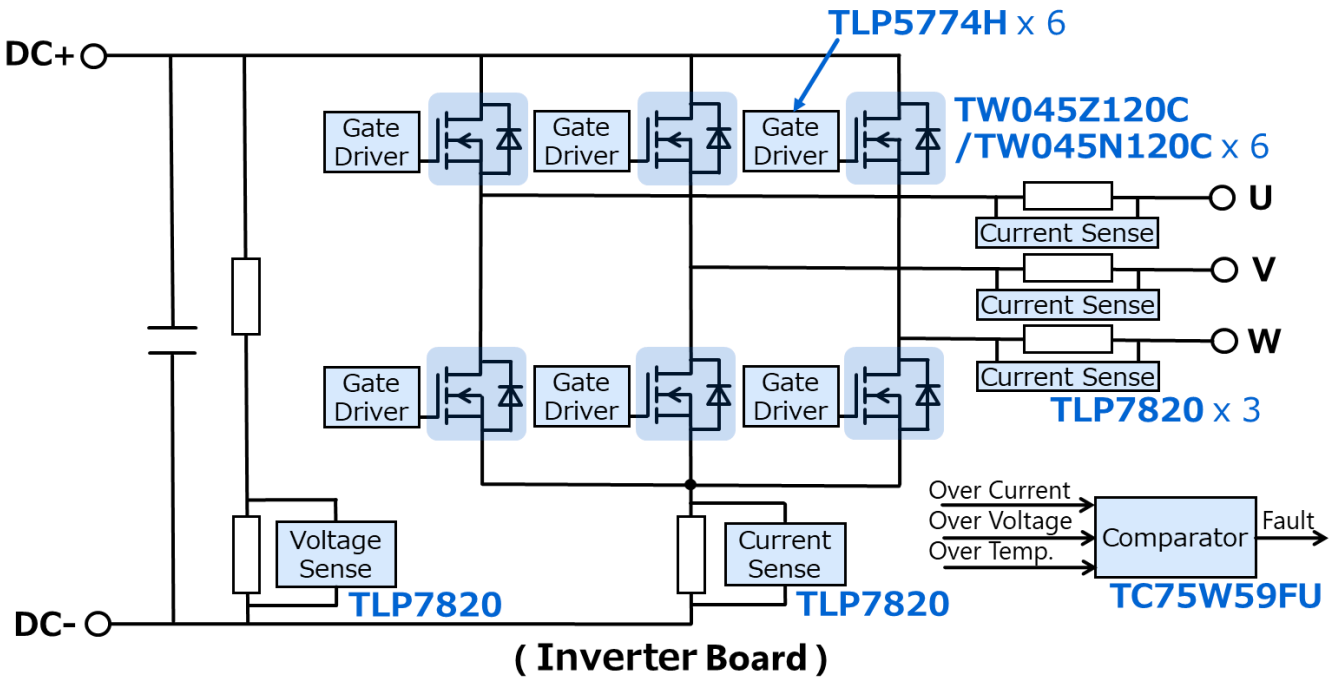


Fig. 4.1 3-Phase Inverter Using SiC MOSFET (Inverter Board)

4.1. Isolated Power Supply Circuit

The inverter board of this inverter generates four lines of isolated power based on 20 V power input from the control power input terminal (inverter board, CN1-CN2). Since the source potential of the upper arm MOSFET of each phase of the inverter changes during switching operation, a gate driver power supply is required for each phase. Since the reference potential of the lower arm of each phase is the same, four independent isolated power supplies are implemented for the U-phase upper arm (gate drive and phase current sensor), the V-phase upper arm (gate drive and phase current sensor), the W-phase upper arm (gate drive and phase current sensor), and the lower arm (gate drive and bus current sensor in the U-phase /V-phase /W-phase).

Fig. 4.2 shows the primary circuit of the isolated power supply.

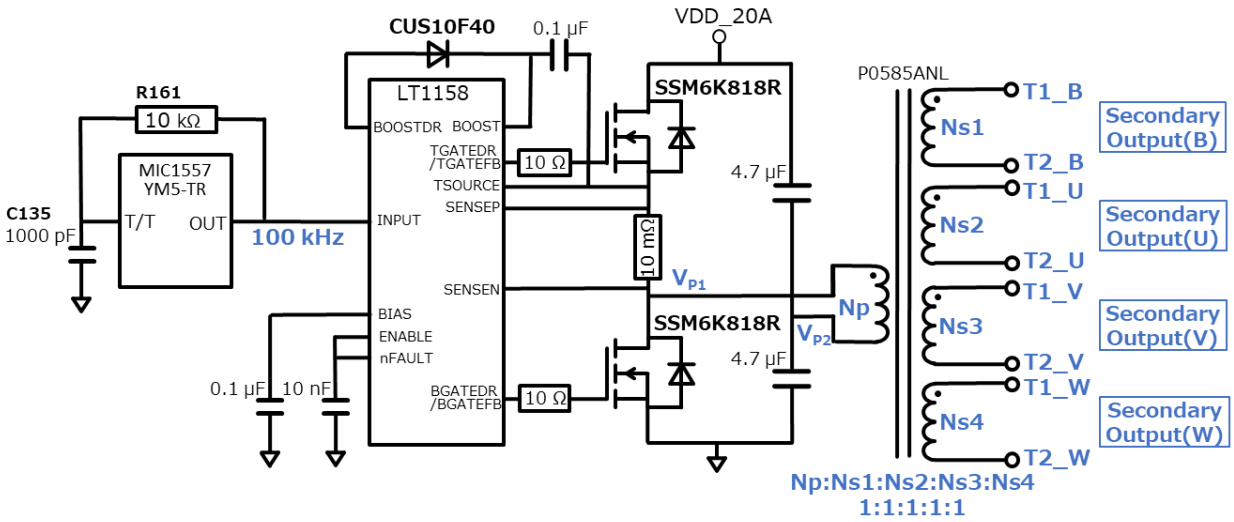


Fig. 4.2 Isolated Power Circuit (Primary Side)

Half-bridge gate driver LT1158 (ADI) drives a half-bridge composed of SSM6K818R MOSFETs to form a half-bridge isolated DC-DC converter. A RC oscillator MIC1557YM5-TR (Microchip) is used to switch the half-bridge. The connected resistor R161 (10 kΩ) and capacitor C135 (1000 pF) produce a square wave of 100 kHz, with 50 % duty, which is applied to the half-bridge gate driver. The voltage potentials at both ends of the primary winding are V_{P1} and V_{P2}. V_{P1} switches between 0 V and 20 V by complementary switching of the half bridge, and V_{P2} is the midpoint voltage of 10 V between two 4.7 µF capacitors. Therefore, a rectangular wave of ±10 V is generated at the primary side of the isolation transformer.

Fig. 4.3 shows one of the secondary circuits for four isolated power systems.

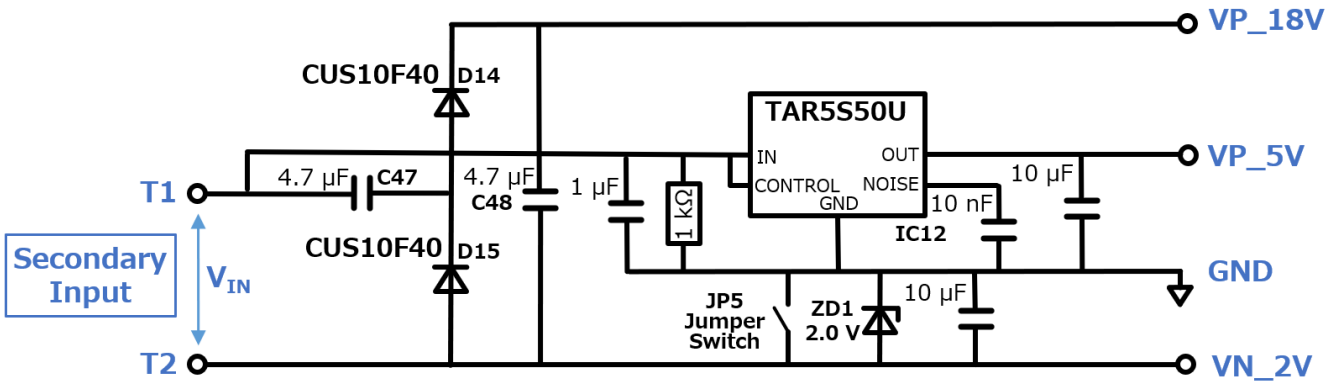


Fig. 4.3 Isolated Power Circuit (Secondary Side)

Since the winding ratio Np:Ns1:Ns2:Ns3:Ns4 of the isolation transformer is 1:1:1:1:1, a square-wave output of ±10 V can be obtained at all the secondary terminals of the isolation transformer. However, a half wave voltage doubler circuit consisting of C47, C48, D14, D15 in the secondary circuit generates a DC voltage with a potential difference 20 V between VP_18V, VN_2V. The rectifier diodes D14 and D15 use a small size Schottky Barrier Diode CUS10F40 (V_R = 40 V(Max.), I_F = 1 A(Max)). By supplying the secondary input voltage to a 5 V output LDO TAR5S50U, a DC voltage of 5 V (GND reference) is generated in VP_5V and used as the power supply for each phase.

In this inverter, a Zener diode ZD1 is placed between VN_2V and GND to make the potential of VN_2V lower than GND by ZD1 Zener voltage (In this design, a 2 V Zener voltage device is mounted as ZD1, and thus VN_2V is set to -2 V((0-2) V), and VP_18V is set to 18V((20-2) V). The jumper switch JP5 allows the user to change the potential of VP_18V, VN_2V in relation to GND. Since the source of SiC MOSFET is connected to the GND signal of corresponding isolated power supply and gate signal is switched between VP_18V/VP_2V, the V_{GS} of SiC MOSFET can be changed with this jumper JP5. Table 4.1 shows the relationship between the jumper switch status and the output voltage of each isolated power supply.

Table 4.1 Relationship between Jumper Switch Status and Isolated Power Supply Output Voltage

Jumper switch status	ON (short)	OFF (open)
VP_18V (GND reference) and SiC MOSFET on-state V_{GS}	20 V	18 V
VN_2V (GND reference) and SiC MOSFET off-state V_{GS}	0 V	-2 V
VP_5V (GND reference)	5 V	5 V

4.2. SiC MOSFET Gate-Drive Circuit

SiC MOSFET gate-driver is shown in Fig. 4.4. Similar gate-drive circuits are implemented in a total of six circuits, one for every SiC MOSFET. A driver coupler TLP5774H is used to drive the gate. The low-voltage side such as the controller and the high-voltage side such as SiC MOSFET are electrically isolated. The primary-side light-emitting device of TLP5774H is connected to a MOSFET SSM3K15AFU which acts as a switch. And this MOSFET SSM3K15AFU is controlled on/off by a gate-control signal from a MCU or another controller. When SSM3K15AFU turns on, the primary light-emitting device of TLP5774H turns on, and the gate driver output goes to H. The truth table for TLP5774H is shown in Table 4.2.

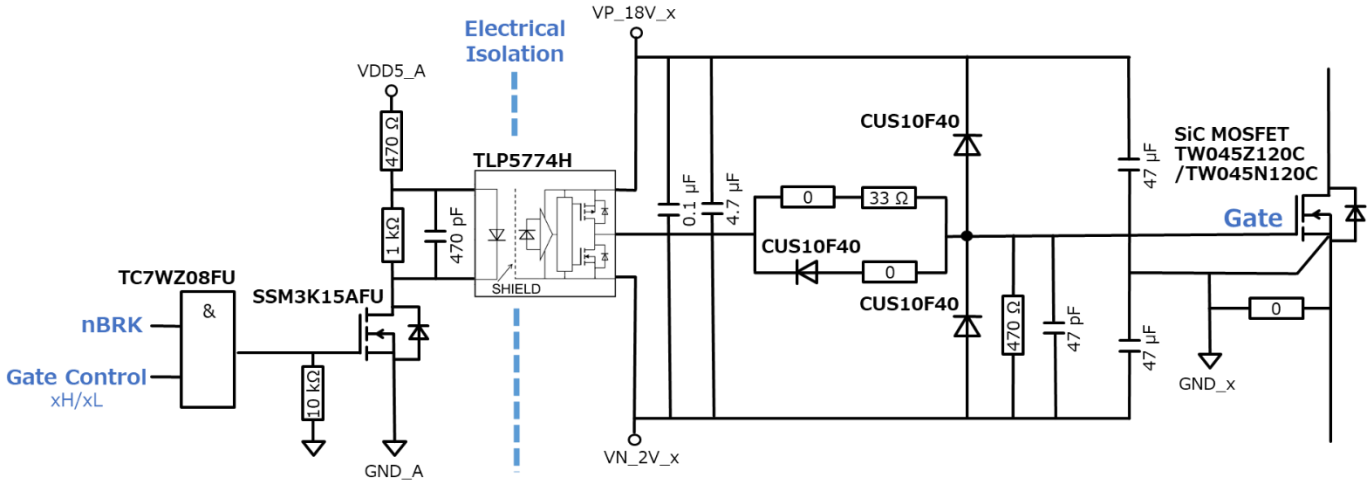


Fig. 4.4 SiC MOSFET Gate-Drive Circuit

Table 4.2 Driver Coupler TLP5774H Truth Table

Input	LED	M1	M2	V_O
H	ON	ON	OFF	H (≈V_{CC})
L	OFF	OFF	ON	L (≈GND)

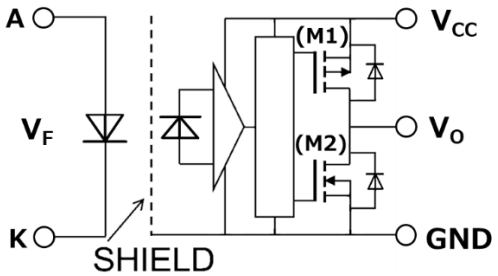


Fig. 4.5 shows the off-time operation of the gate drive circuit when the gate control signal is L. Fig. 4.6 shows the on-time operation of the gate drive circuit when the gate control signal is H. In this inverter, the external gate resistance at turn-on is set to 33 Ω and the external gate resistance at turn-off is set to 0 Ω. However, the optimum value differs depending on the switching frequency and bus voltage to be used. Therefore, these values must be adjusted according to the actual design specifications.

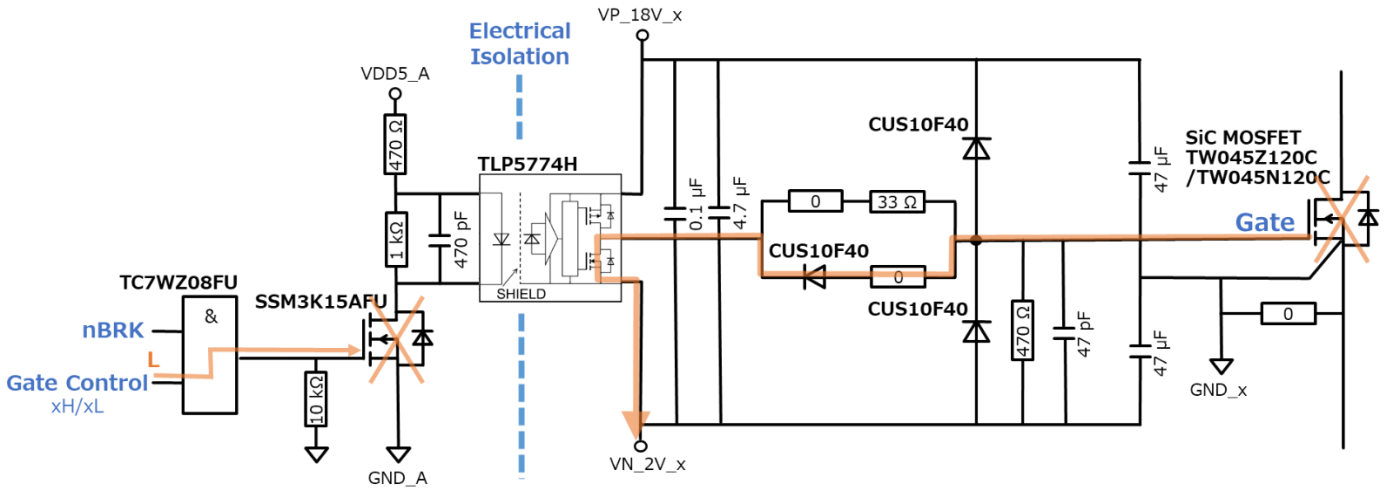


Fig. 4.5 MOSFET Gate-Drive Operation (Off-State)

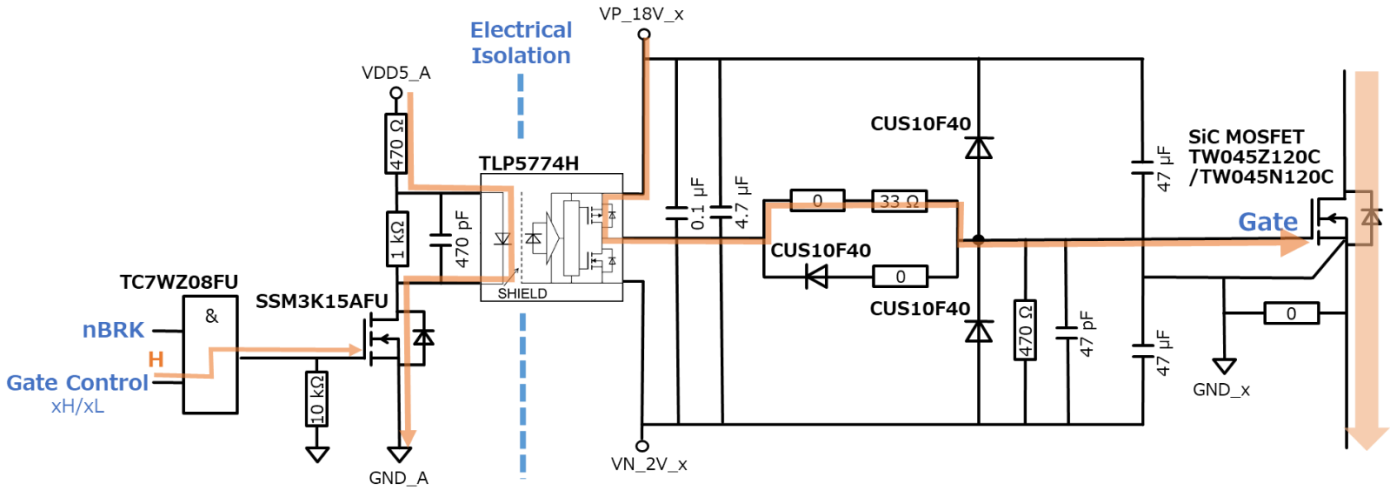


Fig. 4.6 MOSFET Gate-Drive Operation (On-State)

4.3. Components of the Sensor Circuit

4.3.1. Isolation Amplifier Circuit

Each sensor circuit that detects the phase current, bus current, and bus voltage of this inverter is electrically isolated. It consists of the high-voltage side that performs sensing and the low-voltage side that transmits the sensing results to the controller, etc. An isolation amplifier is used to electrically isolate the analog value sensed on the high-voltage side and transmit it to the low-voltage side. TLP7820 is an optically coupled isolation amplifier that receives an analog signal and outputs an analog signal. TLP7820 is equipped with a LED photodiode-based optical transmission function between the primary-side input (V_{IN}) and the secondary-side output (V_{OUT}), and its optical transmission signals are digitally encoded to achieve highly accurate analog-signal isolated transmission. Fig. 4.7 is a functional block diagram of TLP7820. The analog-input signal on the primary side is digitally encoded by the delta-sigma A/D converter and transmitted to the secondary side by the LED. On the secondary side, the signal is received by the photodiode, demodulated by the transimpedance amplifier and the decoder circuit, and the analog-output is generated by the D/A converter circuit and the LPF. Since the primary-side and secondary-side power supplies are isolated, it is also used to detect signals with different reference potentials, prevent common mode noise contamination, etc.

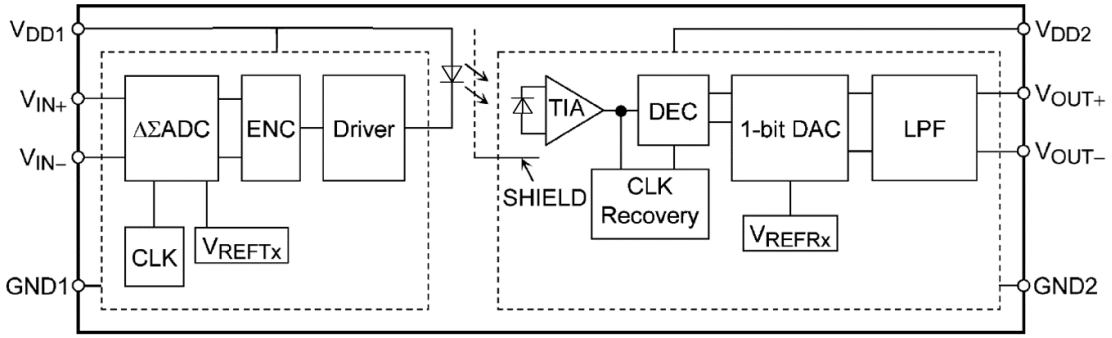


Fig. 4.7 Internal-Block Diagram of Isolation Amplifier TLP7820

Fig. 4.8 shows the I/O properties of TLP7820. The differential voltage input between V_{IN+} and V_{IN-} can be amplified by a gain of 8.2 times (Typ.) as shown in the following equation, and the resulting differential voltage is output between V_{OUT+} and V_{OUT-}.

$$V_{OUT+} - V_{OUT-} = 8.2 \cdot (V_{IN+} - V_{IN-}) \quad (4\text{-}1)$$

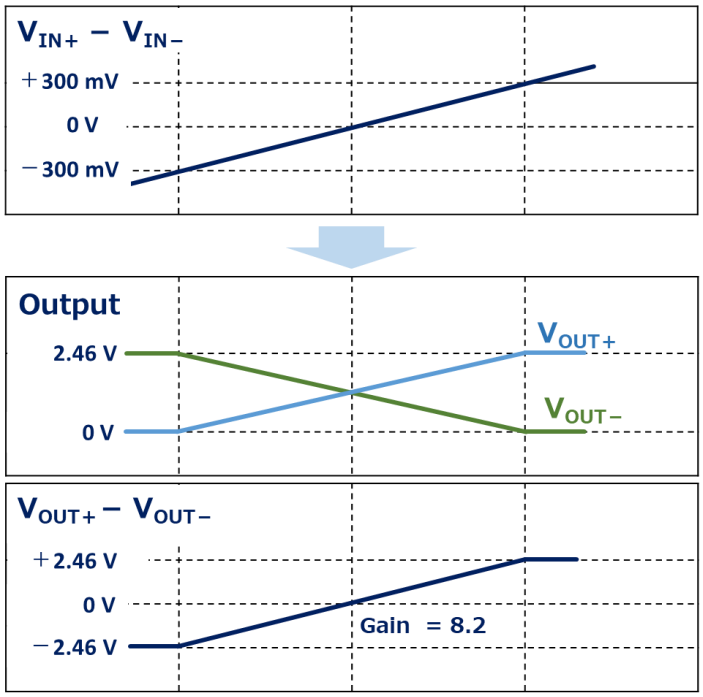


Fig. 4.8 Isolation Amplifier TLP7820 Input/Output Characteristics

4.3.2. Differential Amplifier Circuit

This section describes the differential amplifier circuit used in the phase current sensor, bus current sensor, and bus voltage sensor of this inverter. Consider a differential amplifier circuit using the op-amp shown in Fig. 4.9.

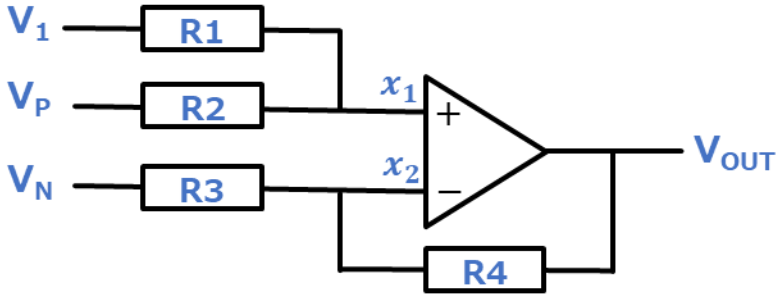


Fig. 4.9 Example of Differential Amplifier Circuit

The potentials of $\boldsymbol{x_1}$ and $\boldsymbol{x_2}$ are expressed as follows.

$$x_1 = V_P + (V_1 - V_P)\frac{R2}{R1 + R2}$$

$$x_2 = V_N + (V_{OUT} - V_N)\frac{R3}{R3 + R4}$$

In an op-amp circuit, the positive and negative inputs of an op-amp are considered to be at the same potential (virtual short) and thus following equations are established.

$$x_1 = x_2$$

From the above equation

$$V_P + (V_1 - V_P)\frac{R2}{R1 + R2} = V_N + (V_{OUT} - V_N)\frac{R3}{R3 + R4}$$

Here

$$R1 = R4, \quad R2 = R3$$

In this case

$$\boldsymbol{V_{OUT} = \frac{R1}{R2}(V_P - V_N) + V_1} \qquad (4\text{-}2)$$

As a result, this circuit operates as a differential amplifier that amplifies the potential difference between V_P, V_N at a gain of R1/R2 and adds an offset-voltage V_1.

4.4. Phase Current Sensor Circuit

Fig. 4.10 shows the phase current sensor circuit. The current flowing through the shunt resistor is converted into sensor output voltage by the isolation amplifier circuit and differential amplifier circuit. And the phase current sensor output voltage V_{ADx} (actually V_{ADU}, V_{ADV}, V_{ADW}) of each phase is isolated and is output to the controller (ADU:CN3-36 pin, ADV:CN3-38 pin, ADW:CN3-40 pin) and the fault detection circuit. This inverter implements a phase current sensor circuit for each of the 3 phases (U, V, W). However, since the sum of the 3-phase inverter output currents is generally 0, only two-phase current sensors may also be implemented.

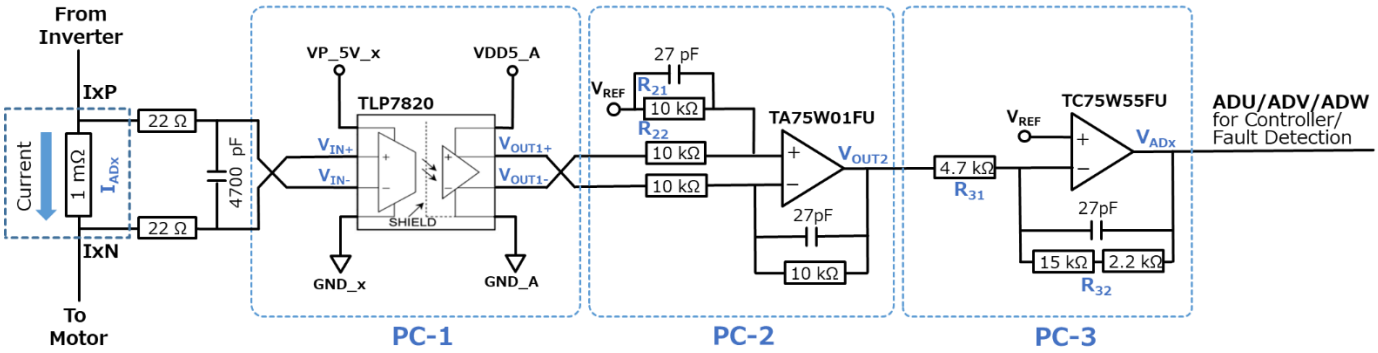


Fig. 4.10 Phase Current Sensor Circuit

The phase current sensor circuit consists of an isolated amplifier circuit (PC-1), a differential amplifier circuit (PC-2), and an inverting amplifier circuit (PC-3). When the current going to the motor from the inverter is I_{ADx}, and the resistance of the shunt resistor is 1 mΩ, the voltage at the input of isolation amplifier (PC-1) will be as follows:

$$V_{IN+} - V_{IN-} = -1.00 \times 10^{-3} \cdot I_{ADx}$$

From equation (4-1) for the isolation amplifier (PC-1):

$$V_{OUT1+} - V_{OUT1-} = 8.2 \cdot (V_{IN+} - V_{IN-})$$

From equation (4-2) for the differential amplifier (PC-2):

$$\begin{aligned} V_{OUT2} &= \frac{R_{21}}{R_{22}} \cdot -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= \frac{10 \times 10^3}{10 \times 10^3} \cdot -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \end{aligned}$$

From equation for the inverting amplifier (PC-3):

$$\begin{aligned} V_{ADx} &= -\frac{R_{32}}{R_{31}} \cdot (V_{OUT2} - V_{REF}) + V_{REF} \\ &= -\frac{(15 + 2.2) \times 10^3}{4.7 \times 10^3} \times (V_{OUT2} - V_{REF}) + V_{REF} \\ &\cong -3.66 \times (V_{OUT2} - V_{REF}) + V_{REF} \end{aligned}$$

From the above equations and $V_{REF} = 2.5\ V$, the phase current sensor output-voltage V_{ADx} becomes:

$$\begin{aligned} \boldsymbol{V_{ADx} &\cong -8.2 \cdot 3.66 \cdot 1.00 \times 10^{-3} \cdot I_{ADx} + V_{REF}} \\ &\boldsymbol{\cong -30 \times 10^{-3} \cdot I_{ADx} + 2.5} \end{aligned} \quad (4\text{-}3)$$

So, if I_{ADx} is 1 A, the output voltage becomes -30 mV plus the offset voltage 2.5 V.

4.5. Bus Current Sensor Circuit

Fig. 4.11 shows the bus current sensor circuit. The bus current (total current in inverter leg) flowing through the shunt resistor is converted into sensor output voltage by the isolation amplifier circuit and the differential amplifier circuit. And the bus current sensor output voltage V_{ADB} is isolated and is output to the fault detection circuit.

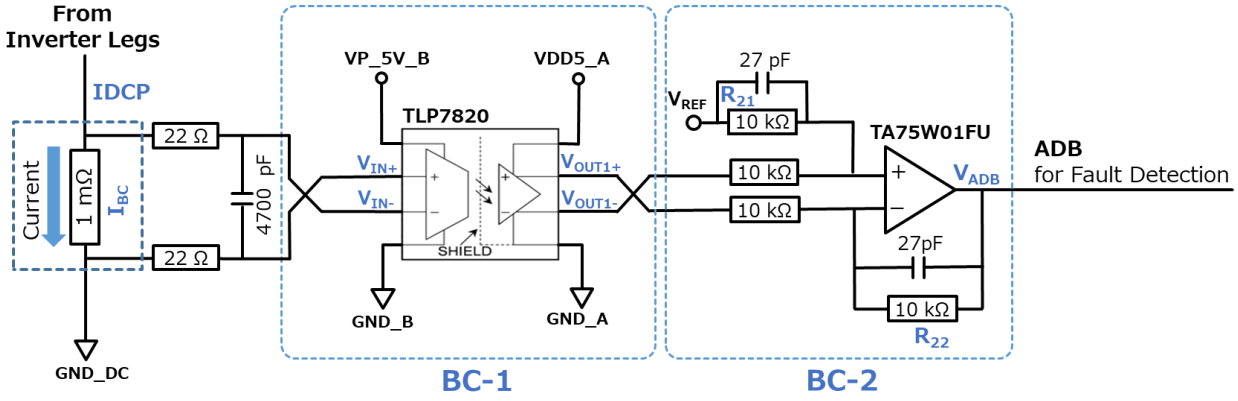


Fig. 4.11 Bus Current Sensor Circuit

The bus current sensor circuit consists of an isolated amplifier circuit (BC-1) and a differential amplifier circuit (BC-2). When the current going to GND_DC from all the legs of the inverter is I_{ADB}, the resistance of the shunt resistor is 1 mΩ, the voltage at the input of isolation amplifier (BC-1) will be as follows:

$$V_{IN+} - V_{IN-} = -1.00 \times 10^{-3} \cdot I_{ADB}$$

From equation (4-1) for the isolation amplifier (BC-1):

$$V_{OUT1+} - V_{OUT1-} = 8.2 \cdot (V_{IN+} - V_{IN-})$$

From equation (4-2) for the differential amplifier (BC-2):

$$\begin{aligned} V_{OUT2} &= \frac{R_{21}}{R_{22}} \cdot -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= \frac{10 \times 10^3}{10 \times 10^3} \cdot -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= -(V_{OUT1+} - V_{OUT1-}) + V_{REF} \end{aligned}$$

From the above equations and $V_{REF} = 2.5\ V$, the bus current sensor output voltage V_{ADB} becomes:

$$\begin{aligned} \boldsymbol{V_{ADB}} &= \boldsymbol{8.2 \cdot 1.00 \times 10^{-3} \cdot I_{ADB} + V_{REF}} \\ &= \boldsymbol{8.2 \times 10^{-3} \cdot I_{ADB} + 2.5} \end{aligned} \quad (4\text{-}4)$$

So, if I_{ADB} is 1 A, then output voltage becomes 8.2 mV plus the offset voltage 2.5 V.

4.6. Bus Voltage Sensor Circuit

Fig. 4.12 shows the bus voltage sensor circuit. The bus voltage divided by the resistors is converted to the sensor output voltage by the isolation amplifier circuit and the differential amplifier circuit. And the bus voltage sensor output voltage V_{VDC} is isolated and is output to the controller (CN3-26 pin: VDC) and the fault detection circuit.

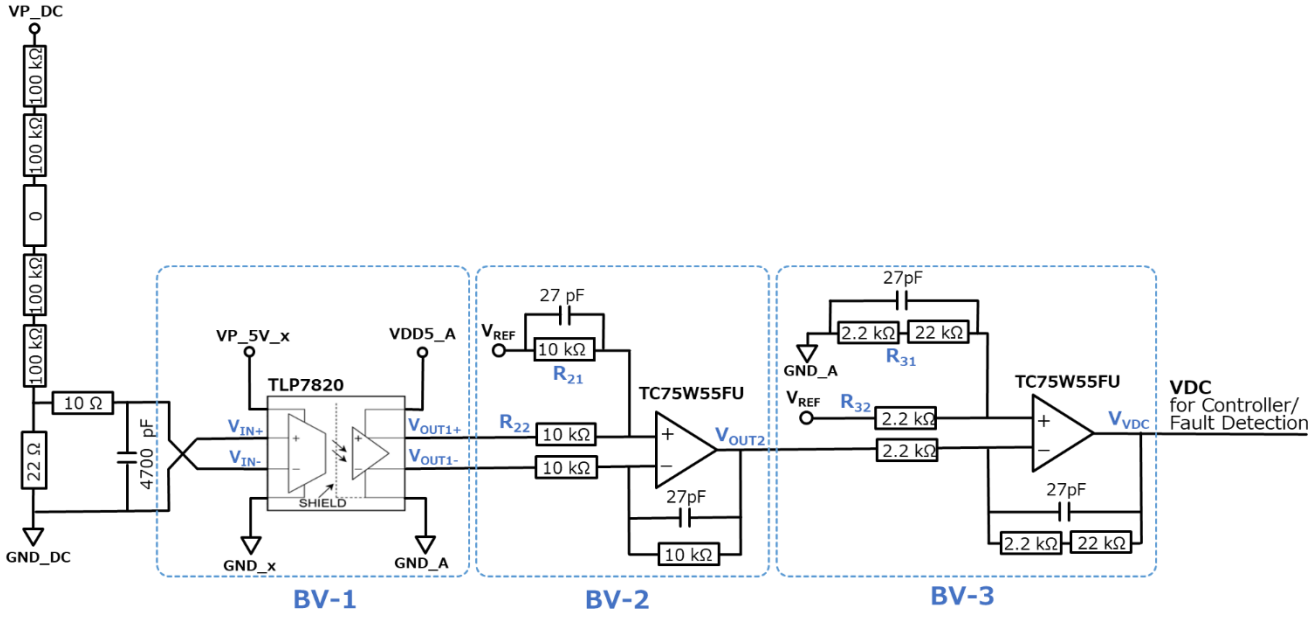


Fig. 4.12 Bus Voltage Sensor Circuit

The bus voltage sensor circuit consists of an isolated amplifier circuit (BV-1) and two differential amplifier circuits (BV-2, BV-3). If the bus voltage is VP_DC, then according to the voltage divider resistance ratio, the voltage at the input of isolation amplifier (BV-1) will be as follows:

$$\mathrm{V_{IN+}} - \mathrm{V_{IN-}} = -\frac{22}{40000+22} \cdot \mathrm{VP\_DC}$$

From equation (4-1) for the isolation amplifier (BV-1):

$$V_{OUT1+} - V_{OUT1-} = 8.2 \cdot (V_{IN+} - V_{IN-})$$

From equation (4-2) for the differential amplifier (BV-2):

$$\begin{aligned} V_{OUT2} &= \frac{R_{21}}{R_{22}}(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= \frac{10 \times 10^3}{10 \times 10^3}(V_{OUT1+} - V_{OUT1-}) + V_{REF} \\ &= (V_{OUT1+} - V_{OUT1-}) + V_{REF} \end{aligned}$$

From equation (4-2) for the differential amplifier (BV-3)

$$\begin{aligned} \boldsymbol{V_{VDC}} &= \frac{\boldsymbol{R_{31}}}{\boldsymbol{R_{32}}}(\boldsymbol{V_{REF}} - \boldsymbol{V_{OUT2}}) - \mathbf{0} \\ &= \frac{(\mathbf{2.2}+\mathbf{22}) \times \mathbf{10^3}}{\mathbf{2.2} \times \mathbf{10^3}} \cdot \mathbf{8.2} \cdot \frac{\mathbf{22}}{\mathbf{40000}+\mathbf{22}} \cdot \boldsymbol{VP\_DC} \\ &\cong \mathbf{4.96} \times \mathbf{10^{-3}} \cdot \boldsymbol{VP\_DC} \end{aligned} \quad (4\text{-}5)$$

So, if VP_DC is 1 V, then the bus voltage sensor output voltage becomes 4.96 mV.

4.7. Temperature Sensor Circuit

Fig. 4.13 shows the temperature sensor circuit. TH_HS NTC thermistor (for measuring the temperature of SiC MOSFET heat sink) and TH_RY thermistor (for measuring the temperature of the inrush-proof relays on AC-DC board) are used to measure the temperature at two points. The resistor divider voltage output (V_{TH_HS}, V_{TH_RY}) of each thermistor is sent to the fault detection circuit. And the resistor divider voltage output (V_{TH_HS}) of TH_HS thermistor is separately amplified by an op-amp and is sent to the controller (CN3-24 pin: THM1). Since the resistance value of NTC thermistor decreases as the temperature rises, the temperature sensor output voltage also decreases as the temperature rises.

This inverter uses B57703M0103A017 (TDK) NTC thermistor with the resistance of 10 kΩ at 25 °C and the B-constant of 3988 K. Thermistors can be connected by soldering the thermistor leads between through-holes J1-J2 (for TH_HS) and between J3-J4 (for TH_RY) on the inverter board.

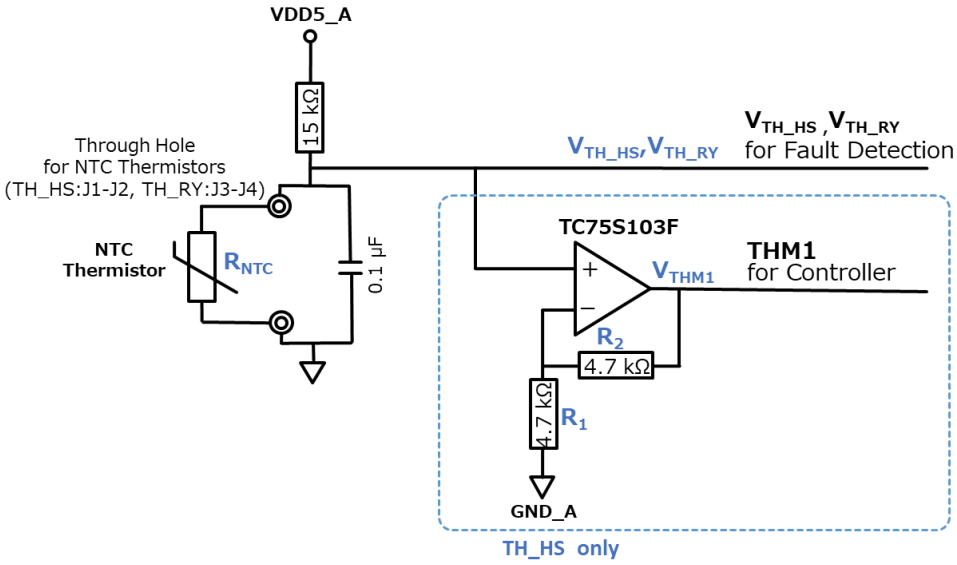


Fig. 4.13 Temperature Sensor Circuit

If the resistance of NTC thermistor is R_{NTC}, then the temperature-sensor output voltage V_{TH_xx} (actually V_{TH_HS} and V_{TH_RY}) going to the fault detection circuit will be as follows:

$$V_{TH\_XX} = 5.0 \cdot \frac{R_{NTC}}{R_{NTC} + 15 \times 10^3} \tag{4-6}$$

The temperature sensor output voltage V_{THM1} going to the controller is produced by amplifying the voltage divider circuit output V_{TH_HS} using a non-inverting amplifier circuit consisting of TC75S103F operational amplifier. This output voltage will be as follows:

$$V_{THM1} = \frac{R_1 + R_2}{R_1} \cdot V_{TH\_HS}$$

$$= \frac{4.7 \times 10^3 + 4.7 \times 10^3}{4.7 \times 10^3} \cdot 5.0 \cdot \frac{R_{NTC}}{R_{NTC} + 15 \times 10^3}$$

$$= 10.0 \cdot \frac{R_{NTC}}{R_{NTC} + 15 \times 10^3} \tag{4-7}$$

4.8. Fault Detection Circuit

The Fault detection circuit detects the fault by comparing the sensor output voltages from the phase current sensor circuit, bus current sensor circuit, bus voltage sensor circuit, and temperature sensor circuit described above with threshold voltages using a comparator. Fig. 4.14 shows the fault detection circuit. A CMOS comparator TC75W59FU is used for comparing sensor output voltages with respective threshold voltages. The comparator detects phase overcurrent error, bus overcurrent error, bus overvoltage error and overtemperature error. Because of the open-drain output, if any of these errors is detected, the L level is output to the fault detection output (nEMG). When nEMG goes low, all gate signals going to SiC MOSFETs are disabled. When all the error factors recover to normal, H level is output to nEMG.

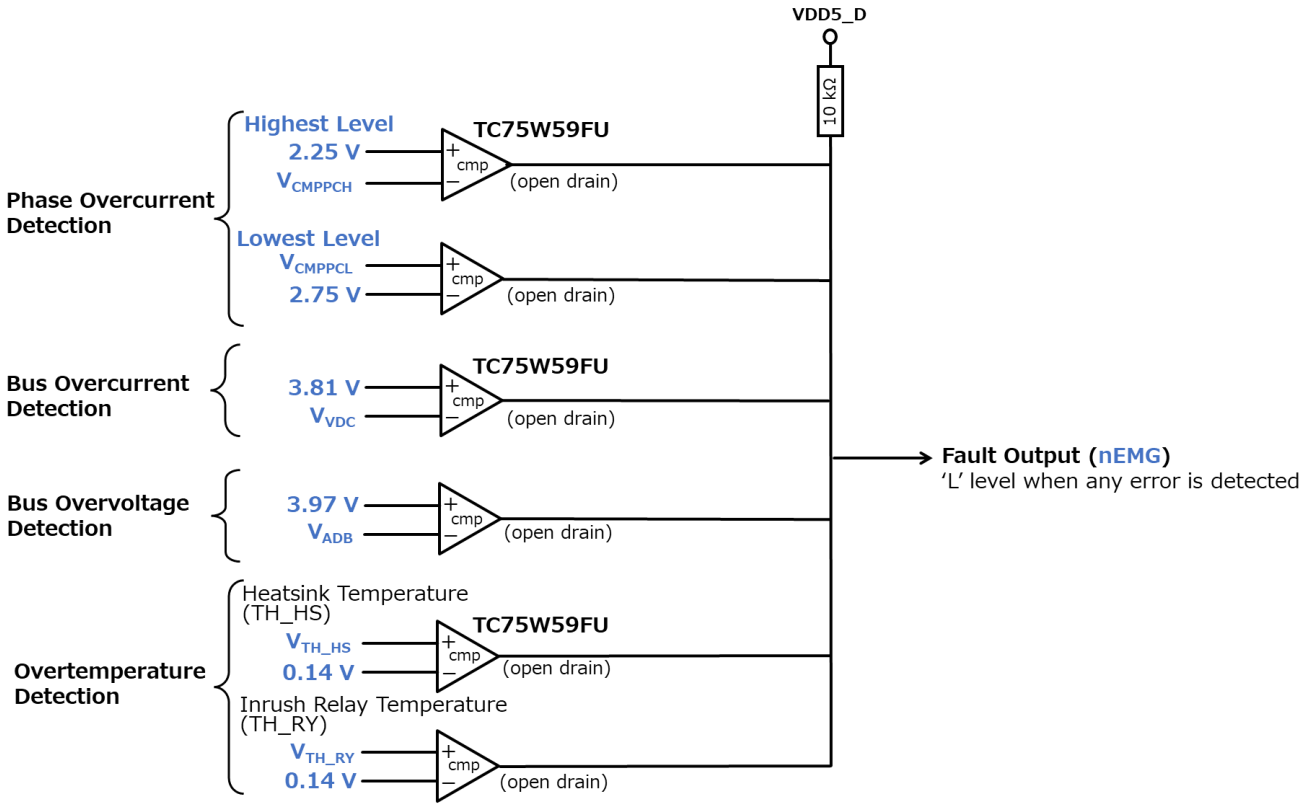


Fig. 4.14 Fault Detection Circuit

4.8.1. Phase Overcurrent Error Detection

Fig. 4.15 shows the voltage divider circuit for phase overcurrent error detection. This circuit does not use comparators to compare the phase current of each phase. By using 1SS389 diodes and voltage dividers, the highest and lowest phase current sensor output voltages are separated, and their output signals (V_{CMPPCH} and V_{CMPPCL}) are sent to fault detection circuit to be compared with respective threshold voltages. This reduces the total number of comparators required.

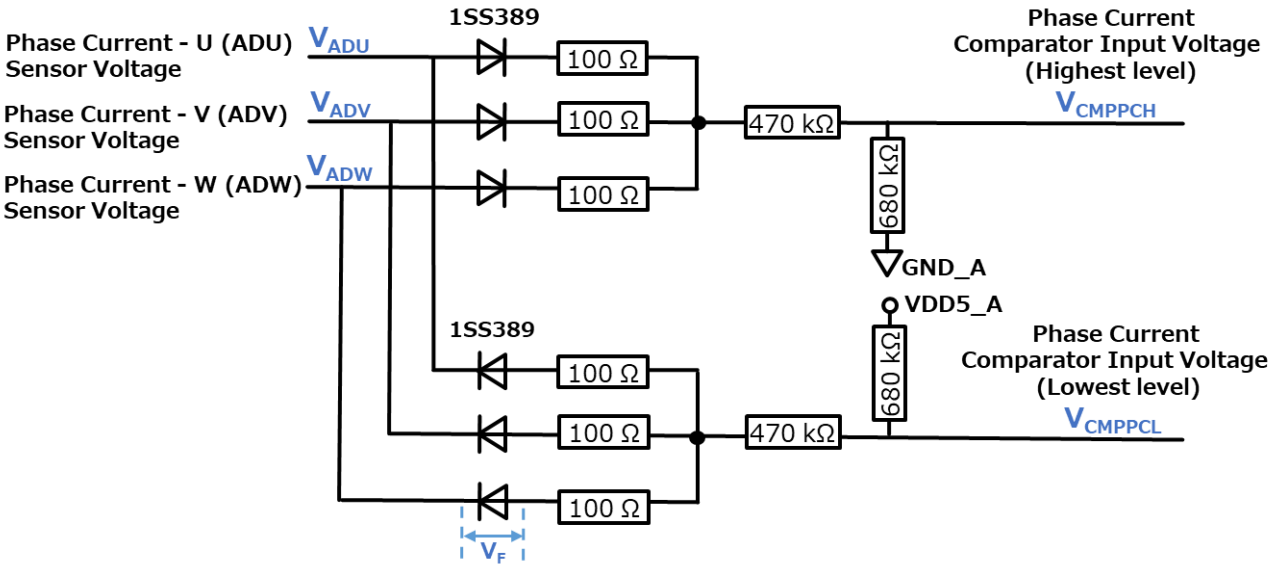


Fig. 4.15 Divider Circuit for Phase Current Error Detection

The threshold voltage V_{CMP} of the comparator with the highest phase current sensor voltage is obtained by dividing 5 V with 33 kΩ and 27 kΩ.

$$V_{CMP} = 5.0 \times \frac{27 \times 10^3}{33 \times 10^3 + 27 \times 10^3}$$
$$= 2.25\ (V)$$

The threshold voltage V_{CMP} is connected to the + input side of the comparator, and the voltage divider output (V_{CMPPCH}) of the highest phase current sensor voltage is connected to the - input side of the comparator. Therefore, the error is detected when following condition is met.

$$V_{CMPPCH} > V_{CMP} = 2.25\ \ (V)$$

The phase current sensor voltage output V_{ADx} of each phase when V_{CMPPCH} = 2.25 V is obtained as follows when the diode forward voltage drop V_F in the minute current area is taken as 50 mV.

$$V_{ADx} = 2.25 + \frac{2.25}{680 \times 10^3}(470 \times 10^3 + 100) + 50 \times 10^{-3}$$
$$\cong 3.86\ (V)$$

The phase current I_{ADx} at this time is calculated from Equation (4-3) as shown below.

$$I_{ADx} \cong \frac{(V_{ADx} - 2.5)}{-30\ \times\ 10^{-3}}$$
$$\cong \frac{(3.86 - 2.5)}{-30\ \times\ 10^{-3}} \cong -45\ (A)$$

Therefore, if any one of the phase currents I_{ADU}, I_{ADV}, I_{ADU} fall below -45 A, L-level is output to the fault detection output (nEMG).

Similarly, the threshold voltage V_{CMP} of the comparator with the lowest phase current sensor voltage is obtained by dividing 5 V with 27 kΩ and 33 kΩ.

$$V_{CMP} = 5.0 \times \frac{33 \times 10^3}{27 \times 10^3 + 33 \times 10^3}$$
$$= 2.75\ (V)$$

The voltage divider output (V_{CMPPCL}) of the lowest phase current sensor voltage is connected to the + input side of the comparator, and the threshold voltage V_{CMP} is connected to the - input side of the comparator. Therefore, the error is detected when following condition is met.

$$V_{CMPPCL} < V_{CMP} = 2.75\ \ (V)$$

The phase current sensor voltage output V_{ADx} of each phase when V_{CMPPCL} = 2.75 V is obtained as follows when the diode forward voltage drop V_F in the minute current area is taken as 50 mV.

$$V_{ADx} = 2.75 - \frac{(5 - 2.75)}{680 \times 10^3}(470 \times 10^3 + 100) - 50 \times 10^{-3}$$
$$\cong 1.14\ (V)$$

The phase current I_{ADx} at this time is calculated from Equation (4-3) as shown below.

$$I_{ADx} \cong \frac{(V_{ADx} - 2.5)}{-30\ \times\ 10^{-3}}$$
$$= \frac{(1.14 - 2.5)}{-30\ \times\ 10^{-3}} \cong 45\ (A)$$

Therefore, if any one of the phase currents I_{ADU}, I_{ADV}, I_{ADU} exceed 45 A, L-level is output to the fault detection output (nEMG).

4.8.2. Bus Overcurrent Error Detection

The threshold voltage V_{CMP} of the bus overcurrent error detecting comparator is obtained as follows because 5 V voltage is divided by 4.7 kΩ and 15 kΩ.

$$V_{CMP} = 5.0 \times \frac{15 \times 10^3}{4.7 \times 10^3 + 15 \times 10^3}$$
$$= 3.81\ (V)$$

The threshold voltage V_{CMP} is connected to the +input side of the comparator, and a bus current sensor output V_{ADB} is connected to the - input side of the comparator. Therefore, the error is detected when the following condition is met.

$$V_{ADB} > V_{CMP} = 3.81\ \ (V)$$

The bus current I_{ADB} when V_{ADB} = 3.81 V is calculated from Equation (4-4) as shown below.

$$I_{ADB} = \frac{V_{ADB} - 2.5}{8.2\ \times\ 10^{-3}}$$
$$= \frac{3.81 - 2.5}{8.2\ \times\ 10^{-3}} \cong 160\ (A)$$

Therefore, if the bus current I_{ADB} exceeds 160 A, L-level is output to the fault detection output (nEMG).

4.8.3. Bus Overvoltage Error Detection

The threshold voltage V_{CMP} of the bus overvoltage error detecting comparator is obtained as follows because 5 V voltage is divided by 3.9 kΩ and 15 kΩ.

$$V_{CMP} = 5.0 \times \frac{15 \times 10^3}{3.9 \times 10^3 + 15 \times 10^3}$$
$$= 3.97\ (V)$$

A threshold voltage V_{CMP} is connected to the +input side of the comparator, and a bus voltage sensor output V_{VDC} is connected to the - input side of the comparator. Therefore, the error is detected when the following condition is met.

$$V_{VDC} > V_{CMP} = 3.97\ \ (V)$$

The bus voltage VP_DC when V_{VDC} = 3.97 V is calculated from Equation (4-5) as shown below.

$$VP\_DC = \frac{V_{VDC}}{4.96\ \times\ 10^{-3}}$$
$$= \frac{3.97}{4.96\ \times\ 10^{-3}} \cong 800\ (V)$$

Therefore, when the bus voltage VP_DC exceeds 800 V, L-level is output to the fault detection output (nEMG).

4.8.4. Overtemperature Error Detection

The threshold voltage V_{CMP} of the overtemperature error detecting comparator is obtained as follows because 5 V voltage is divided by 33 kΩ and 1 kΩ. 。

$$V_{CMP} = 5.0 \times \frac{1 \times 10^3}{33 \times 10^3 + 1 \times 10^3}$$
$$= 0.147\ (V)$$

Since the temperature sensor output V_{TH_XX} is connected to the + input side of the comparator and the threshold voltage V_{CMP} is connected to the - input side of the comparator. Therefore, the error is detected when the following condition is met.

$$V_{TH\_XX} < V_{CMP} = 0.147\ \ (V)$$

The resistance R_{NTC} of NTC thermistor when V_{VDC} = 0.147 V is calculated from Equation (4-7) as shown below.

$$R_{NTC} = \frac{15 \times 10^3 \cdot V_{TH\_XX}}{5 - V_{TH\_XX}}$$
$$= \frac{15 \times 10^3 \cdot 0.147}{5 - 0.147} \cong 454\ (\Omega)$$

From the temperature properties of NTC thermistor (B57703M0502G040), when the measured temperature exceeds approximately 115 °C, L-level is output to the fault detection output (nEMG).

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