Fe Fuji Electric
Innovating Energy Technology

Small IPM (Intelligent Power Module)

P633C Series

6MBP**XS*065-50

Application Manual

⚠ Cautions

This Instruction contains the product specifications, characteristics, data, materials, and structures as of August 2023. The contents are subject to change without notice for specification changes or other reason. When using a product listed in this Instruction be sure to obtain the latest specifications.

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The products described in this application manual are manufactured with the intention of being used in the following industrial electronic and electrical devices that require normal reliability.

- ・Compressor motor inverter
- ・Fan motor inverter for room air conditioner
- ・Compressor motor inverter for heat pump applications, etc.

If you need to use a semiconductor product in this application note for equipment requiring higher reliability than normal, such as listed below, be sure to contact Fuji Electric Co., Ltd. to obtain prior approval. When using these products, take adequate safety measures such as a backup system to prevent the equipment from malfunctioning when a Fuji Electric's product incorporated in the equipment becomes faulty.

- ・Transportation equipment (mounted on vehicles and ships)
- ・Trunk communications equipment
- ・Traffic-signal control equipment
- ・Gas leakage detectors with an auto-shutoff function
- ・Disaster prevention / security equipment
- ・Safety devices, etc.

Do not use a product in this application note for equipment requiring extremely high reliability such as:

- ・Space equipment   ・Airborne equipment   ・Atomic control equipment
- ・Submarine repeater equipment   ・Medical equipment

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Chapter 3 Details of Signal Input/Output Terminals

1. Control Power Supply Terminals VCCH, VCCL, COM

<Voltage Range of control power supply terminals VCCH, VCCL>

- For control supply voltage, please connect a 15V±10% DC power supply between VCCH, VCCL and COM terminals.
- Table 3-1 describes the operation of the product for various control supply voltages. A low impedance capacitor and a high frequency decoupling capacitor should be connected close to the terminals of the power supply.
- High frequency noise on the power supply might cause malfunction of the internal control IC or erroneous fault signal output. To avoid these problems, the maximum amplitude of voltage ripple on the power supply should be less than ±1V/μs.
- The potential at the COM terminal is different from that at the N(U, V, W) power terminal. It is very important that all control circuits and power supplies are referred to the COM terminal and not to the N(U, V, W) terminals. If circuits are improperly connected, current might flow through the shunt resistor and cause improper operation of the short-circuit protection function. In general, it is recommended to make the COM terminal as the ground potential in the PCB layout.
- The main control power supply is also connected to the bootstrap circuit which provide floating power supplies for the high-side gate drivers.
- When high-side control supply voltage V_{CCH} falls below $V_{CCH(OFF)}$, only the IGBT which under voltage condition occurred becomes off-state even though input signal is ON condition.
- When low-side control supply voltage V_{CCL} falls below $V_{CCL(OFF)}$, all low-side IGBTs become off-state even though the input signal is ON condition.

Table 3-1 IPM operations versus control supply voltage V_{CCH}, V_{CCL}

Control Voltage Range [V]	Operations and functions
0 ~ 4	The product doesn't operate. UV and fault output are not activated. dv/dt noise on the main P-N supply might cause malfunction of the IGBTs.
4 ~ 13	The product starts to operate. UV is activated, control input signals are blocked and fault output VFO is generated.
13 ~ 13.5	UV is reset. IGBTs perform switching in accordance to input signal. Drive voltage is below the recommended range, so $V_{CE(sat)}$ and the switching loss will be larger than that under normal condition. High side IGBTs do not switch until $V_{B(*)}$[*1] reaches $V_{B(ON)}$ after initial charging.
13.5 ~ 16.5	Normal operation. This is the recommended operating condition.
16.5 ~ 20	IGBTs perform switching. Because drive voltage is above the recommended range, IGBT's switching is faster and causes an increase in system noise. Even with proper overcurrent protection design, the short-circuit peak current can become very large and might lead to failure.
Over 20	Control circuit in the product might be damaged. It is recommended to insert a Zener diode between each pair of control supply terminals if necessary.

*1 : $V_{B(*)}$ is applied between VB(U)-U, VB(V)-V, VB(W)-W.

<Under Voltage (UV) protection of control power supply terminals VCCH, VCCL>
- Fig.3-1 shows the UV protection circuit of VCCH and VCCL.
- Fig.3-2 and Fig.3-3 shows the operation sequence of UV operation of V_{CCH} and V_{CCL}.
- As shown in Fig.3-1, a diode is connected between VCCH-COM and VCCL-COM terminals. The diode is connected to protect the Small IPM from the input surge voltage. Do not use the diode for voltage clamp purpose otherwise the product might be damaged.
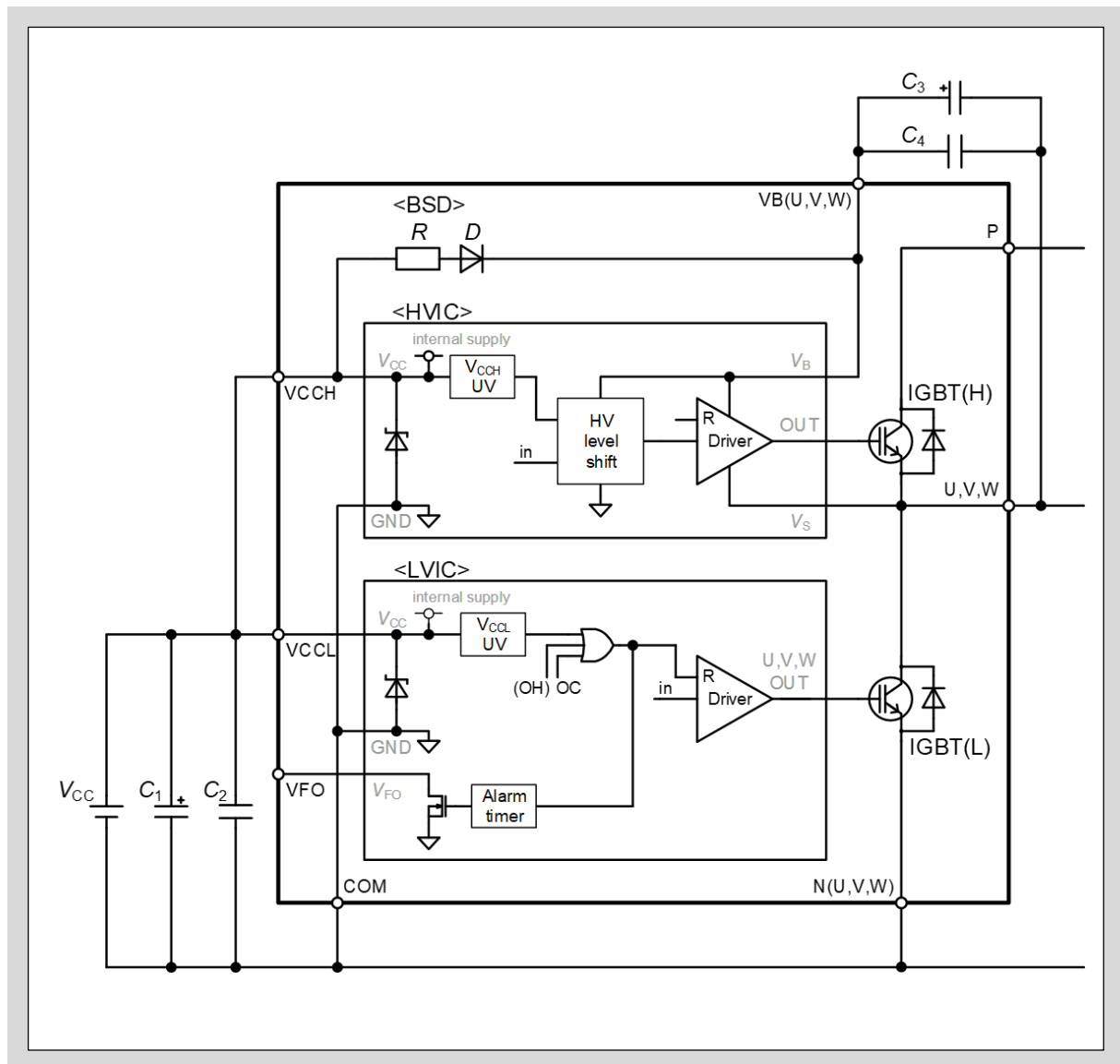

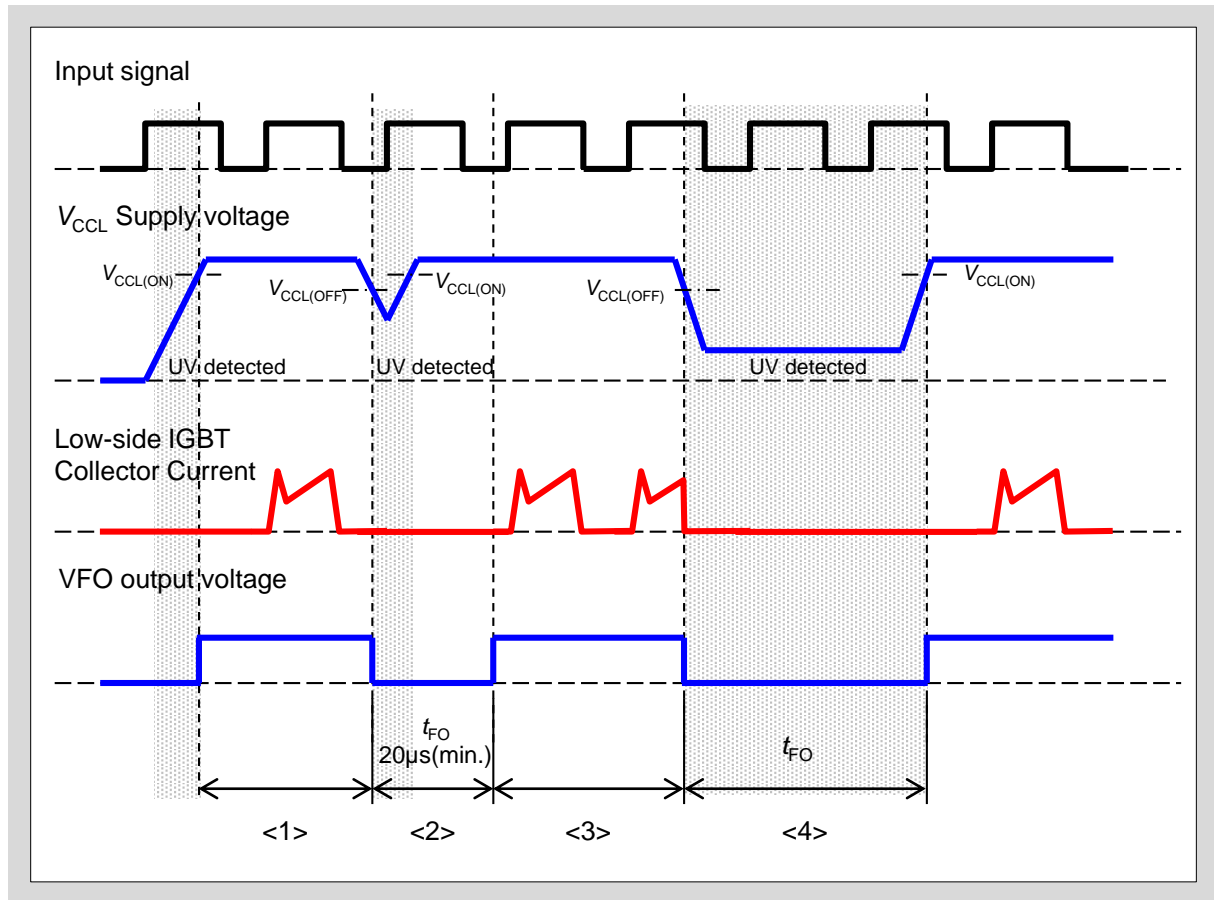Fig.3-1 UV protection circuit of VCCH, VCCL

Fig.3-2 Operation sequence of V_{CCL} Under Voltage protection (Low-side)

When V_{CCL} is below 4V, under voltage (UV) protection of low-side and fault output are not activated.

<1> When V_{CCL} is lower than $V_{CCL(ON)}$, all low-side IGBTs are in OFF state. After V_{CCL} exceeds $V_{CCL(ON)}$, the fault output V_{FO} is reset from L level to H level. The low-side IGBTs start switching operation from the next input signal.

<2> The fault output V_{FO} is activated when VCCL falls below $V_{CCL(OFF)}$, and all low-side IGBTs are turned-off. If the voltage drop period is less than 20μs, the minimum pulse width of the fault output is t_{FO}=20μs(min.). During this period, all low-side IGBTs remain in OFF state regardless of the input signal condition.

<3> When V_{CCL} exceeds $V_{CCL(ON)}$ after t_{FO} elapsed, UV protection is reset and the fault output V_{FO} is reset simultaneously. The low-side IGBTs start switching operation from the next input signal.

<4> If the voltage drop period is longer than t_{FO}, the fault output V_{FO} with the same width is generated. During this period, all low-side IGBTs are in OFF state regardless of the input signal condition.
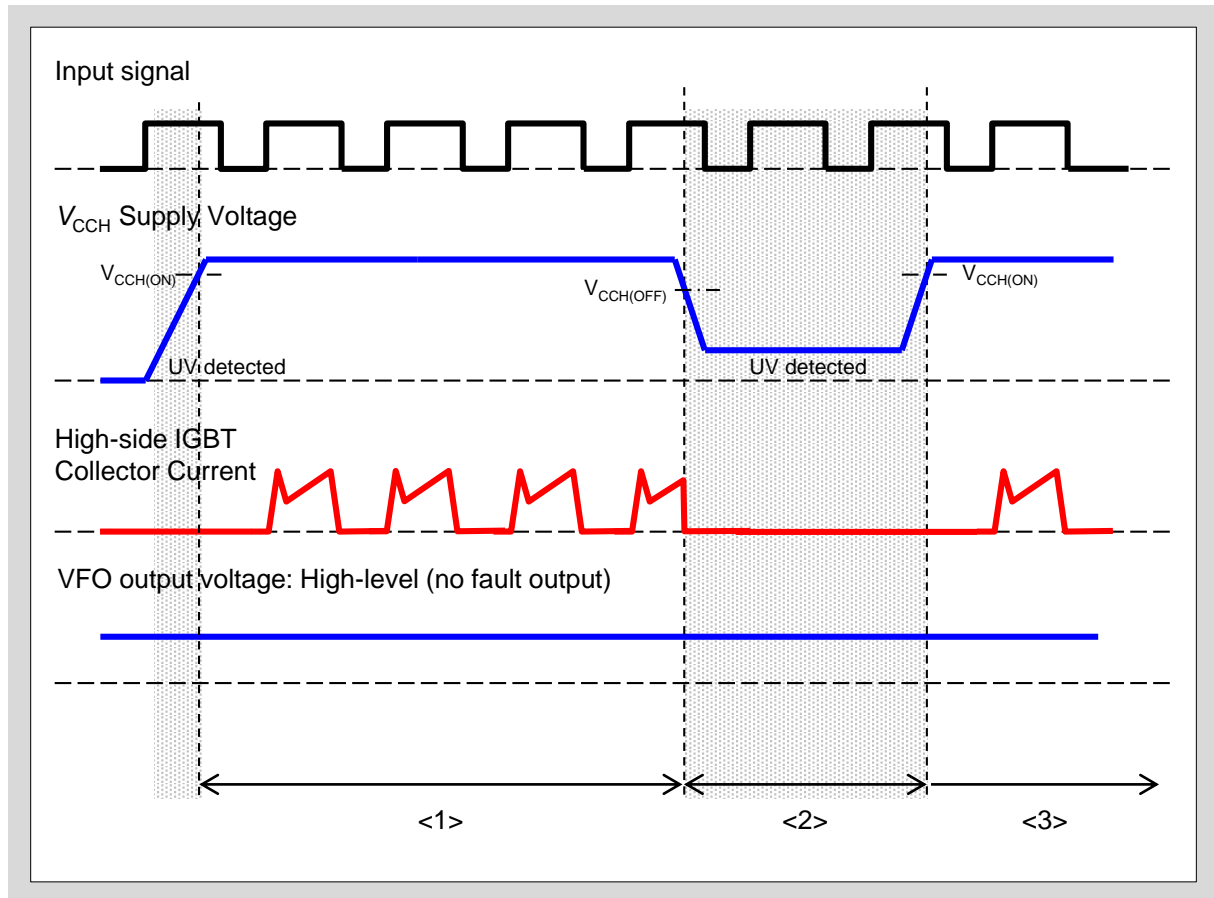
Fig.3-3 Operation sequence of V_{CCH} Under Voltage protection (High-side)

<1> When V_{CCH} is lower than $V_{CCH(ON)}$, the high-side IGBTs is in OFF state. After V_{CCH} exceeds $V_{CCH(ON)}$, the upper side IGBTs start switching operation from the next input signal. The fault output VFO remains at H level regardless of V_{CCH}.*1

<2> When V_{CCH} falls below $V_{CCH(OFF)}$, the high-side IGBTs are turned-off. The fault output V_{FO} remains H level.

<3> After the UV protection operation is reset, the upper side IGBTs start switching operation from the next input signal.

*1: The fault output does not depend on the HVIC bias conditions.

2. Power Supply Terminals of High-Side VB(U,V,W)

<Voltage range of high-side bias voltage for IGBT driving terminals VB(U, V, W)>

- The voltage $V_{B(*)}$, which is the voltage between VB(U,V,W) and U, V, W, provides the power supply to the HVICs within the product. The HVIC can drive the high-side IGBT when this voltage is in the range of 13.0~18.5V.
- The product includes UV protection for $V_{B(*)}$ to ensure that the HVICs do not drive the high-side IGBTs when $V_{B(*)}$ drops below a specified voltage (refer to the datasheet). This function prevents the IGBT from operating in a high dissipation mode. Please note that the UV protection only works on the triggered phase and doesn't generate fault output.
- In the case of using bootstrap circuit, the IGBT drive power supply for high-side can be generated from the high-side/low-side control power supply.
- The power supply of the high-side is charged when the low-side IGBT is turned on or when freewheel current flows through the low-side FWD. Table 3-2 describes the operation of the product for various control supply voltages. The control supply should be well filtered with a low impedance capacitor and a high frequency decoupling capacitor connected close to the terminals in order to prevent malfunction of the internal control IC caused by a high frequency noise on the power supply.
- When $V_{B(*)}$ falls below $V_{B(OFF)}$, only the triggered phase IGBT is off-state even though the input signal is provided.

Table 3-2 IPM operations versus high-side voltage for IGBT driving $V_{B(*)}$

Control Voltage Range [V]	Operations and functions
0 ~ 4	HVICs are not activated. UV does not operate. dv/dt noise on the main P-N supply might trigger the IGBTs.
4 ~ 12.5	HVICs start to operate. As the UV is activated, control input signals are blocked.
12.5 ~ 13	UV is reset. The high side IGBTs perform switching in accordance to input signal. Driving voltage is below the recommended range, so $V_{CE(sat)}$ and the switching loss will be larger than that under normal condition.
13 ~ 18.5	Normal operation. This is the recommended operating condition.
18.5 ~ 20	The high side IGBTs perform switching. Because drive voltage is above the recommended range, IGBT's switching is faster and causes an increase in system noise. Even with proper overcurrent protection design, the short-circuit peak current can become very large and might lead to failure.
Over 20	Control circuit in the product might be damaged. It is recommended to insert a Zener diode between each pair of high side power supply terminals.

<Under Voltage (UV) protection of high-side power supply terminals VB(U,V,W)>

- Fig.3-4 shows the UV protection circuit of high-side power supply terminals VB(U)-U, VB(V)-V, VB(W)-W, $V_{B(*)}$.
- Fig.3-5 shows the operation sequence of $V_{B(*)}$ UV protection.
- As shown in Fig.3-4, diodes are electrically connected to the VB(U,V,W)-(U,V,W) and VB(U,V,W)-COM terminals. These diodes are built-in to protect the product from surge input. Do not use these diodes as voltage clamp diodes as it might damage the product.
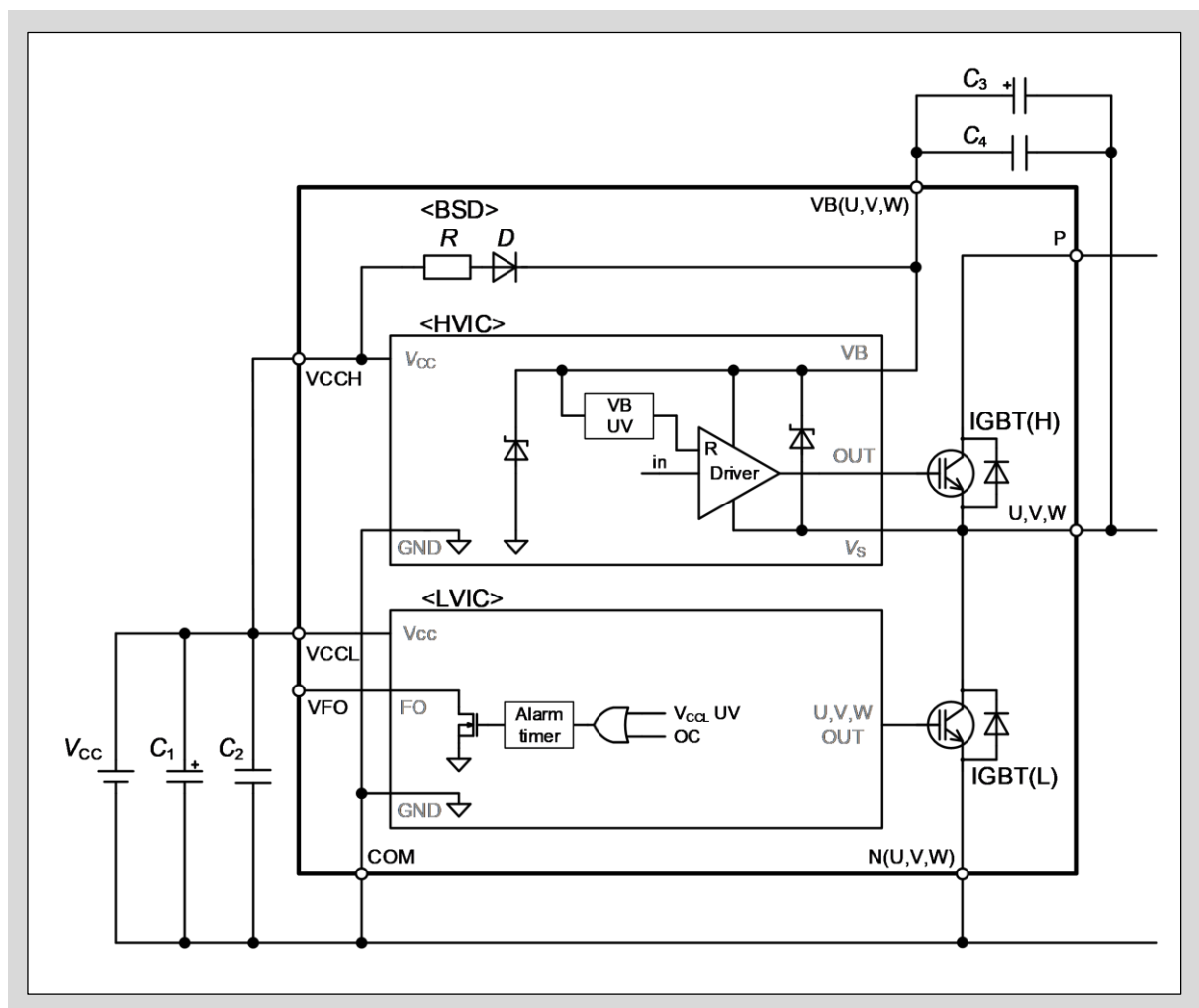

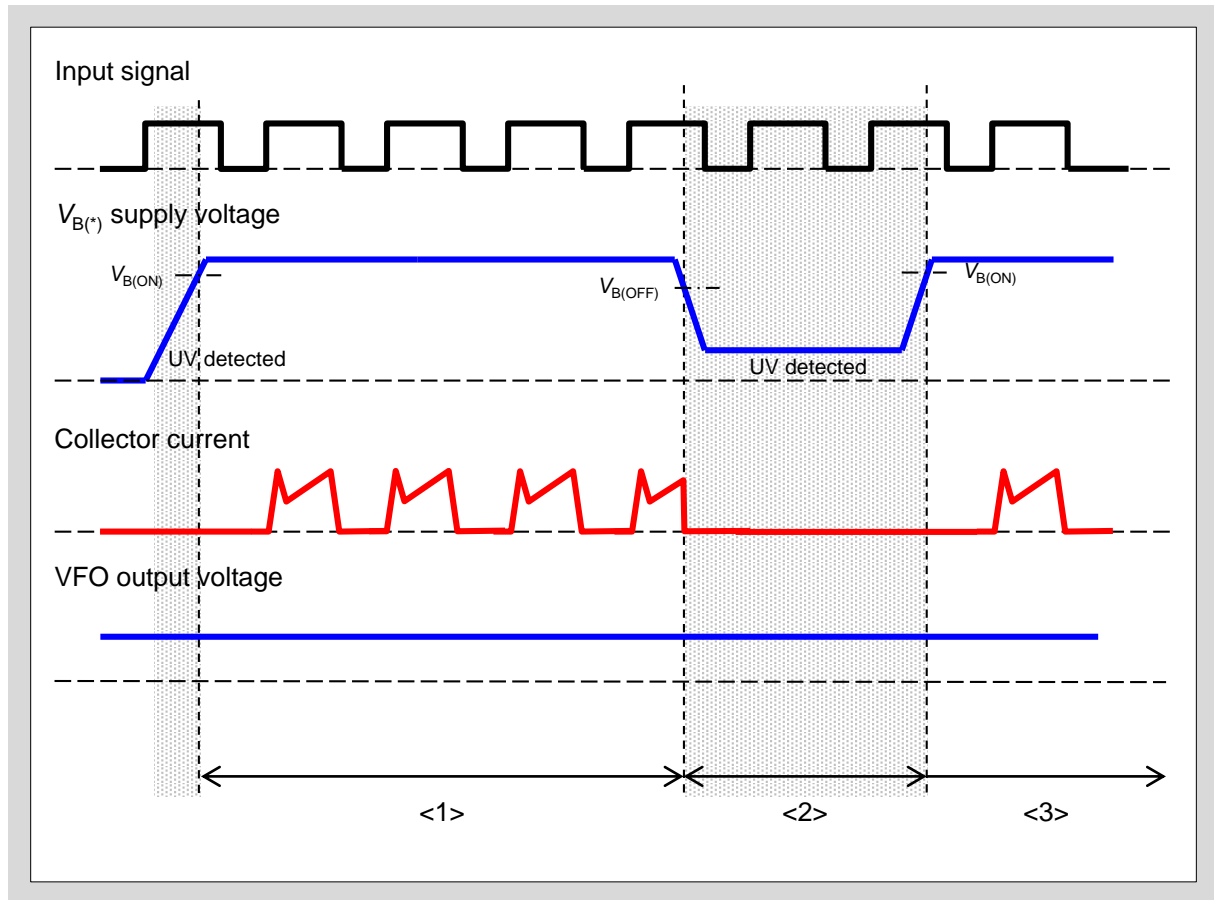Fig.3-4 UV protection circuit of V_B(U, V, W)

Fig.3-5 Operation sequence of $V_{B(*)}$ Under voltage protection (High-side)

<1> When the voltage between VB(U)-U, VB(V)-V, VB(W)-W, $V_{B(*)}$ is lower than $V_{B(ON)}$, the high-side IGBT is in OFF state. After $V_{B(*)}$ exceeds $V_{B(ON)}$, the high-side IGBT starts switching operation from the next input signal. The fault output VFO does not depend on $V_{B(*)}$ and remains at H level. *1

<2> When $V_{B(*)}$ falls below $V_{B(OFF)}$, the high-side IGBT is turned-off. However, the fault output VFO remains at H level.

<3> After the UV protection operation is reset, the high-side IGBT starts switching operation from the next input signal.

*1: The fault output does not depend on the HVIC bias conditions.

3. Function of Built-in BSDs (bootstrap Diodes)

There are several ways to supply the voltage $V_{B(*)}$ between the high-side drive power supply terminals VB(U)-U, VB(V)-V, VB(W)-W. This product can configure a bootstrap circuit by using the built-in BSD. The bootstrap method is a simple and cheap solution. However, the duty cycle and on-time are limited by the charging operation of the bootstrap capacitor. As shown in Fig. 3-6, Fig. 3-8 and Fig. 3-11, the bootstrap circuit consists of bootstrap diode with current limiting resistor, which are integrated in the Small IPM and an external capacitor.

<Charging and Discharging of Bootstrap Capacitor During Inverter Operation>
When low-side IGBT is ON state, the charging voltage on the bootstrap capacitance $V_{C(t1)}$ is calculated by the following equations. Fig.3-6 shows the circuit diagram of charging operation, and Fig.3-7 shows the timing chart.

$V_{C(t1)} = V_{CC} - V_{F(D)} - V_{CE(sat)} - I_b \cdot R$......Transient state

$V_{C(t1)} \approx V_{CC}$…………………………..…Steady state

$V_{F(D)}$: Forward voltage of Bootstrap diode D

$V_{CE(sat)}$: Saturation voltage of low side IGBT

R : Bootstrap resistance

I_b : Bootstrap charging current

When low-side IGBT is turned off, the freewheeling current flows through the freewheel path of the high-side FWD. Once V_S rises above V_{CC}, the charging of bootstrap capacitor, C stops, and the voltage of C gradually decreases due to current consumption of high-side drive circuit.
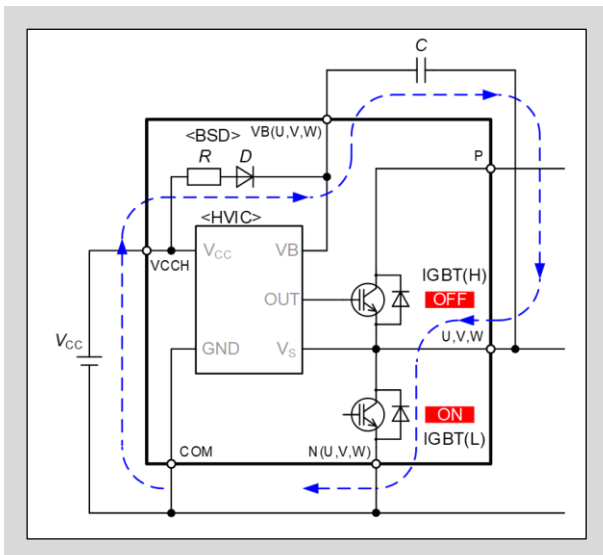

Fig.3-6 Circuit diagram of charging operation

Fig.3-7 Timing chart of charging operation

When the low-side IGBT is OFF and the low-side FWD is ON, freewheeling current flows through the low-side FWD. The voltage on the bootstrap capacitance $V_{C(t2)}$ is calculated by the following equations. Fig.3-8 shows the circuit diagram of charging operation, and Fig.3-9 shows the timing chart.

$$V_{C(t2)} = V_{CC} - V_F + V_{F(FWD)} - I_b \cdot R \ldots\ldots\text{Transient state}$$
$$V_{C(t2)} \approx V_{CC} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Steady state}$$

$V_{F(D)}$: Forward voltage of Bootstrap diode D
$V_{F(FWD)}$: Forward voltage of low-side FWD
R : Current limiting resistance
I_b : Bootstrap charging current

When both the low-side and high-side IGBTs are OFF, a regenerative current flows continuously through the low-side FWD. Therefore V_s drops to $-V_F$ of FWD, then the bootstrap capacitor, C is re-charged to restore the declined potential. When the high-side IGBT is turned ON and V_s exceeds V_{CC}, the charging of C stops, and the voltage of C gradually decreases due to current consumption of high-side drive circuit.

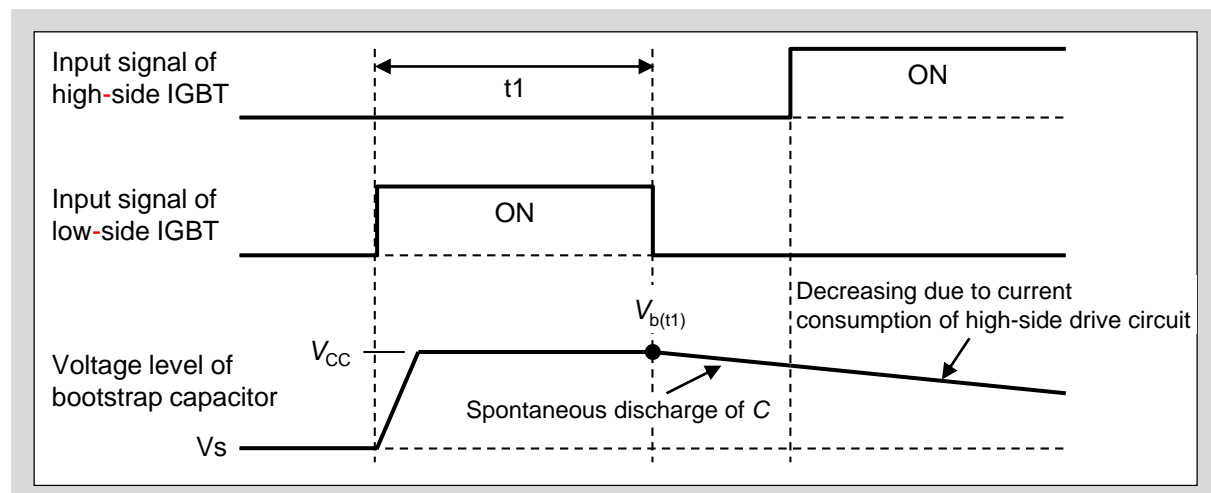Fig.3-8 Circuit diagram of charging operation when the low-side FWD is ON

Fig.3-9 Timing chart of charging operation when the low-side FWD is ON

<Setting the bootstrap capacitance and minimum ON/OFF pulse width>

The parameter of bootstrap capacitor can be calculated by the following equation:

$$C = I_{CCHB} \cdot \frac{t_1}{dV_b}$$

t_1 Maximum ON pulse width of the high-side IGBT

I_{CCHB}:   Drive current of the HVIC (depends on temperature and frequency characteristics)

dV_b: Allowable discharge voltage. (see Fig.3-10)

- A certain margin should be added to the calculated capacitance.
- The bootstrap capacitance is generally selected 2~3 times the value of the calculated result.
- The recommended minimum ON pulse width (t_2) of the low-side IGBT should be determined such that the time constant $C \cdot R$ will enable the discharged voltage (dV) to be fully recharged during the ON period.
- In the operation mode in which the high-side IGBT performs switching operation and charges when the low-side FWD is turned-on (timing chart in Fig. 3-10), the time constant is set so that the power consumed during the ON period of the high-side IGBT can be recharged during the OFF period.
- The minimum pulse width is decided by the minimum ON pulse width of the low-side IGBT or the minimum OFF pulse width of the high-side IGBT, whichever is shorter.

$$t_2 \geq \frac{R \cdot C \cdot dV_b}{V_{CC} - V_{b(min)}}$$

R: Current limiting resistance of Bootstrap diode ΔRF(BSD)

C: Bootstrap capacitance

dV: Allowable discharge voltage.

V_{CC} Control power supply voltage (ex.15V)

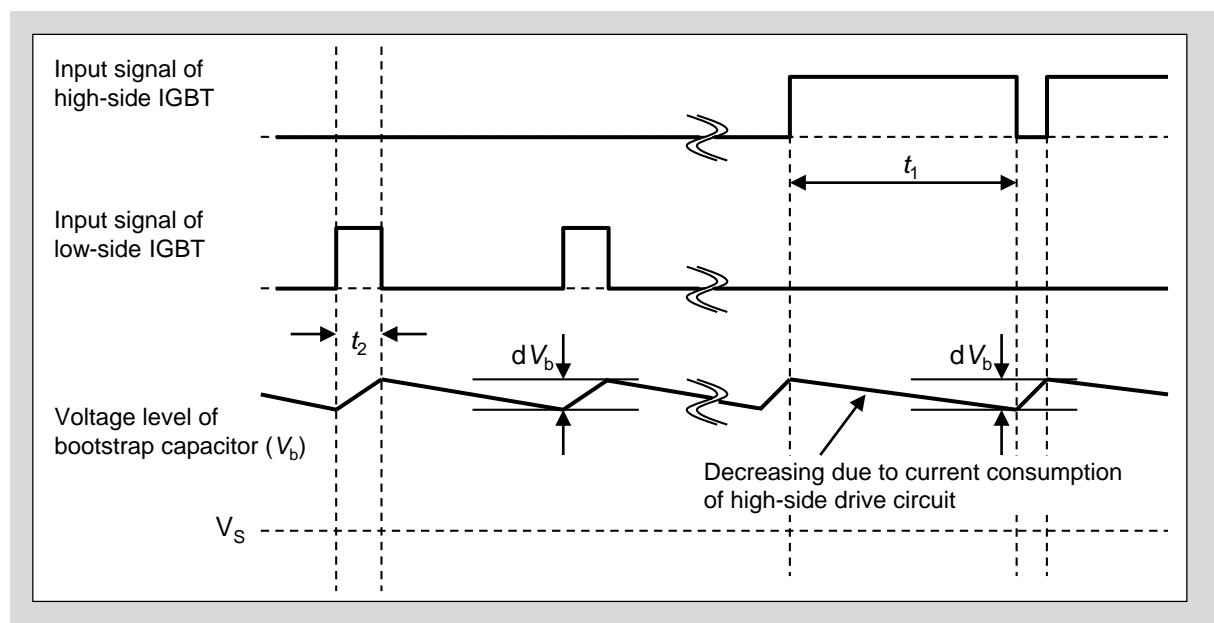$V_{b(min)}$: Minimum voltage of high-side IGBT drive voltage (Added margin to UV. ex. 14V)

Fig.3-10 Timing chart of charging and discharging operation

<Setting the bootstrap capacitance for Initial charging>

- Initial charging of the bootstrap capacitor is required to start the inverter.
- The pulse width or number of pulses should be long enough to fully charge the bootstrap capacitor.
- For reference, the charging time of a 10μF capacitor through the internal bootstrap diode is about 2ms.

Fig.3-11 Circuit diagram of initial charging operation

Fig.3-12 Timing chart of initial charging operation

<Resistance characteristics of built-in BSD>

The BSD forms a current limiting resistance of 100Ω (typ.) inside the chip. Fig. 3-13 and 3-14 show the V_F-I_F characteristics of the BSD.
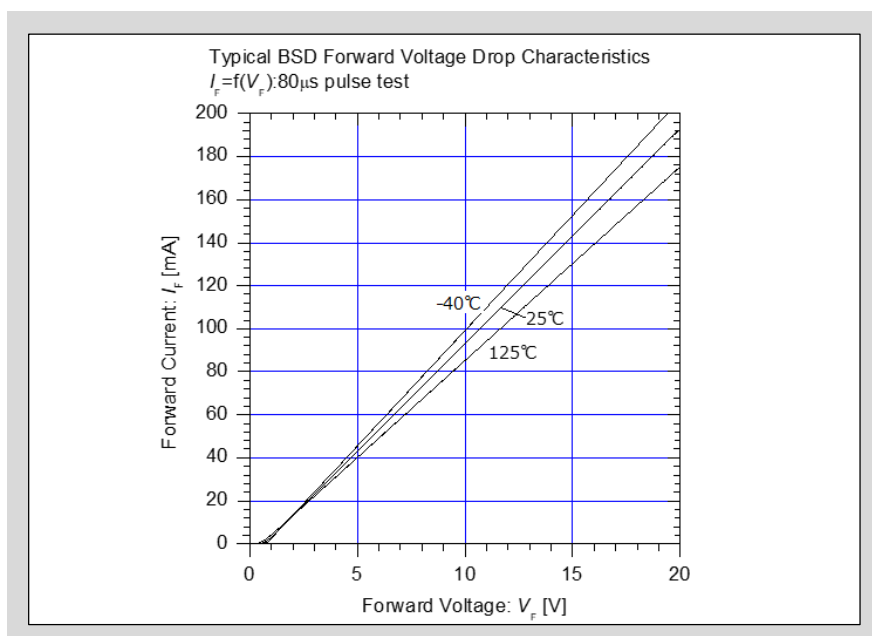
Typical BSD Forward Voltage Drop Characteristics
I_F=f(V_F):80μs pulse test

Fig.3-13 V_F-I_F curve of boot strap diode

Zoom up typical BSD Forward Voltage Drop Characteristics
I_F=f(V_F):80μs pulse test
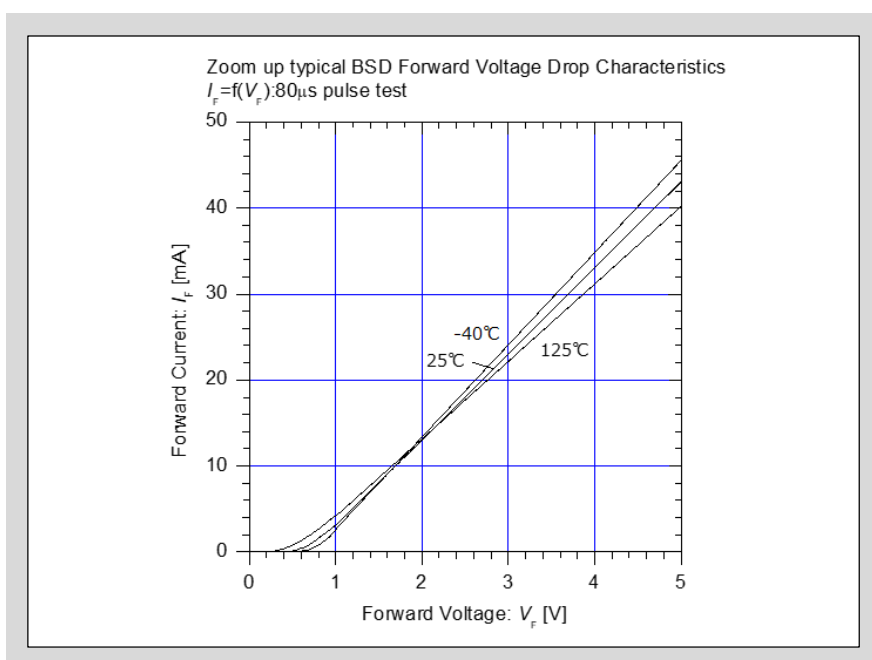
Fig. 3-14 V_F-I_F curve of boot strap diode（Expansion of low current area）

4. Input Terminals IN(HU,HV,HW), IN(LU,LV,LW)

<Input terminals Connection>

- Fig.3-15 shows the input interface circuit between the MPU and the product. The input terminals can be directly connected to the MPU. The input terminals have built-in pull down resistors, thus external pull-down resistors are not required. Also, the input logic is active high, thus external pull-up resistors are not required.
- If the signal wiring is long and noise is superimposed, insert RC filter circuit indicated by the dotted line in Figure 3-15. Adjust the R and C constants according to the PWM control method and wiring pattern of the PCB.
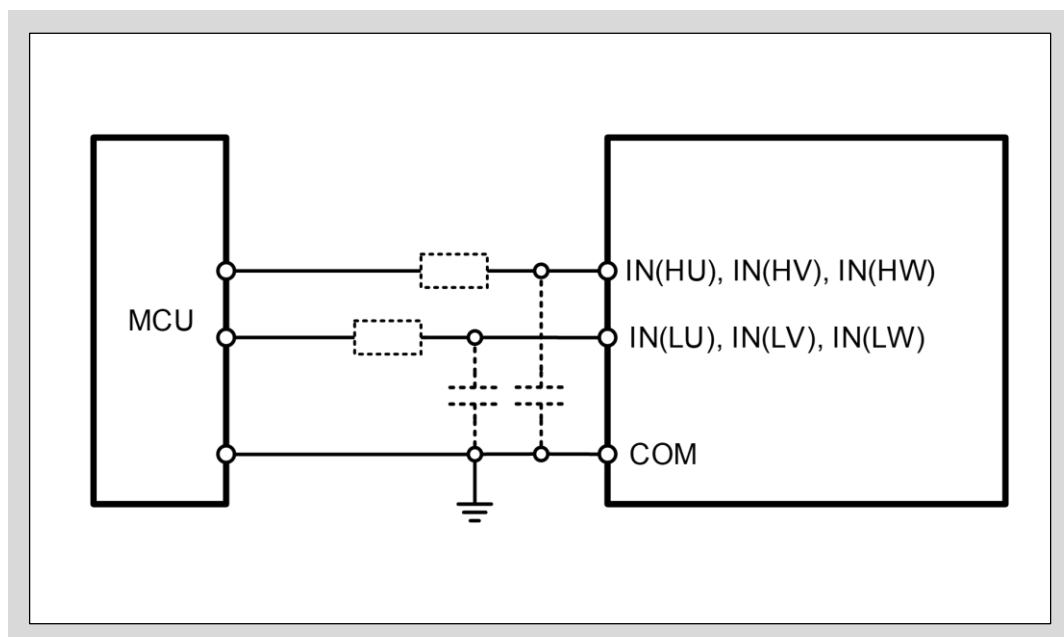

Fig.3-15 Recommended MPU I/O Interface Circuit of IN(HU,HV,HW), IN(LU,LV,LW) terminals

<Input terminal circuit>

- The input logic of this product is active high. This logic has removed the sequence restriction between the control power supply and the input signal during startup or shut down operation. Therefore it makes the system fail safe. In addition, pull-down resistors are built into each input terminals in Fig.3-16. Thus, external pull-down resistors are not needed and reduces the number of system components. Furthermore, by setting the input threshold voltage low,. a 3.3V-class MPU can be connected directly.
- As shown in Fig.3-16, the input circuit integrates a pull-down resistor. Therefore, when using an external filtering resistor between the MPU output and input of the product, please consider the signal voltage drop at the input terminals to satisfy the turn-on threshold voltage requirement. For instance, R=100Ω and C=1000pF for the parts shown by the dotted line in Fig.3-15.
- Fig.3-16 shows that internal diodes are connected to the VCCL-IN(LU, LV, LW) and IN(HU, HV, HW, LU, LV, LW)-COM terminals. Do not use these diodes for voltage clamp purpose otherwise the product might be damaged.
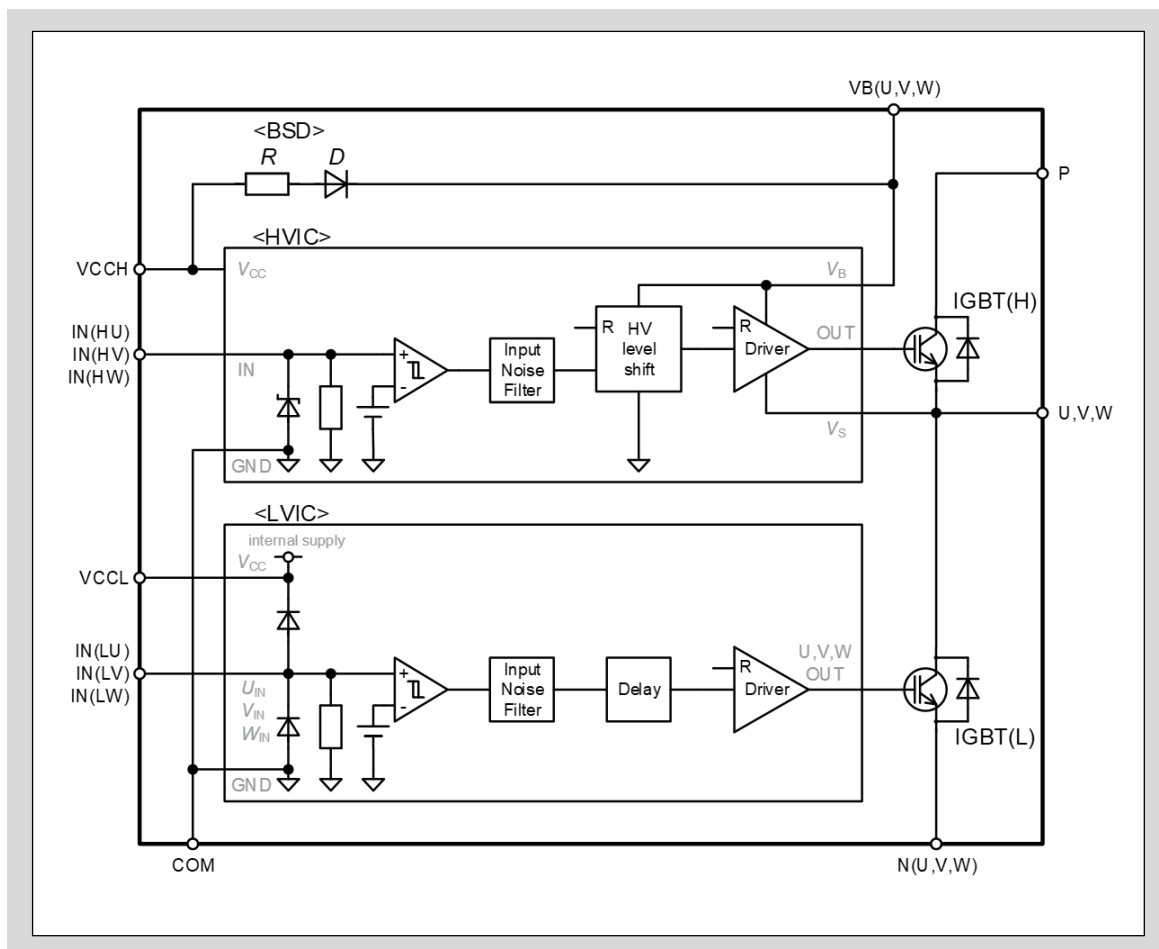

Fig.3-16 Input terminals IN(HU, HV, HW), IN(LU, LV, LW) circuit

<IGBT drive state versus Control signal pulse width>

$t_{IN(ON)}$ is the recommended minimum turn-on pulse width for changing the IGBT state from OFF to ON, and $t_{IN(OFF)}$ is the recommended minimum turn-off pulse width for changing the IGBT state from ON to OFF. Fig.3-17 and Fig.3-18 show the IGBT drive state for various control signal pulse width.

A: IGBT may turn on occasionally, even when the ON pulse width of control signal is less than minimum $t_{IN(ON)}$. Also if the ON pulse width of control signal is less than minimum $t_{IN(ON)}$ and voltage below -5V is applied between U-COM,V-COM,W-COM , it may not turn off due to malfunction of the control circuit.

B: IGBT can turn on operates in the linear region under normal conditions.

C: IGBT may turn off occasionally, even when the OFF pulse width of control signal is less than minimum $t_{IN(OFF)}$. Also if the OFF pulse width of control signal is less than minimum $t_{IN(OFF)}$ and voltage below -5V is applied between U-COM, V-COM, W-COM, it may not turn on due to malfunction of the control circuit.
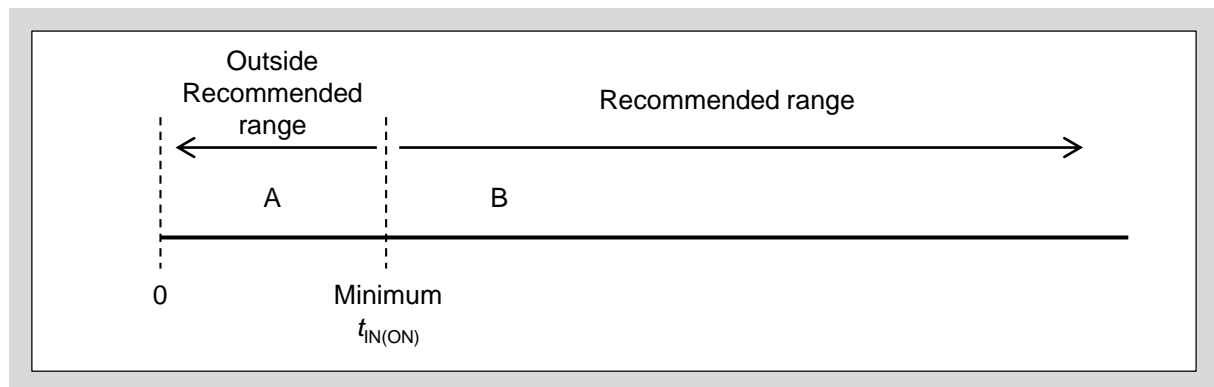
D: IGBT can turn off fully under normal condition.

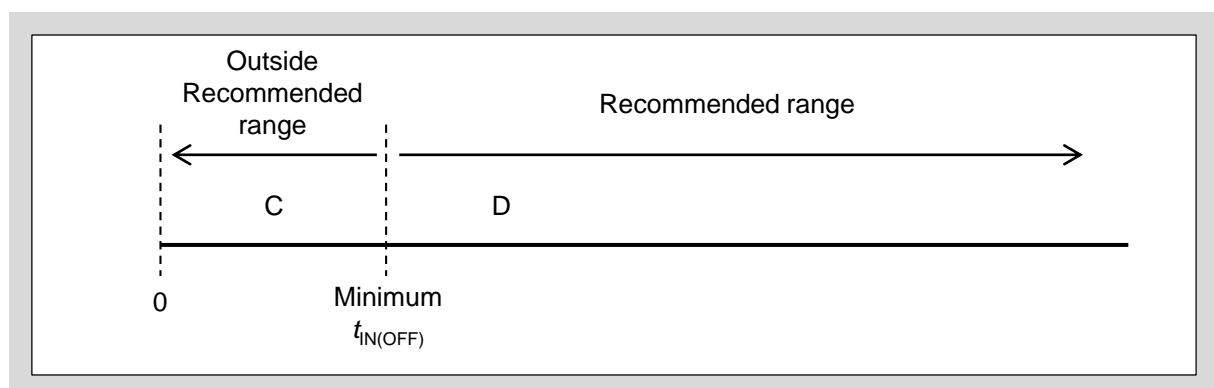Fig.3-17 IGBT drive state versus ON pulse width of input signal

Fig.3-18 IGBT drive state versus OFF pulse width of input signal

5. Over Current Protection Input Terminal IS

- Over current (OC) protection function works by detecting the voltage generated by the external shunt resistor connected between N(U, V, W) and COM at the IS terminal, turn off the IGBTs and output an alarm signal.
- Fig.3-19 shows the over current sensing voltage input IS circuit block, and Fig.3-20 shows the OC operation sequence.
- To prevent the product from unnecessary operations due to normal switching noise or recovery current, it is necessary to apply an external R-C filter (time constant is approximately 0.7µs) to the IS terminal. The shunt resistor should be connected to the product as close as possible.
- Fig.3-19 shows that the diodes in the product are connected to the VCCL-IS and IS-COM terminals. Do not use these diodes for voltage clamp purpose otherwise the product might be damaged.
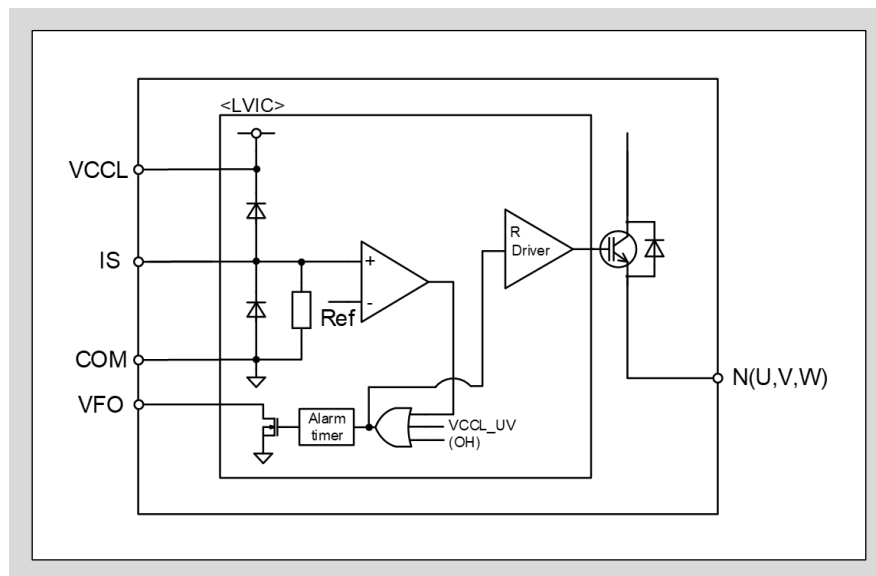

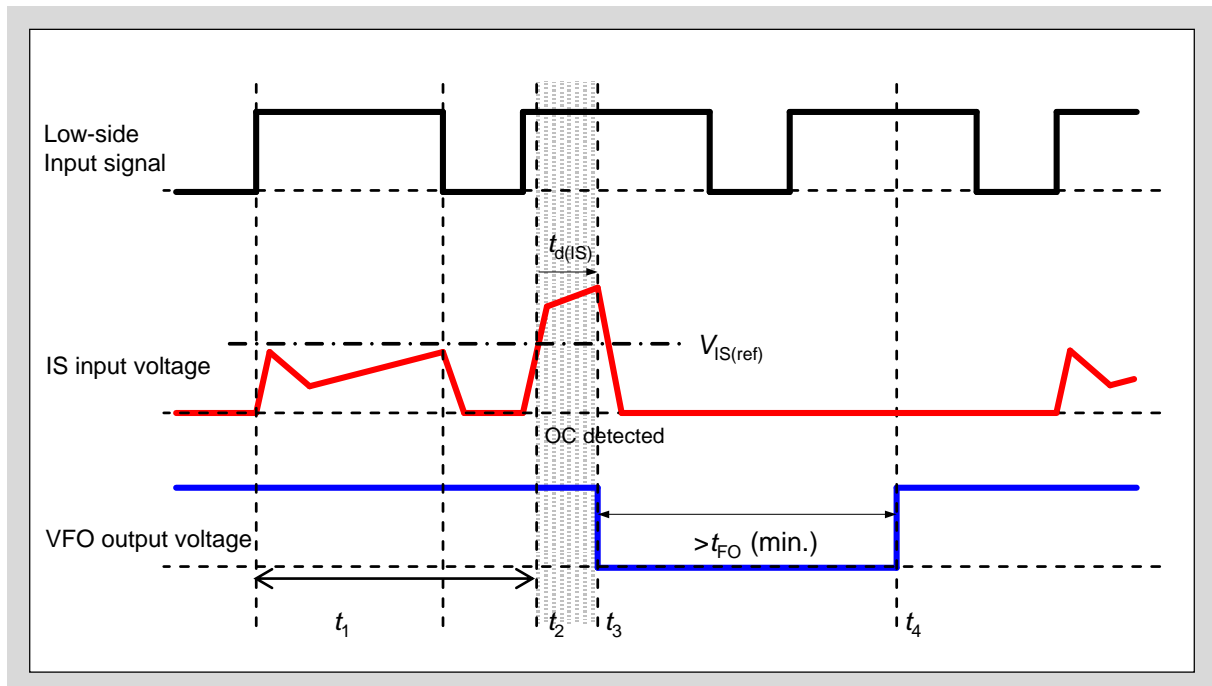Fig.3-19 Over current sensing voltage input IS circuit

Fig.3-20 Operation sequence of Over Current protection

<t1>: IS input voltage does not exceed $V_{IS(ref)}$, while the collector current of the low-side IGBT is under the normal operation.

t2: When IS input voltage exceeds $V_{IS(ref)}$, the OC is detected.

t3: The fault output V_{FO} is activated and all low-side IGBT shut down simultaneously after the over current protection delay time $t_{d(IS)}$. Inherently there is dead time of LVIC in $t_{d(IS)}$.

t4: After the fault output pulse width t_{FO}, the OC is reset. Then next input signal is activated.

6. Fault Status Output Terminal VFO

- As shown in Fig.3-21, it is possible to connect the fault status output VFO terminal directly to the MPU. VFO terminal is open drain configured, thus this terminal should be pulled up by a resistor of approximate 10kΩ to the positive side of the 5V or 3.3V external logic power supply. It is also recommended that the bypass capacitor C1 and the inrush current limitation resistor R1 above 5kΩ, should be connected between the MPU and the VFO terminal. These signal lines should be wired as short as possible.
- Fault status output VFO function is activated by the UV of VCCL, OC and OH. (OH protection function is applied to "6MBP**XSK065-50".)
- Fig.3-21 shows that the diodes in the IPM are electrically connected to the VCCL-VFO and VCCL-COM terminals. Do not use these diodes for voltage clamp purpose otherwise the product might be damaged.
- Fig.3-22 shows the Voltage-current characteristics of VFO terminal at fault state condition. The I_{FO} is the sink current of the VFO terminal as shown in Fig.3-21.

Fig.3-21 Recommended MPU I/O Interface Circuit of VFO terminal

Fig.3-22 Voltage-current Characteristics of VFO terminal at the fault state condition

7. Temperature Sensor Output Terminal TEMP

- As shown in Fig. 3-23, the temperature sensor output TEMP can be connected to MPU directly.
- It is recommended that a by-pass capacitor C_{TEMP} and inrush current limiting resistor R_{TEMP} above 10kΩ is connected between the TEMP terminal and the MPU. These signal lines should be wired as short as possible to each device.
- The product has a built-in temperature sensor, and it can output an analog voltage according to the LVIC temperature. This function doesn't protect the product, and there is no fault signal output.
- "6MBP**XSK065-50" has built-in overheating protection. If the temperature exceeds TOH, fault signal will output due to the overheating protection function.
- Since the position of the IGBT chip and the position of the temperature sensor are different, it is not possible to respond to sudden rise in T_{vj} such as during motor lock and short circuit (see Fig. 2-2).
- A diode is electrically connected between TEMP-COM terminal as shown in Fig. 3-12. The diode protect the product from input surge voltage. Do not use the diode for voltage clamp purpose otherwise the product might be damaged.
- Fig.3-24 shows the LVIC temperature versus TEMP output voltage characteristics. A Zener diode should be connected to the TEMP terminal when the power supply of MPU is 3.3V. The output voltage shows clamp characteristic at below room temperature. Connect a 22kΩ±10% pull-down resistor to the TEMP terminal if linear characteristic is required.
- Fig. 3-25 shows the LVIC temperature versus TEMP output voltage characteristics with 22kΩ pull-down resistor $R_{pulldown}$.
- Fig.3-26 shows the operation sequence of TEMP terminal at during the LVIC startup and shut down conditions.
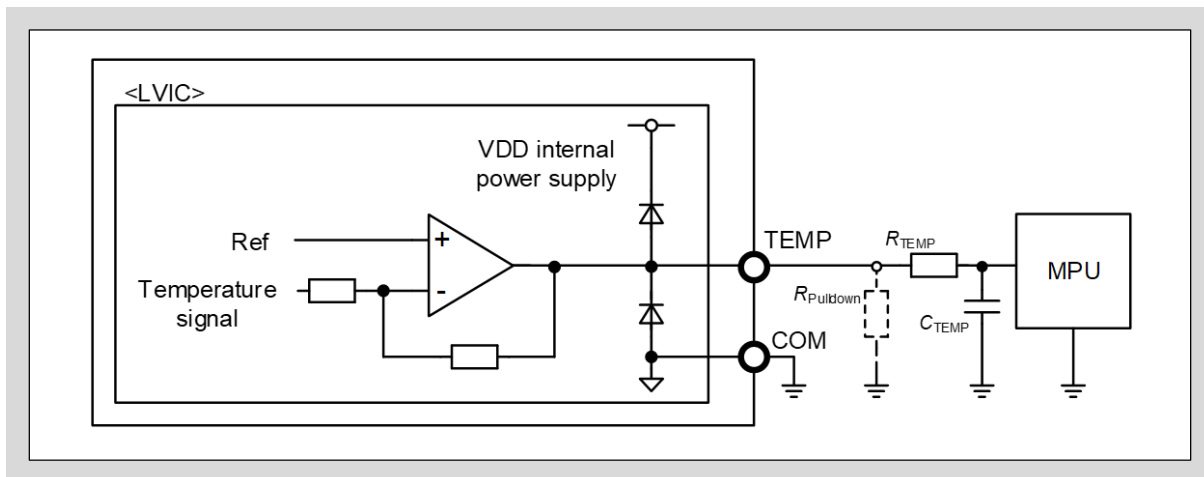

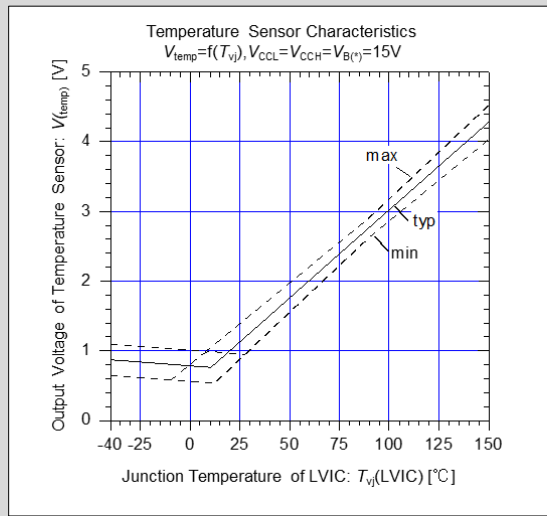Fig.3-23 Recommended MPU I/O Interface Circuit of TEMP terminal

Fig.3-24 LVIC temperature vs. TEMP output
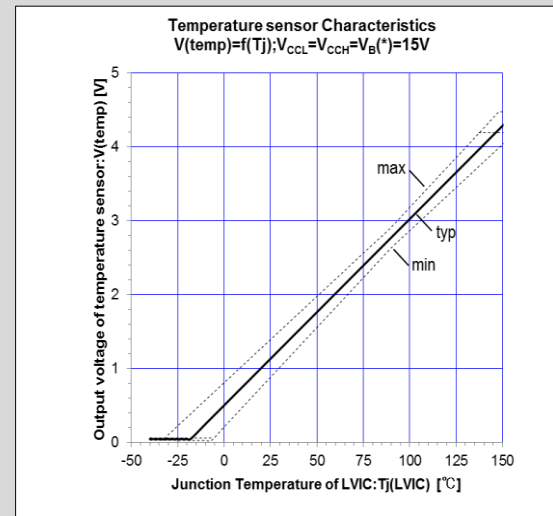voltage characteristics
without pull-down resistor

Fig.3-25 LVIC temperature vs. TEMP output
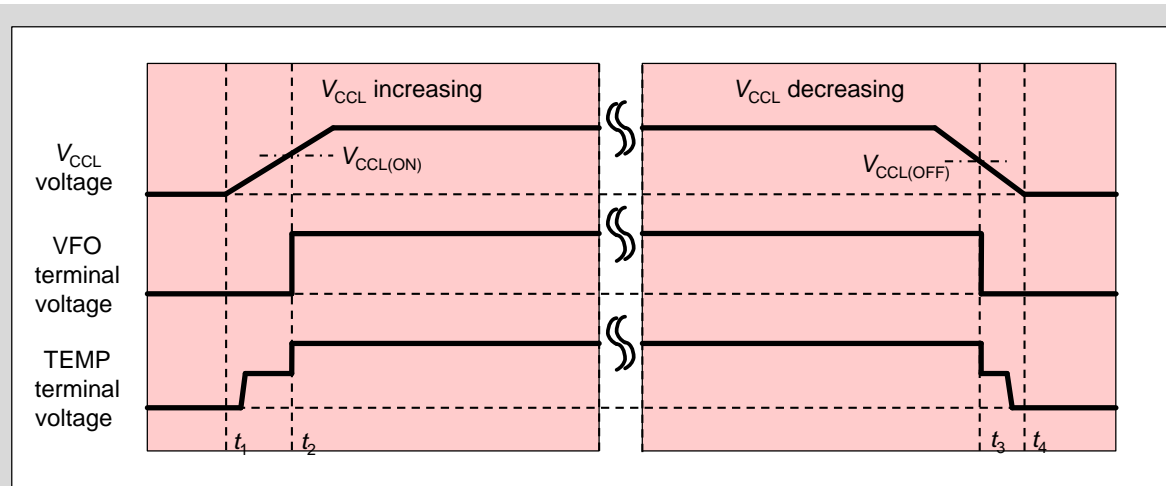voltage characteristics
with 22kΩ pull-down resistor

Fig.3-26 Operation sequence of TEMP terminal during LVIC startup and shut down conditions

t_1-t_2 : TEMP function is activated when V_{CCL} exceeds $V_{CCL(ON)}$. If V_{CCL} is lower than $V_{CCL(ON)}$, the TEMP terminal voltage is the same as the clamp voltage.

t_2-t_3 : TEMP terminal voltage rises to the voltage determined by LVIC temperature. In the case that the temperature is under clamping condition, the TEMP terminal voltage is the clamp voltage even though V_{CCL} is above $V_{CCL(ON)}$.

t_3-t_4 : TEMP function is reset when V_{CCL} falls below $V_{CCL(OFF)}$. TEMP terminal voltage is the same as the clamp voltage.

8. Overheating protection

- The Overheating (OH) protection functions is integrated into "6MBP**XSK065-50".
- The OH function monitors the LVIC junction temperature. Since the position of the IGBT chip and the position of the temperature sensor are different, it is not possible to respond to sudden rise in T_{vj} such as during motor lock and short circuit (see Fig. 2-2).
- The T_{OH} sensor position is shown in Fig.2-2.
- As shown in Fig.3-27, the product shuts down all low side IGBTs when the LVIC temperature exceeds T_{OH}. The fault status is reset when the LVIC temperature drops below $T_{OH} - T_{OH(hys)}$.
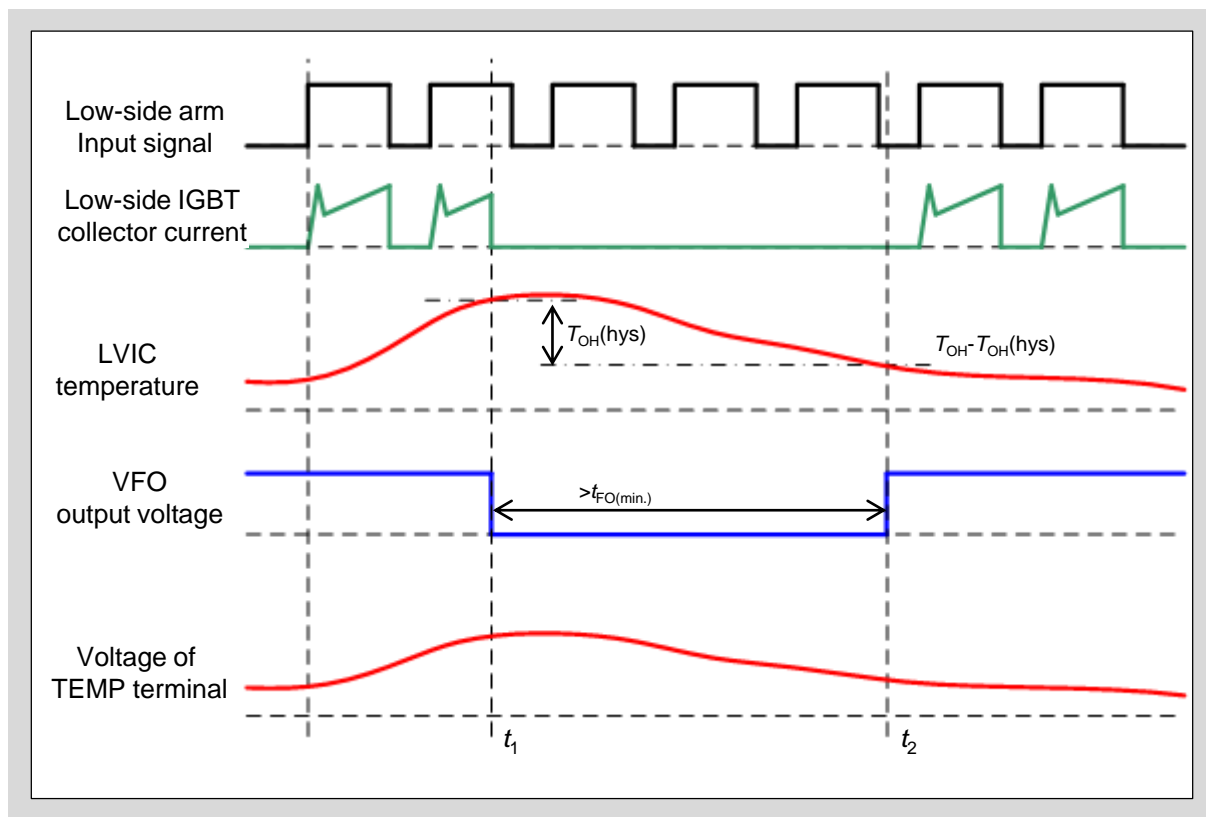

Fig.3-27 Operation sequence of the over heating operation

t_1 : The fault status is activated and all IGBTs of the low-side arm shut down, when LVIC temperature exceeds T_{OH}.

t_2 : When LVIC temperature falls below $T_{OH} - T_{OH(hys)}$, the fault status is reset after t_{FO} and next input signal is activated. $T_{OH(hys)}$ is the over heating protection hysteresis