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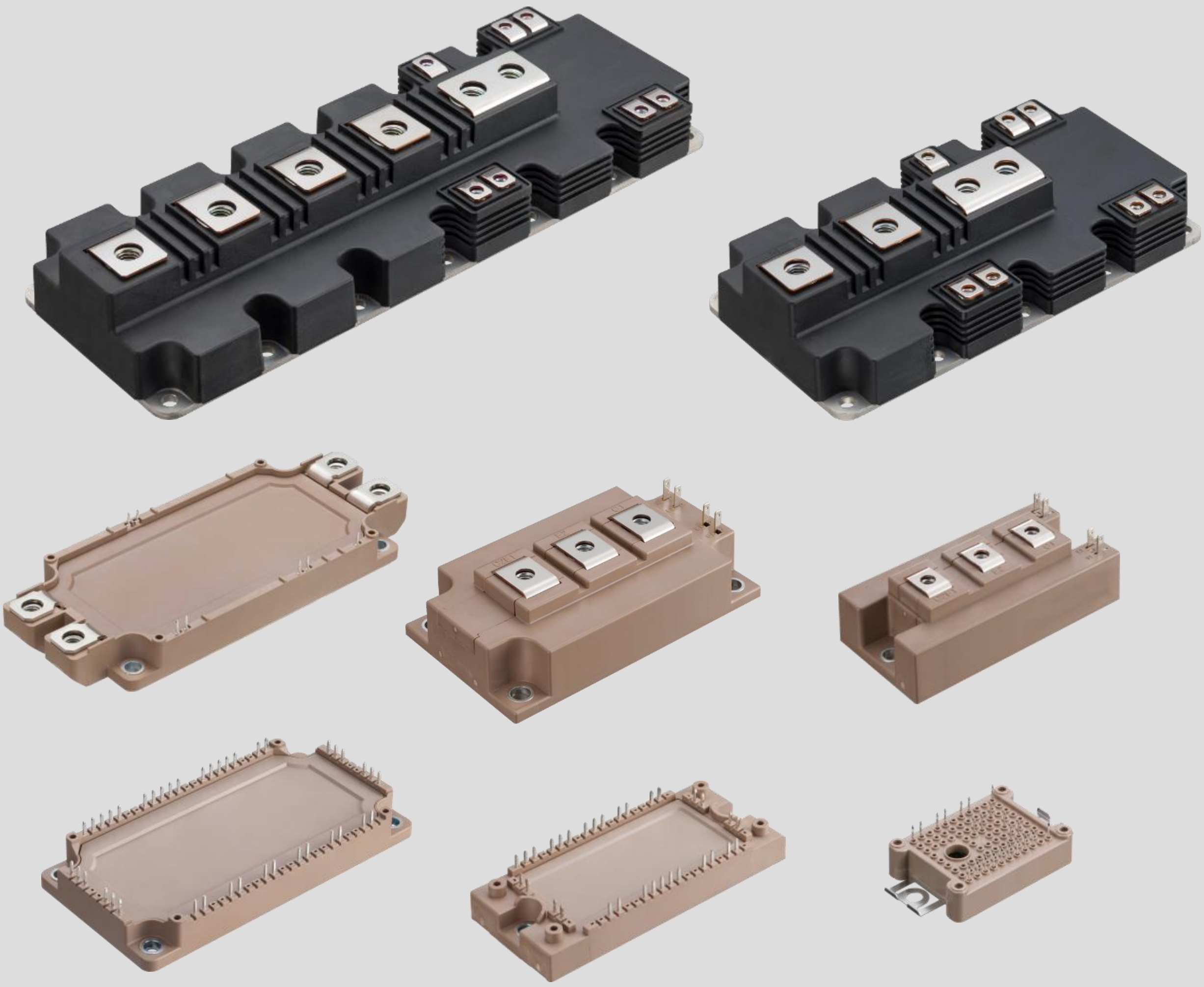

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co., Ltd.

⚠ Cautions

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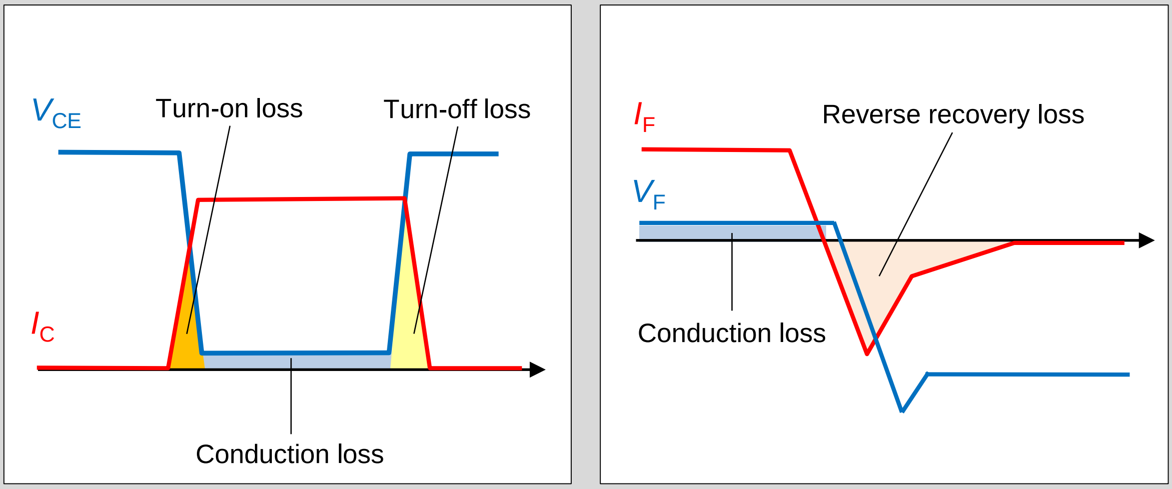
Chapter 6 Cooling Design

1. Power Loss of IGBT Module

The IGBT module consists of IGBT and FWD, and the sum of power loss of each chip is the total power loss of the IGBT module. As shown in Fig. 6-1, the power loss include conduction loss and switching loss. The types of power loss is summarized in Fig. 6-2.



(a) IGBT loss (b) FWD loss

Fig. 6-1 Switching waveform and power loss of IGBT and FWD

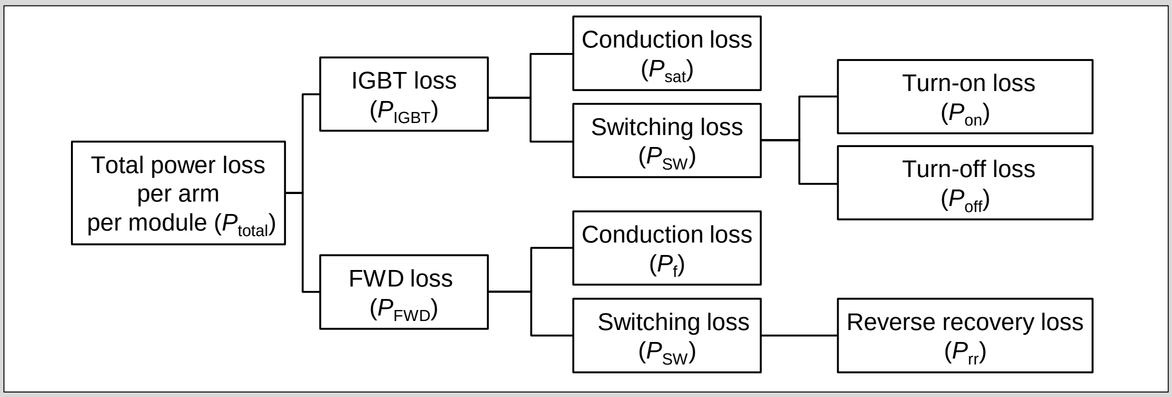


Fig. 6-2 Classification of IGBT module power loss

For RC-IGBT, although the RC-IGBT combines IGBT and FWD in one chip, by considering the power loss generated at IGBT part and FWD part, the concept of power loss is the same as that of a normal IGBT module. For RB-IGBT, although the RB-IGBT does not have FWD part, there are cases where RB-IGBT is operated as FWD, which causes P_{sat} and P_{rr}.

The conduction loss of the IGBT part is calculated from the $V_{CE(sat)}$ -I_C characteristic, and the conduction loss of the FWD part is calculated from the V_F-I_F characteristic shown in the datasheet. In addition, each switching loss is calculated from the E_{on}-I_C, E_{off}-I_C, E_{rr}-I_F characteristics. Heat dissipation design is performed based on these power loss so that the T_{vj} of the IGBT and FWD do not exceed the temperature rating. Therefore, calculate the power loss using the data when T_{vj} is high.

2. Power Loss Calculation Method of Boost Chopper Circuit

In the case of a boost chopper circuit as shown in Fig. 6-3, if the current flowing through the IGBT (T_1) and FWD (D_1) is considered to be a continuous rectangular waveform, the power loss per unit time of T_1 and D_1 (unit: W) can be approximated by the following formulas.

P_{IGBT} = Conduction loss + Turn-on loss + Turn-off loss

$$= V_{CE(sat)} \cdot I_C \cdot d + (E_{on} + E_{off}) \cdot f_C \cdot \left(\frac{V_{cc}}{V_{cc0}}\right)^{\alpha} \quad \text{.........(1)}$$

P_{FWD} = Conduction loss + Reverse recovery loss

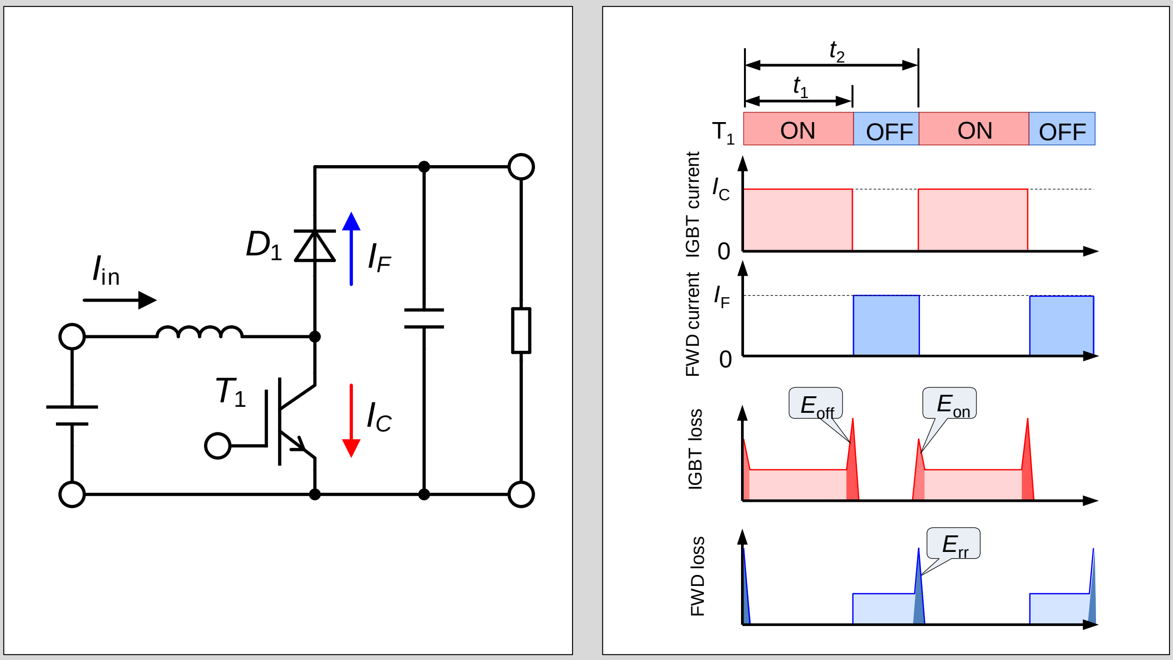
$$= V_F \cdot I_F \cdot (1 - d) + E_{rr} \cdot f_C \cdot \left(\frac{V_{CC}}{V_{CC0}}\right)^{\alpha} \quad \text{.........(2)}$$

where

d	:IGBT ON duty= t_1 / t_2
f_c	:Switching frequency = 1 / t_2
V_{CC}	:Switching voltage
V_{CC0}	:Switching voltage of switching loss data in datasheet
α	:Coefficient of switching voltage dependence to switching energy

If we consider the switching energy to be proportional to the switching voltage, then we can set α=1.

On the other hand, the values of $V_{CE(sat)}$, V_F, E_{on}, E_{off}, and E_{rr} depend on the junction temperature T_{vj} of the device. Thus, if the T_{vj} is different from the T_{vj} described in the datasheet, refer to the T_{vj} dependency graphs in the datasheet for conversion. The values of E_{on}, E_{off}, and E_{rr} also depend on the gate resistance value R_G, so refer to the R_G dependency graph in the datasheet for conversion.



(a) Boost chopper circuit (b) Waveforms, power loss of boost chopper circuit

Fig. 6-3 Power loss in boost chopper circuit

3. Power Loss Calculation Method of 3-phase 2-level PWM Inverter Circuit

As shown in Fig. 6-4, the current values of the IGBT and FWD in a 3-phase 2-level PWM inverter are constantly changing. Thus, an accurate calculation of the power loss requires complex calculations. Here, we introduce a simple method for calculating the power loss of the IGBT and FWD in an inverter circuit using the characteristic curve approximation formula of the IGBT module.

The following conditions are assumed for the calculation.

- The inverter is a PWM controlled 3-phase 2-level inverter
- PWM is triangle wave comparison sinusoidal modulation method
- The output current should be an ideal sine wave

Assuming that the RMS value of the output phase current of the inverter is I_o, the current waveform of the sine wave is expressed by the following formula.

$$i_O(\theta) = \sqrt{2} \cdot I_O \cdot \sin\theta \qquad \text{(3)}$$

The on-duty waveform $d(\theta)$ of the IGBT is expressed by the following formula, where m is the modulation factor and φ is the delay power factor of the current.

$$d(\theta) = \frac{1 + m \cdot \sin(\theta + \varphi)}{2} \qquad \text{(4)}$$

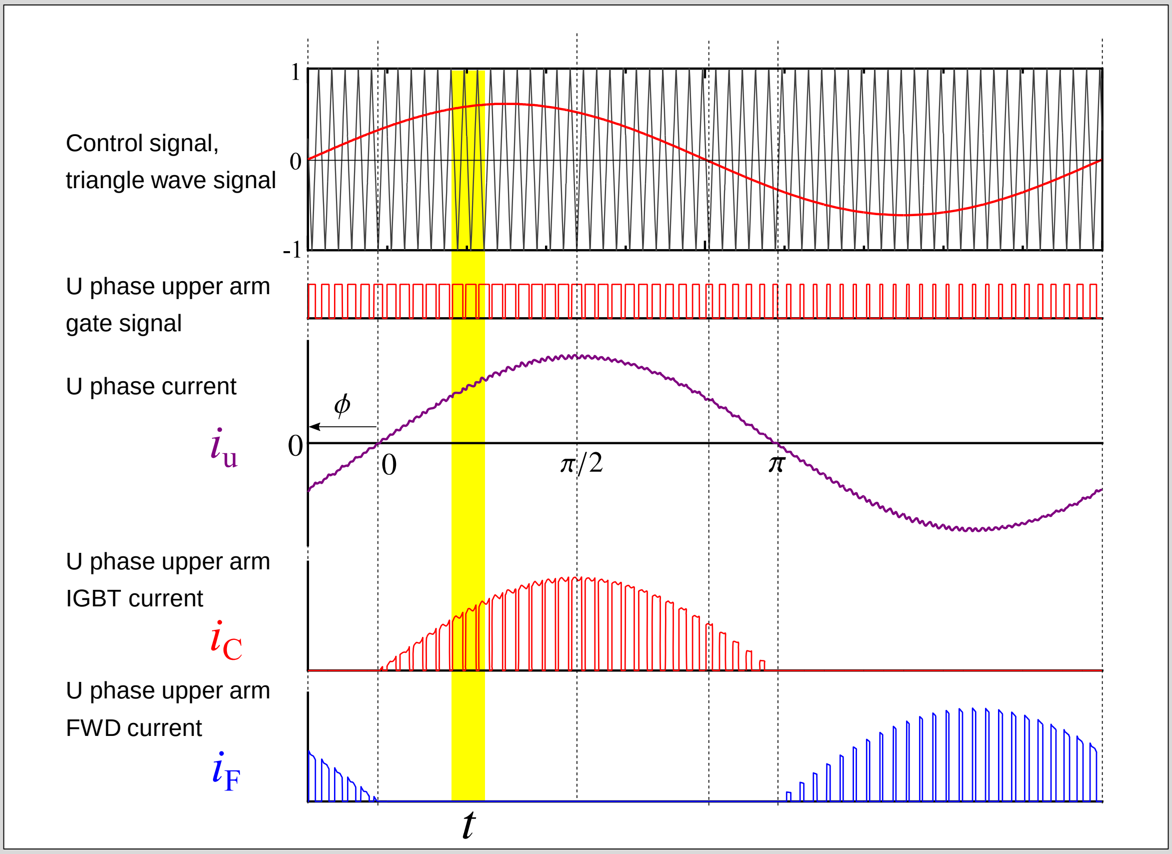


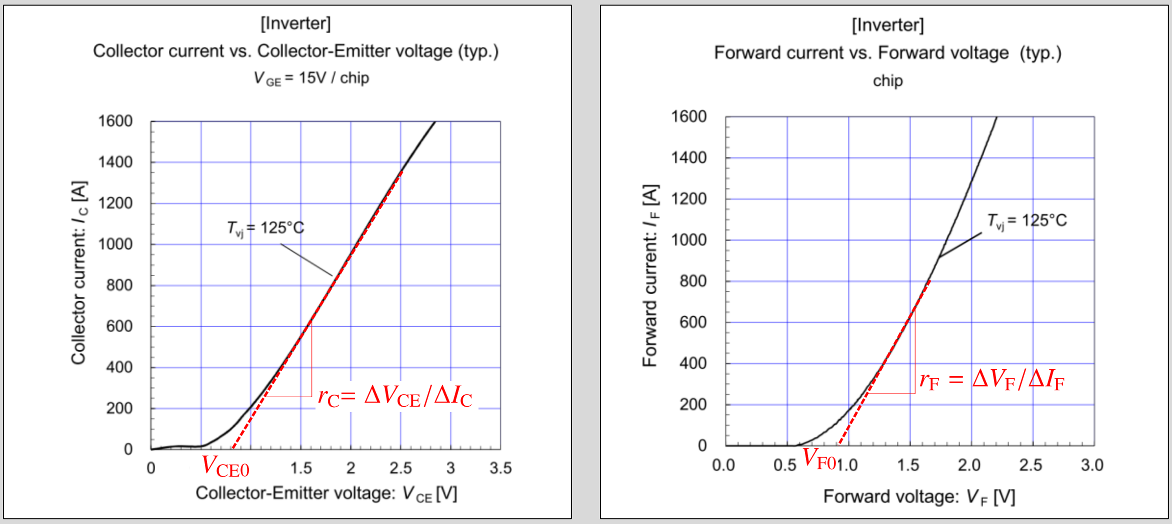
Fig. 6-4 Operating waveform of a 3-phase 2-level PWM inverter

When I_C flows through the IGBT, Collector-Emitter saturation voltage $V_{CE(sat)}$ is generated. $V_{CE(sat)}$ value depends on I_C, and the $V_{CE(sat)}$- I_C graph is shown in the datasheet. In order to calculate the conduction loss of the IGBT, the I_C dependence of $V_{CE(sat)}$ is linearly approximated as shown in Fig. 6-5, and is expressed by the following formula.

$$V_{CEsat} = r_C \cdot I_C + V_{CEO} \qquad \text{(5)}$$

Similarly, the I_F dependence of FWD forward voltage V_F is expressed by the following formula when linearly approximated.

$$V_F = r_F \cdot I_F + V_{FO} \qquad \text{(6)}$$



(a) IGBT output characteristics (b) FWD output characteristics

Fig. 6-5 Linear approximation of output characteristics

From formula (3), (4) and (5), the IGBT conduction loss P_{sat} per arm is calculated as follows.

$$P_{sat} = \frac{1}{2\pi}\int_0^{\pi}\{i_O(\theta)\cdot V_{CEsat}(\theta)\cdot d(\theta)\}d\theta$$
$$= 2I_O^2 \cdot rc\left(\frac{1}{8}+\frac{m}{3\pi}\cos\varphi\right)+\sqrt{2}\cdot I_O\cdot V_{CEO}\left(\frac{1}{2\pi}+\frac{m}{8}\cos\varphi\right) \qquad \text{(7)}$$

Similarly, the FWD conduction loss P_f per arm is calculated as follows.

$$P_f = \frac{1}{2\pi}\int_{\pi}^{2\pi}\{-i_O(\theta)\cdot V_F(\theta)\cdot d(\theta)\}\,d\theta$$
$$= 2I_O^2 \cdot r_F\left(\frac{1}{8}-\frac{m}{3\pi}\cos\varphi\right)+\sqrt{2}\cdot I_O\cdot V_{FO}\left(\frac{1}{2\pi}-\frac{m}{8}\cos\varphi\right) \qquad \text{(8)}$$

Next, in order to calculate the switching loss, the approximate expression of the I_C dependence graph of E_{on}, E_{off}, and E_{rr} described in the datasheet are obtained. As shown in Fig. 6-6, if the I_C dependence curve of the switching energy is linearly approximated, and the coefficient of switching voltage dependence is set as α = 1, E_{on}, E_{off}, and E_{rr} can be expressed by the following formulas, respectively.

$$E_{on}(I_C) = k_{on} \cdot I_C \cdot \left(\frac{V_{CC}}{V_{CC0}}\right) \quad \text{.........(9)}$$

$$E_{off}(I_C) = k_{off} \cdot I_C \cdot \left(\frac{V_{CC}}{V_{CC0}}\right) \quad \text{.........(10)}$$

$$E_{rr}(I_F) = k_{rr} \cdot I_F \cdot \left(\frac{V_{CC}}{V_{CC0}}\right) \quad \text{.........(11)}$$

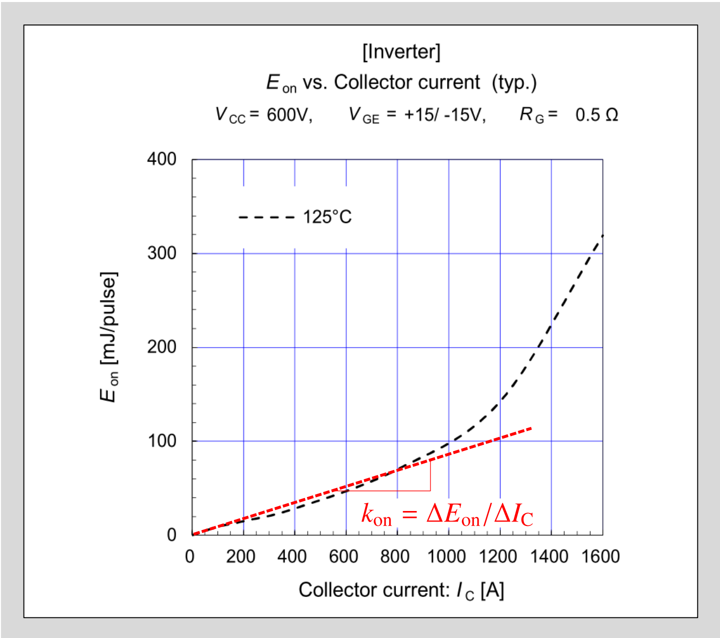


Fig. 6-6 Approximation of I_C dependence of switching energy

Using formula (9), the IGBT turn-on loss P_{on} per arm can be calculated by the following formula.

$$P_{on} = \frac{1}{2\pi}\int_0^{\pi}\left\{k_{on}(\sqrt{2}\cdot I_o \cdot \sin\theta)\cdot\frac{V_{CC}}{V_{CC0}}\cdot f_{SW}\right\}d\theta$$

$$= \frac{\sqrt{2}}{\pi}k_{on}\cdot I_O\cdot\frac{V_{CC}}{V_{CC0}}\cdot f_{SW} \qquad \text{(12)}$$

Similarly, the IGBT turn-off loss P_{off} and the FWD reverse recovery loss P_{rr} can be calculated by the following formulas, respectively.

$$P_{off} = \frac{\sqrt{2}}{\pi}\cdot k_{off}\cdot I_O\cdot\frac{V_{CC}}{V_{CC0}}\cdot f_{SW} \qquad \text{(13)}$$

$$P_{rr} = \frac{\sqrt{2}}{\pi}\cdot k_{rr}\cdot I_O\cdot\frac{V_{CC}}{V_{CC0}}\cdot f_{SW} \qquad \text{(14)}$$

From the above calculation, the IGBT power loss P_{IGBT} and the FWD power loss P_{FWD} per arm can be calculated as follows, respectively.

$$P_{IGBT} = P_{sat} + P_{on} + P_{off} \qquad \text{(15)}$$

$$P_{FWD} = P_f + P_{rr} \qquad \text{(16)}$$

As mentioned, since the values of $V_{CE(sat)}$, V_F, E_{on}, E_{off}, and E_{rr} change depending on T_{vj} and R_G, refer to the T_{vj} and R_G dependency graphs in the datasheet for conversion when calculating.

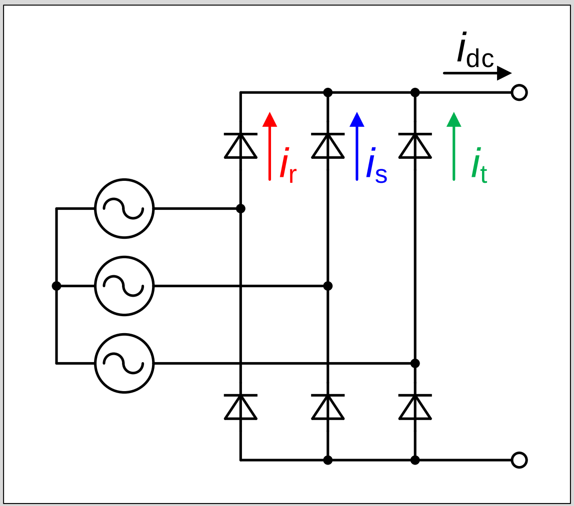
In addition, the FUJI IGBT Simulator performs calculation by approximating the characteristic curves of the data sheet more accurately, and the calculation is performed in consideration of T_{vj} dependence. Therefore, please note that the simulator result may not match the value calculated from the above formula.

* Fuji IGBT Simulator：https://www.fujielectric.com/products/semiconductor/model/igbt/simulation/

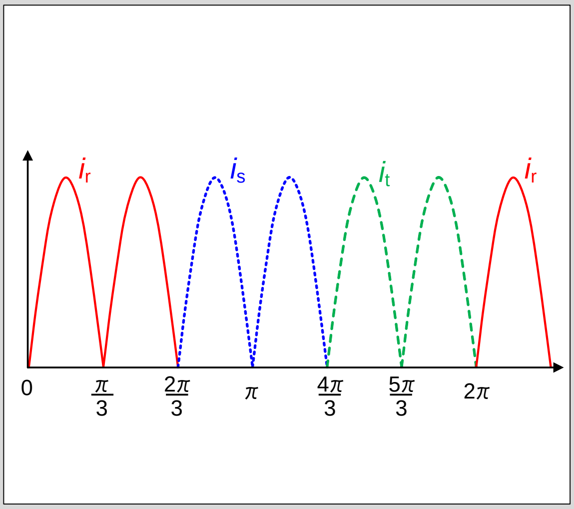
4. Power Loss Calculation Method of 3-phase Diode Rectifier Circuit

Since the diode used in the rectifier circuit does not have reverse recovery operation, there is no need to consider switching loss. Therefore, it is only necessary to calculate the conduction loss of the diode.

Fig. 6-7 shows the current waveform of a 3-phase diode rectifier circuit. Although the diode current waveform changes depending on the circuit conditions, here the calculation is performed assuming the diode current as a continuous half sine wave.



(a) 3-phase diode rectifier circuit



(b) Current waveform of 3-phase diode rectifier

Fig. 6-7 3-phase diode rectifier circuit and current waveform

Assuming the RMS value of the rectified current I_{dc} shown in Fig. 6-7 as I_d, and the output characteristics of the diode is expressed by the linear approximation formula (3), the loss per diode P_{di} can be calculated by the following formula.

$$P_{di} = \frac{1}{2\pi} \cdot 2 \int_0^{\frac{\pi}{3}} \{r_F \cdot i_F(\theta) + V_{FO}\} \cdot i_F(\theta) d\theta$$

$$= \frac{1}{2\pi} \cdot 2 \int_0^{\frac{\pi}{3}} \{r_F \cdot \sqrt{2} I_d \sin(3\theta) + V_{FO}\} \cdot \{\sqrt{2} I_d \sin(3\theta)\} d\theta$$

$$= \frac{2\sqrt{2}}{3\pi} \cdot V_{FO} \cdot I_d + \frac{1}{3} r_F \cdot I_d^2$$

5. Selecting Heatsink

Most power modules such as power diodes, IGBTs, transistors are designed with insulation between the electrodes and mounting bases, thus multiple modules can be mounted on a single heat sink, resulting in easy mounting and compact wiring. However, in order to ensure safe operation, the power loss (heat) generated by each module must be dissipated efficiently, and the heat sink selection is very important. The basic concept of heat sink selection is explained in this section.

5.1 Thermal equations for steady-state

The heat conduction in semiconductors can be calculated with a thermal resistance equivalent circuit. As example, with only one IGBT module mounted on the heat sink, the equivalent circuit is shown in Fig. 6-8.

From this equivalent circuit, the T_{vj} can be calculated by the following thermal equation.

$$T_{vj} = W \cdot \{R_{th(j-c)} + R_{th(C-f)} + R_{th(f-a)}\} + T_a$$

Note that the case temperature T_c and the heat sink temperature T_f represent the temperatures at the positions directly below the chip as shown in Fig. 6-15. As shown in Fig. 6-9, temperatures at different points (B,C) are lower and depend on the heat dissipation capability of the heat sink, thus care must be taken during design.

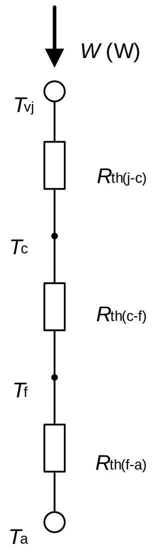
Fig. 6-10 shows the equivalent circuit in which an IGBT module (2-Pack) and a diode bridge module are mounted on a heat sink. The thermal equations in this case are as follows.

$$T_{vj(d)} = W_d \cdot [R_{th(j-c)d} + R_{th(c-f)d}] + [(W_d + 2W_T + 2W_D) \cdot R_{th(f-a)}] + T_a$$

$$T_{vj(T)} = W_T \cdot R_{th(j-c)T} + [(W_T + W_D) \cdot R_{th(c-f)T}] + [(W_d + 2W_T + 2W_D) \cdot R_{th(f-a)}] + T_a$$

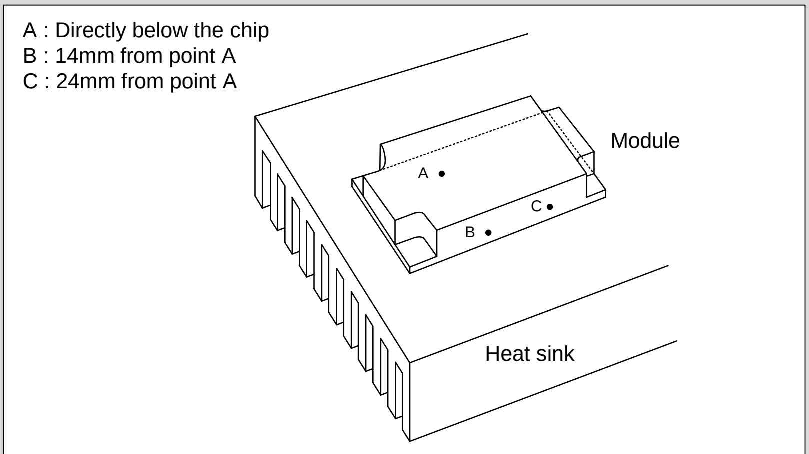
$$T_{vj(D)} = W_D \cdot R_{th(j-c)D} + [(W_T + W_D) \cdot R_{th(c-f)T}] + [(W_d + 2W_T + 2W_D) \cdot R_{th(f-a)}] + T_a$$

Use the above equations to select a heat sink that can keep the T_{vj} below $T_{vj(max)}$.



W	:Power loss
T_{vj}	:Chip virtual junction temperature
T_C	:Case temperature
T_f	:Heat sink surface temperature
T_a	:Ambient temperature
$R_{th(j-c)}$	:Thermal resistance between junction and case
$R_{th(c-f)}$	:Thermal resistance between case and heatsink
$R_{th(f-a)}$	:Thermal resistance between heatsink and ambient

Fig. 6-8 Thermal resistance equivalent circuit



	Point A	Point B	Point C
T_C [°C]	51.9	40.2	31.4
T_f [°C]	45.4	36.9	30.2

Fig. 6-9 Example of case and heatsink temperature measurement

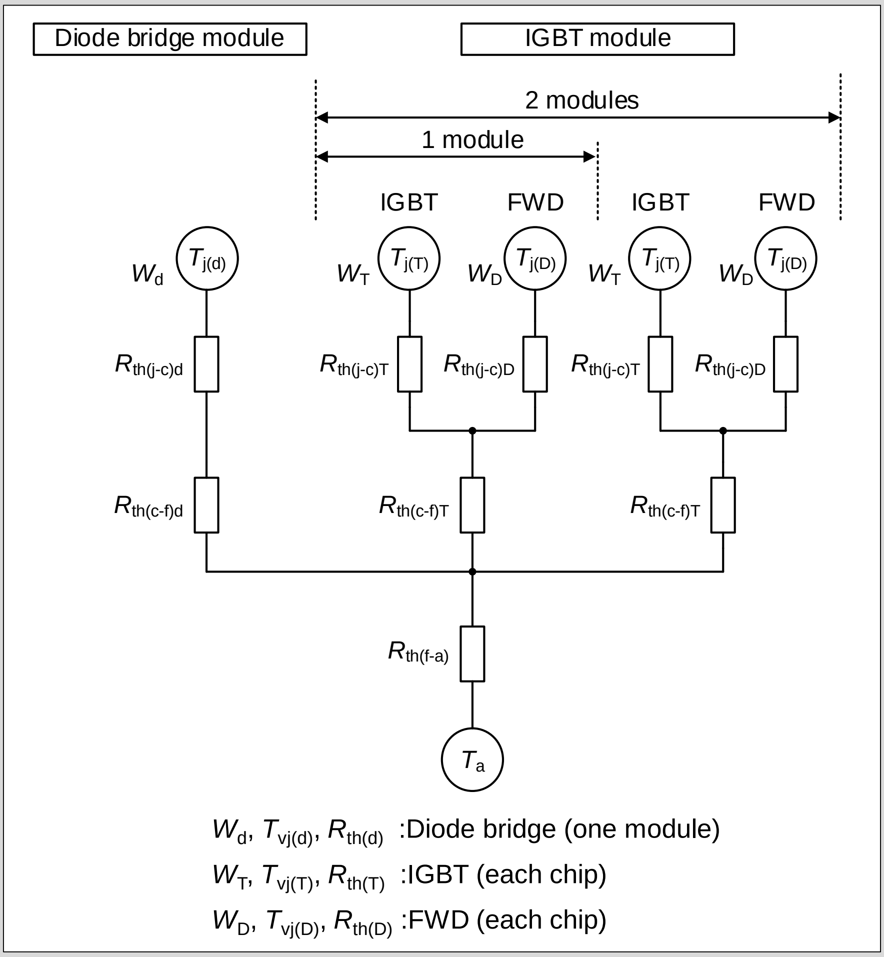


Fig. 6-10 Thermal resistance equivalent circuit

5.2 Thermal equations for transient state

In general, it is sufficient to consider the steady-state T_{vj} from the average power loss. However, in reality, repetitive switching operation generates power loss in pulse and cause temperature ripples as shown in Fig. 6-12. In this case, if the power loss is considered as a continuous rectangular wave with constant period and constant peak value, the peak value of the temperature ripples T_{vjp} can be approximated with the following formula using the transient thermal resistance curve described in the datasheet (Fig. 6-11).

Select a heat sink by confirming that T_{vjp} does not exceed $T_{vj\ (max.)}$.

$$T_{jp} - T_C = P \cdot \left[R(\infty) \cdot \frac{t1}{t2} + \left(1 - \frac{t1}{t2}\right) \cdot R(t1 + t2) - R(t2) + R(t1) \right]$$

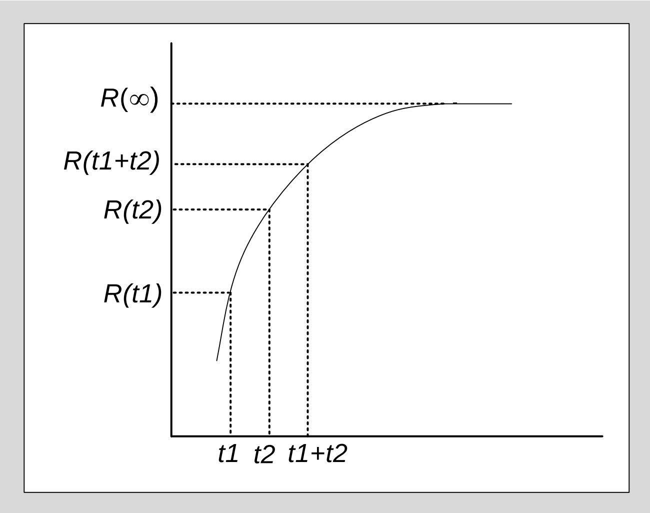


Fig. 6-11 Transient thermal resistance curve

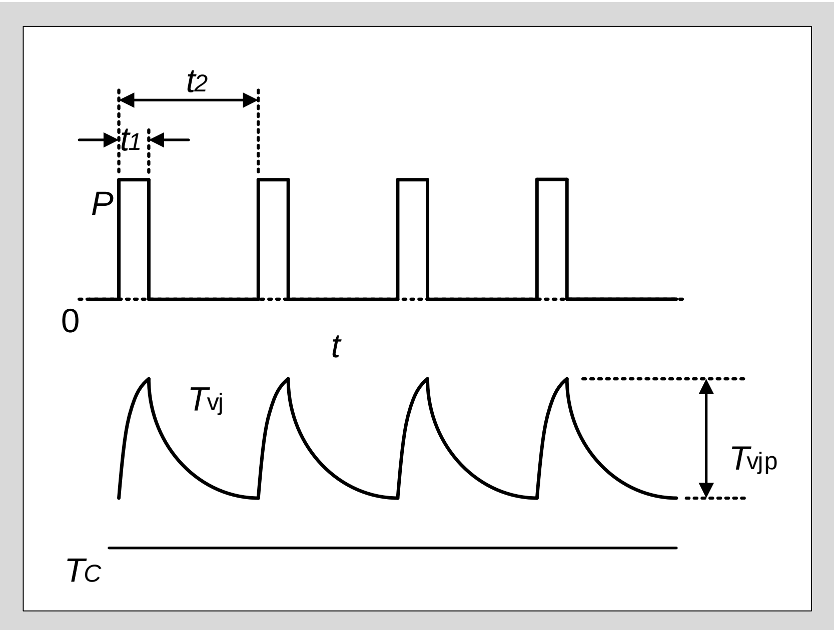


Fig. 6-12 Thermal ripples

6. Mounting Precautions

6.1 Mounting to heat sink

Since the thermal resistance varies according to the IGBT's mounting position, pay attention to the following points.

- When mounting a single IGBT module, position it in the center of the heat sink in order to minimize thermal resistance.
- When mounting several IGBT modules, determine each module position according to the power loss generated by each module. Allow more room for modules that generate more power loss.

6.2 Surface conditions of heat sink

The mounting surface roughness of the heat sink should be 10μm or less, and the surface flatness should be within +50μm (-50μm) per 100mm, taking the straight line connecting the center points of the two screw mounting holes as reference. If the roughness and flatness do not satisfy the conditions, it may cause an increase in contact thermal resistance $R_{th(c\text{-}f)}$, or insulation failure due to cracking of insulating substrate when stress is applied during mounting.

The flatness and surface roughness requirements for heat sink differ for each product. Please refer to the mounting instructions of each product for details.

6.3 Thermal grease application

To reduce contact thermal resistance, apply thermal grease between the heat sink and the mounting surface of the IGBT module.

There are several methods of applying thermal grease such as using a roller or a stencil mask.

Thermal grease improves heat dissipation from IGBT modules to heat sink, but it also has thermal capacity. Therefore, if the applied thermal grease is too thick, it will hinder heat dissipation, causing the chip temperature to rise. On the other hand, if the applied thermal grease is too thin, there is possibility that the contact thermal resistance will increase due to air gap between thermal grease and heat sink. Therefore, thermal grease must be applied with suitable thickness, else the heat dissipation to the heat sink will be poor. In the worst case, the chip temperature may exceed $T_{vj(max)}$, leading to destruction.

From these reasons, thermal grease application using a stencil mask is recommended to apply thermal grease with a uniform thickness. Fig. 6-13 shows the schematic diagram of thermal grease application using a stencil mask. The aim is to apply a specified weight of thermal grease to the module base plate using a stencil mask. After that, fix the IGBT module to the heat sink by tightening the screws with the recommended torque for respective products. In this way, the thermal grease can be applied uniformly. Fuji Electric can provide the recommended stencil mask design upon request.

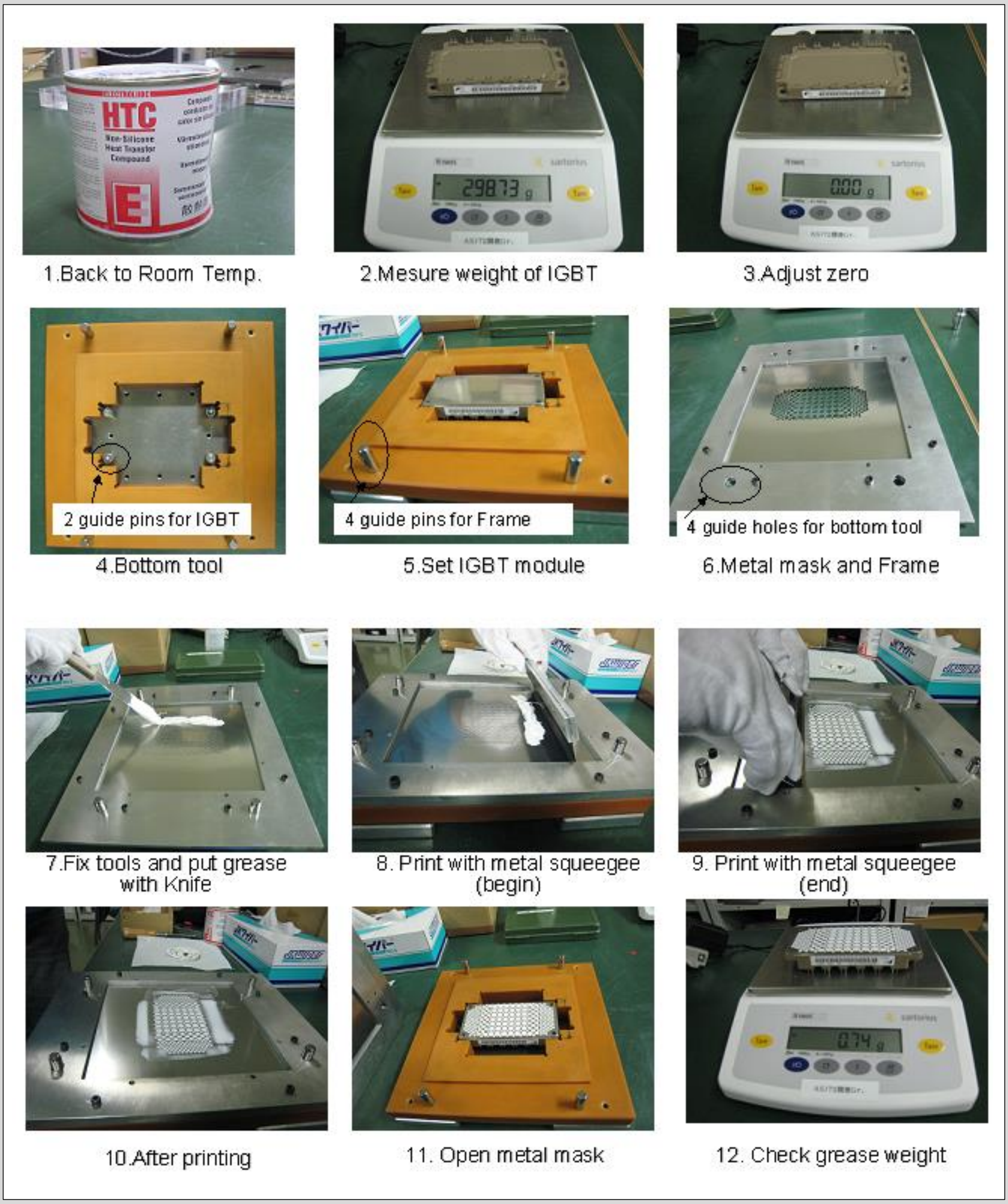


Fig. 6-13 Schematic diagram of example of thermal grease application

If the thermal grease is applied uniformly, the required weight can be calculated as follows.

$$\text{Thermal grease hickness } (\mu m) = \frac{\text{Weight of thermal grease (g)} \times 10^4}{\text{Base area of module (cm}^2\text{)} \times \text{Density of thermal grease (g/cm}^3\text{)}}$$

Calculate the weight for the required thermal grease thickness from the above formula and apply to the IGBT module. The recommended thermal grease thickness is about 100μm after spreading. However, the optimal thickness of the thermal grease differs depending on the thermal grease characteristics and the application method. Please check them before using.

Example of recommended thermal greases are shown in Table 6-1.

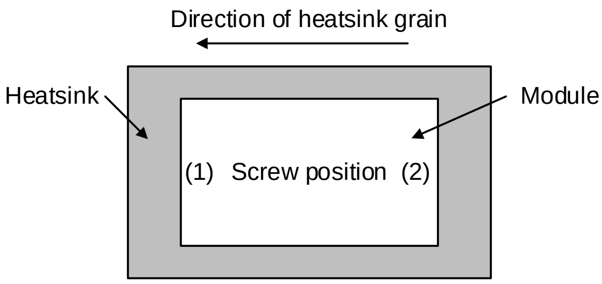
Table 6-1 Example of thermal grease

Product name	Manufacturer
TG221	Nihon Data Material Co., Ltd.
HTC	Electrolube
G747	Shin-Etsu Chemical Co., Ltd.
SC102	DuPont Toray Specialty Materials Co., Ltd.
YG6260	Momentive Performance Materials Japan LLC
P12	Wacker Asahikasei Silicone Co., Ltd.

6.4 Mounting procedure

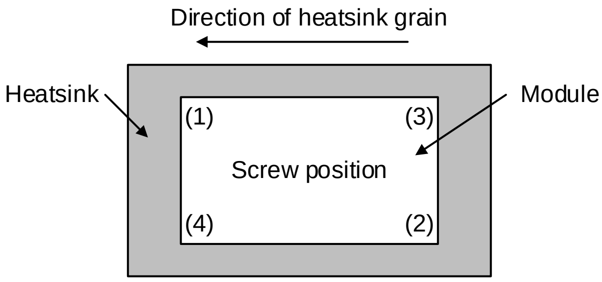
Fig. 6-14 shows examples of screw tightening when mounting an IGBT module to heat sink. Each screw must be tightened with the specified torque. Refer to the module datasheets for the specified torque.

Insufficient tightening torque may cause the contact thermal resistance to increase or the screws to become loose during operation. On the other hand, excessive tightening torque may damage the IGBT's case. The screw tightening method differs for each product. Please refer to the mounting instructions of each product for details.



	Torque	Sequence
Temporary tightening	1/3 of specified torque	(1)→(2)
Final tightening	Specified torque	(2)→(1)

(1) Two points mounting type module



	Torque	Sequence
Temporary tightening	1/3 of specified torque	(1)→(2)→(3)→(4)
Final tightening	Specified torque	(4)→(3)→(2)→(1)

(2) Four points mounting type module

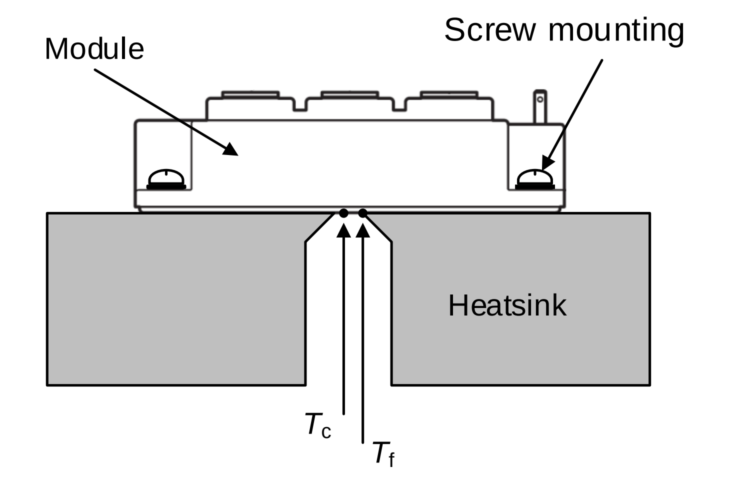
Fig. 6-14 Mounting procedure

6.5 IGBT module mounting direction

When mounting the IGBT module on a heat sink made by an extrusion mold, it is recommended to mount the IGBT module parallel to the heat sink extrusion direction as shown in Fig. 6-14. This is to reduce the effect of heat sink deformation.

6.6 Temperature verification

After selecting a heat sink and determining the mounting positions, measure the temperature of each part to confirm that the T_{vj} of each module is within the module rating or design value. Fig. 6-15 shows an example of how to measure T_C. There is also a measurement method using thermocouple. Please contact us for details.



Bore a hole at the heat sink and measure with an infrared thermometer

Fig. 6-15 T_C measurement method