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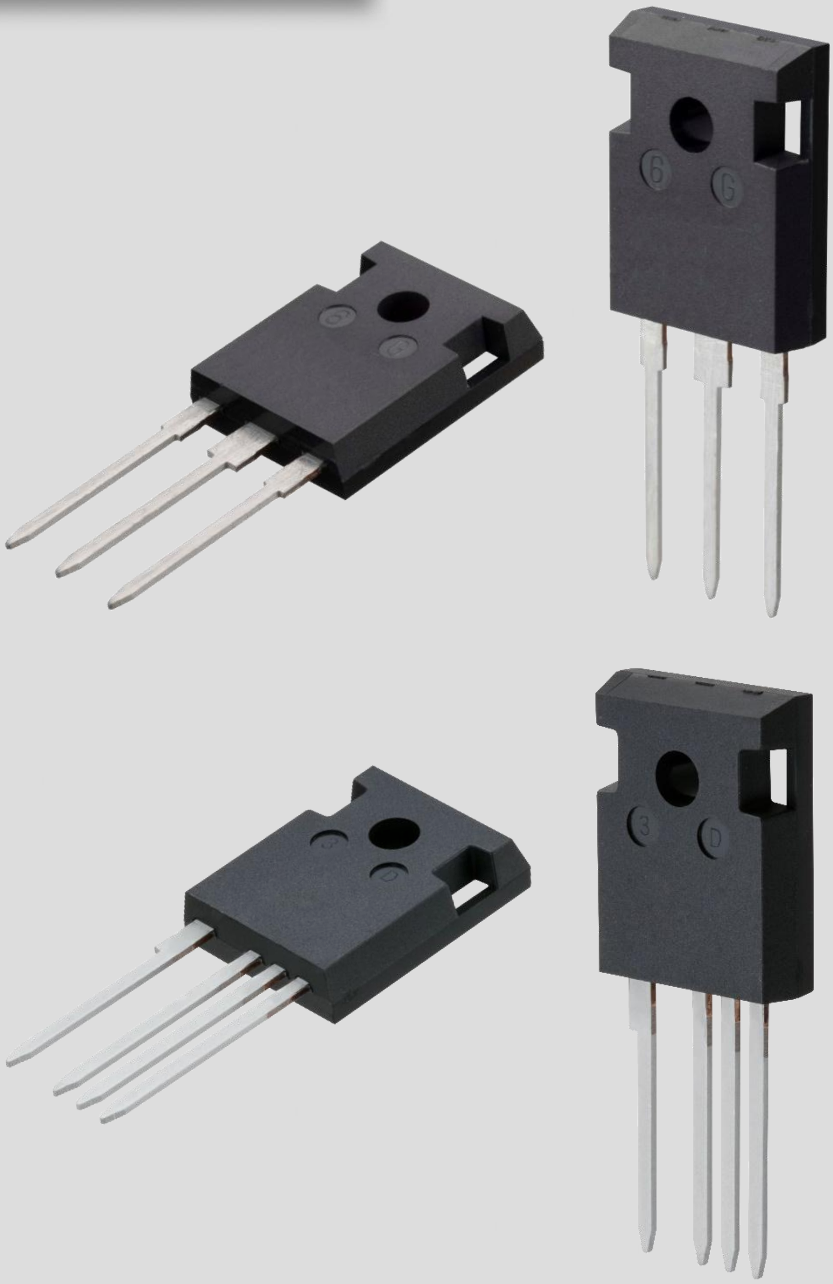

Discrete IGBT

Application Manual

Dec. 2025

Fuji Electric Co., Ltd.

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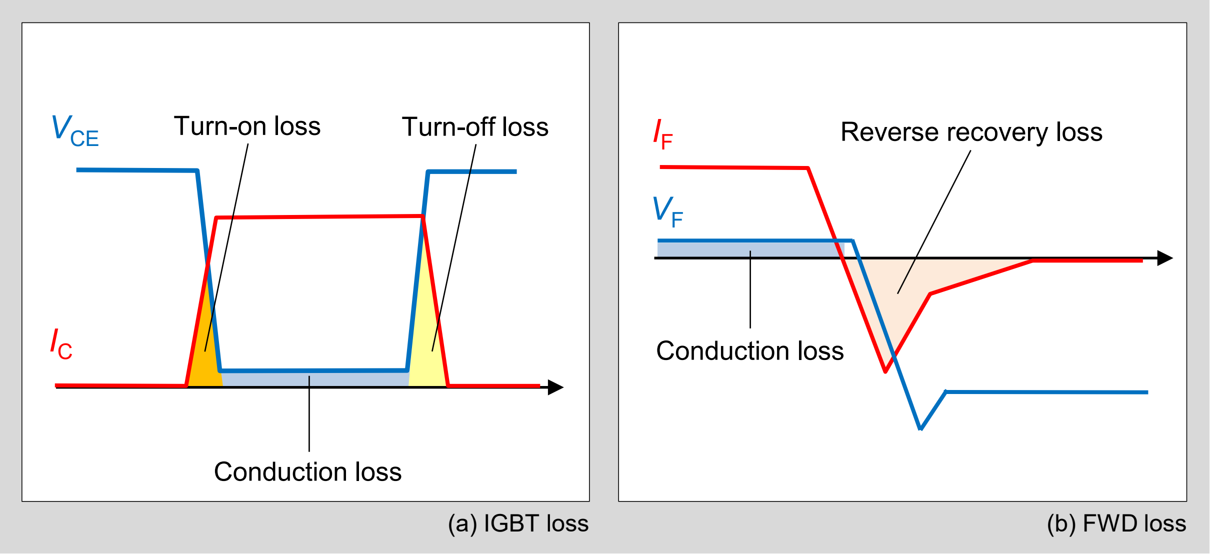
Chapter 6 Cooling Design

1. Power Loss of Discrete IGBT

Discrete IGBTs are available in two types: IGBT only products and products that combine an IGBT with a freewheeling diode (FWD). For the latter, total loss must account for both the IGBT’s loss and the FWD’s loss. As shown in Fig. 6-1, power loss are divided into 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

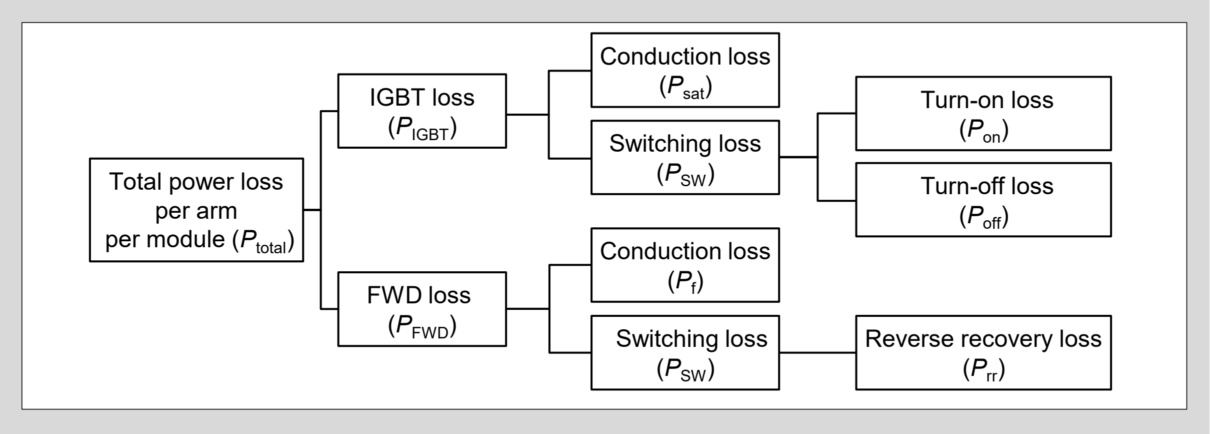


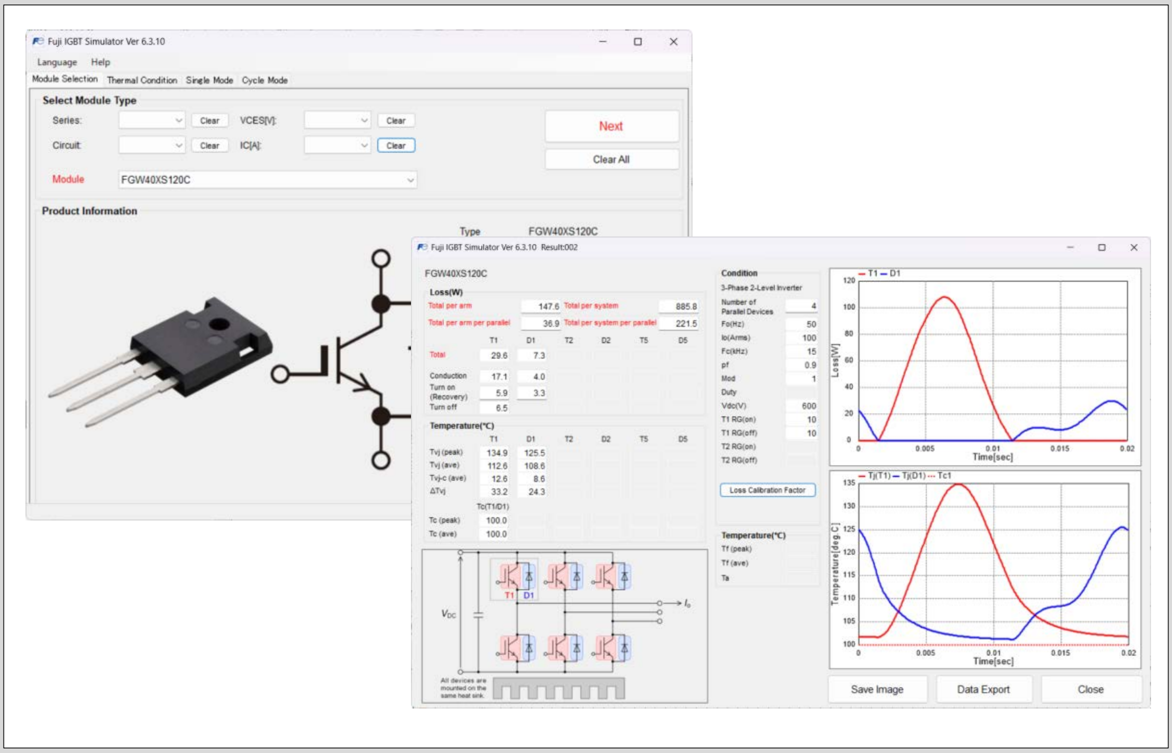
Fig. 6-2 Classification of IGBT module power loss

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. Cooling 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. About Fuji IGBT Simulator

On our website, we provide the “Fuji IGBT Simulator” as a tool for calculating the power loss and junction temperature of discrete IGBTs. This simulator performs calculation by accurately fitting the characteristic curves from the datasheet, and also in consideration of the device’s junction temperature dependence. For instructions on how to use it, please refer to the user manual available on the website.

However, some products or circuit configurations may not be supported by the Fuji IGBT Simulator. In those cases, you will need to perform the loss calculations manually. In the following sections, we describe the methods for calculating each type of power loss.



Module: FGW40XS120C

Type: FGW40XS120C

FGW40XS120C

Loss(W)

Total per arm: 147.6
Total per system: 885.8
Total per arm per parallel: 36.9
Total per system per parallel: 221.5

	T1	D1	T2	D2	T5	D5
Total	29.6	7.3				
Conduction	17.1	4.0				
Turn on (Recovery)	5.9	3.3				
Turn off	6.5					

Temperature(°C)

	T1	D1	T2	D2	T5	D5
Tvj (peak)	134.9	125.5				
Tvj (ave)	112.6	108.6				
Tvj-c (ave)	12.6	8.6				
ΔTvj	33.2	24.3				

	Tc(T1/D1)
Tc (peak)	100.0
Tc (ave)	100.0

Condition

3-Phase 2-Level Inverter

Number of Parallel Devices	4
Fo(Hz)	50
Io(Arms)	100
Fc(kHz)	15
pf	0.9
Mod	1
Duty	
Vdc(V)	600
T1 RG(on)	10
T1 RG(off)	10
T2 RG(on)	
T2 RG(off)	

Temperature(°C)

Tf (peak)
Tf (ave)
Ta

Fig. 6-3 Fuji IGBT Simulator

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

3. Power Loss Calculation Method of Boost Chopper Circuit

In the case of a boost chopper circuit as shown in Fig. 6-4, 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

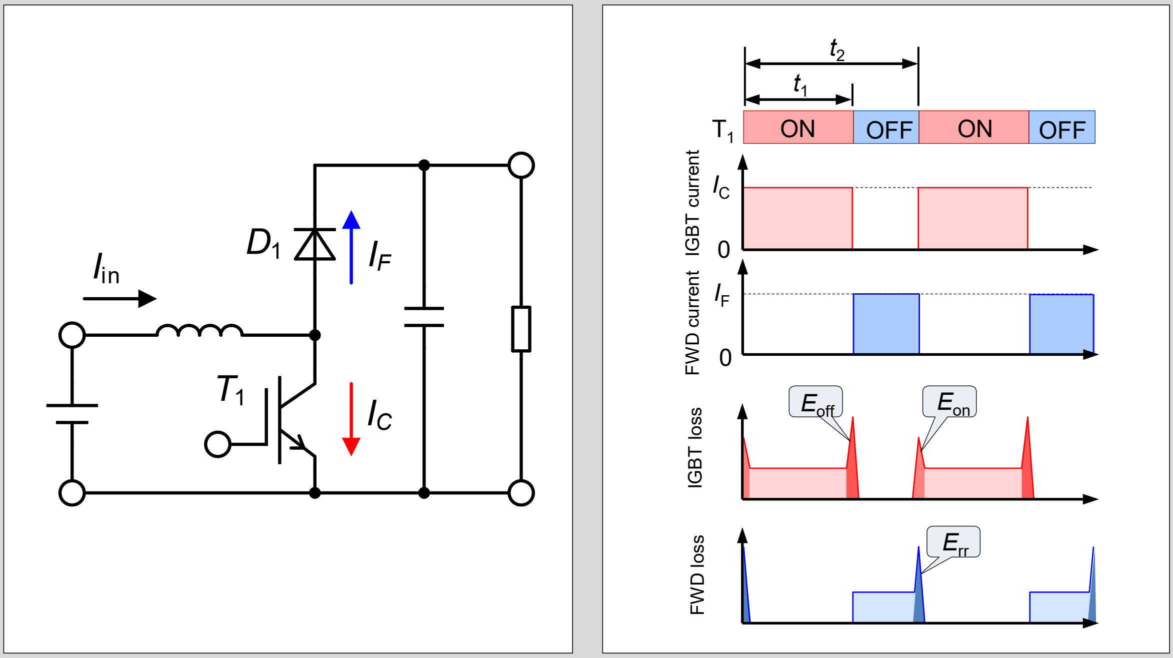
$$= V_F \cdot I_F \cdot (1-d) + E_{rr} \cdot f_C \cdot \left(\frac{V_{CC}}{V_{CC0}}\right)^{\alpha} \quad \text{......(2)}$$

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. 6-4 Power loss in boost chopper circuit

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

As shown in Fig. 6-5, 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.

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

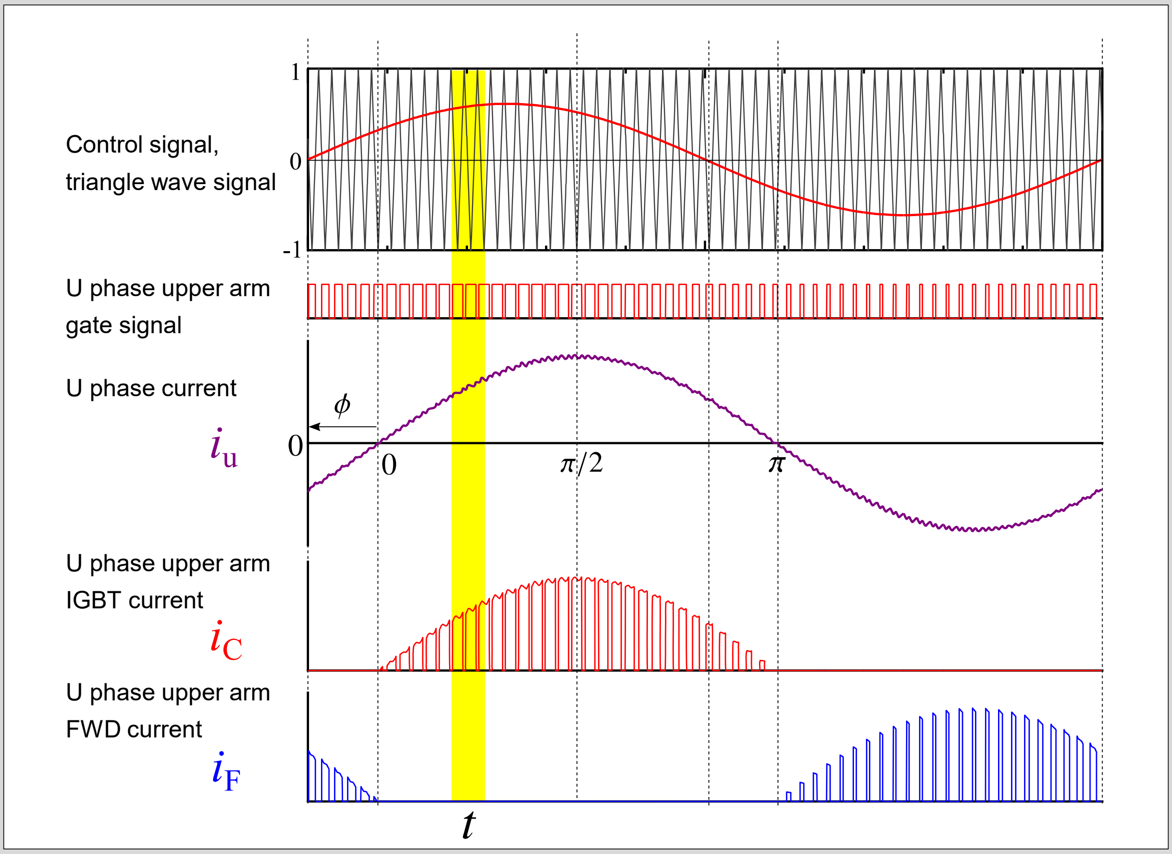


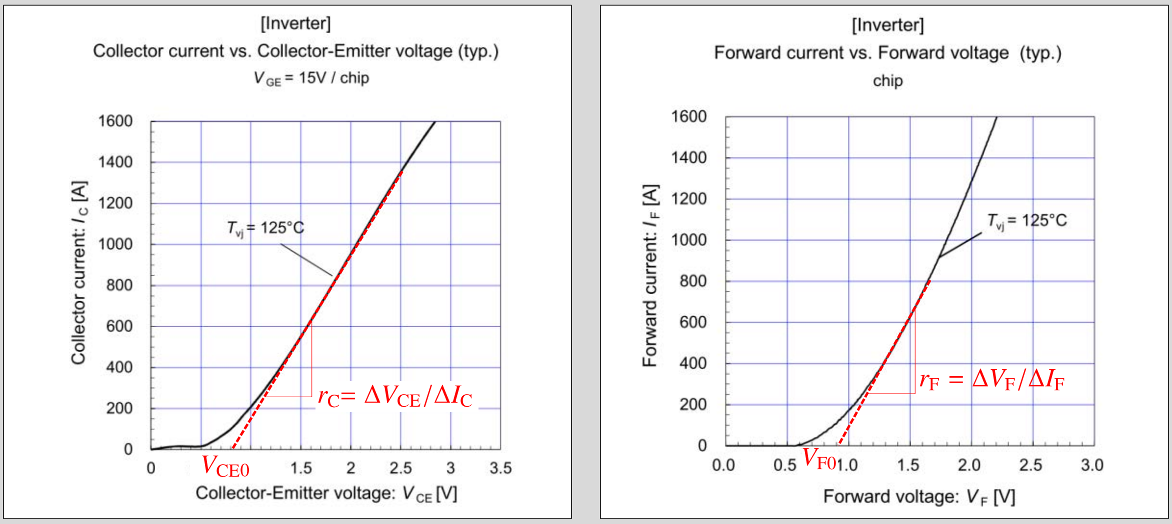
Fig. 6-5 Operating waveform of a 3-phase 2-level PWM inverter

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. 6-6, 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. 6-6 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. 6-7, 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.

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

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

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

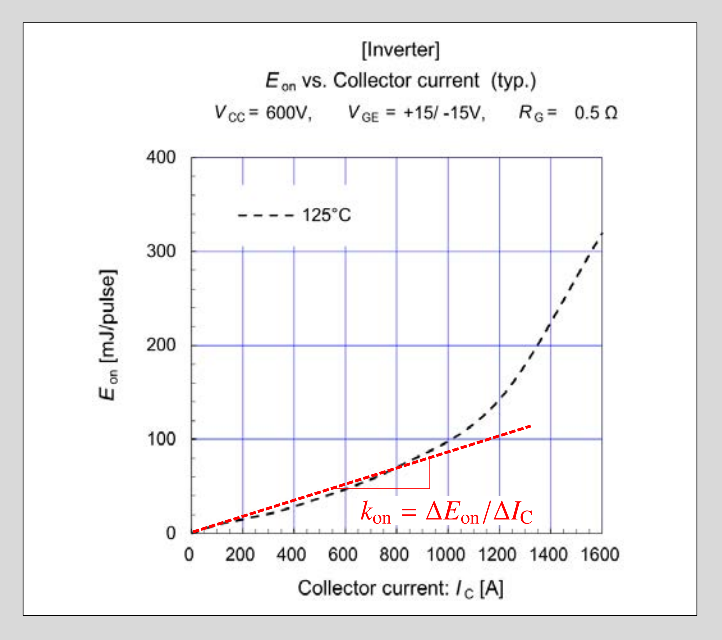


Fig. 6-7 Approximation of I_C dependence of switching energy

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

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

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

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

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

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

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.

$$P_{IGBT} = P_{sat} + P_{on} + P_{off} \quad \cdots\cdots(15)$$

$$P_{FWD} = P_f + P_{rr} \quad \cdots\cdots(16)$$

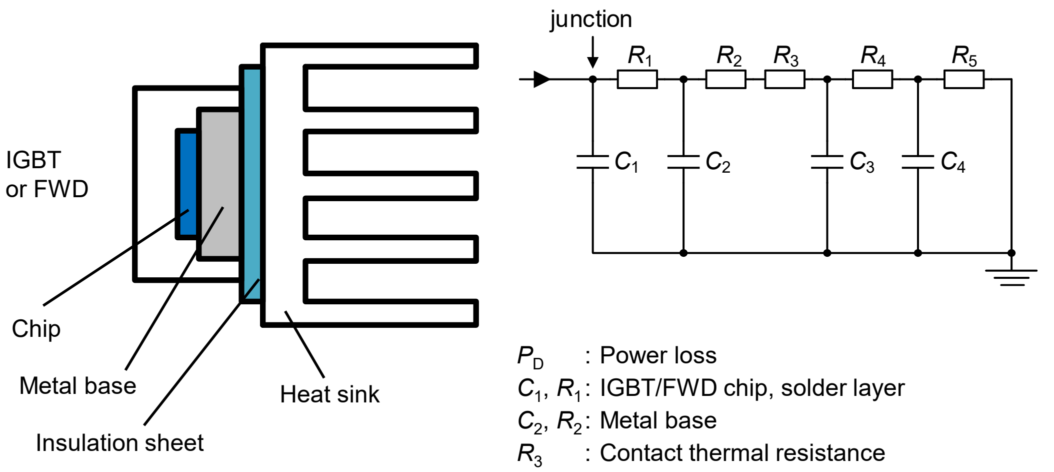
As mentioned, since the values of $V_{CE(sat)}$, V_F, E_{on}, E_{off}, and E_{rr} change depending on T_{vj} and R_G, refer to the T_{vj} and R_G dependency graphs in the datasheet for conversion when calculating.

5. Concept of Cooling Design

In cooling design, the heat sink is selected based on the calculated power loss so that the device temperature stays below its allowable limit. If the cooling design is inadequate, there is a risk that the device may exceed its maximum junction temperature during actual operation and fail.

5.1 Transient thermal impedance and steady-state thermal resistance

When mounting the device on a heat sink, the heat dissipation path for power loss generated at the junction is modeled by the equivalent electrical circuit as shown in Fig. 6-8.



P_D : Power loss
C_1, R_1 : IGBT/FWD chip, solder layer
C_2, R_2 : Metal base
R_3 : Contact thermal resistance
C_3, R_4 : Insulation sheet
(including part of contact thermal resistance)
C_4, R_5 : Heat sink

Fig. 6-8 Equivalent electrical circuit of thermal behavior

Transient thermal impedance, as modeled by the equivalent circuit in Fig. 6-8, is the impedance over the time range in which the thermal capacitances C1-C4 have influences, and is therefore a function of time. The transient thermal impedance characteristic of each device has its maximum value specified in the datasheet, corresponding to a duty cycle D ≅ 0. The transient thermal impedance of the heat sink can be calculated from the following equation.

$$R_{f(t)} = R_{th(f\text{-}a)}\left(1 - e^{-\frac{t}{\tau f}}\right)$$

$$\text{where, } \tau f = R_{th(f\text{-}a)} \cdot V \cdot \gamma \cdot C$$

$R_{th(f\text{-}a)}$: Steady-state thermal resistance of the heat sink [°C/W]
t : Time [s]
τf : Thermal time constant of the heat sink [s]
V : Heat sink volume [cm^3]
γ : Density [g/cm^3]
C : Specific heat [J/g·deg]

The densities and specific heats of the materials required for these calculations are listed in Table 6-1, and the steady-state thermal resistance of the aluminum heat sink is shown in Fig. 6-9.

Table 6-1 Density and specific heat of each material

Material	Density γ [g/cm^3]	Specific heat [J/g･deg]
Aluminum	2.71	0.895
Cooper	8.96	0.383

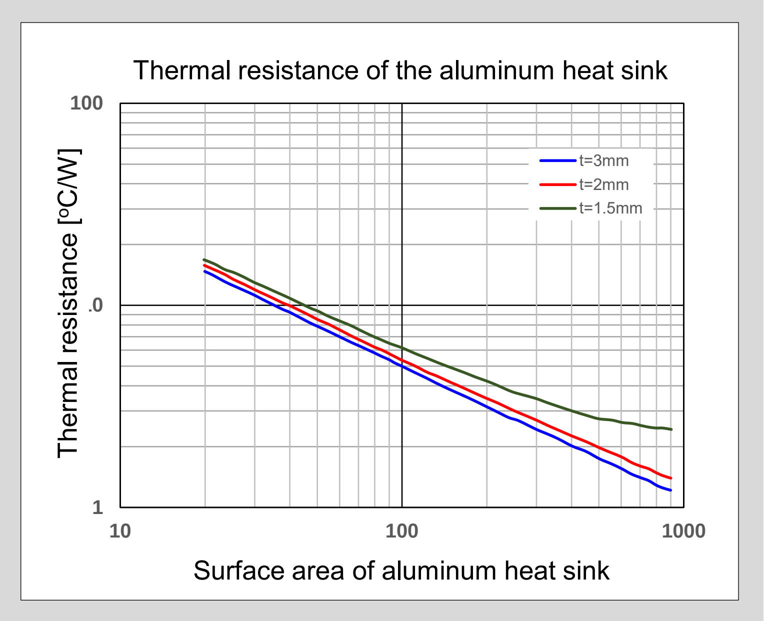


Fig. 6-9 Steady-state thermal resistance of the aluminum heat sink

5.2 Steady-State thermal equation

The steady-state thermal resistance is the thermal resistance when the influences of thermal capacitances have completely disappeared. The device's junction temperature can then be easily calculated.

$$T_{vj} = T_a + P_D \cdot (R_{th(j\text{-}c)} + R_{th(c\text{-}i)} + R_{th(i)} + R_{th(i\text{-}f)} + R_{th(f\text{-}a)})$$

T_{vj} : Junction temperature
T_a : Ambient temperature
$R_{th(j\text{-}c)}$: Junction to case thermal resistance (IGBT or FWD)
$R_{th(i)}$: Insulation sheet thermal resistance
$R_{th(c\text{-}i)}$, $R_{th(i\text{-}f)}$: Contact thermal resistance
$R_{th(f\text{-}a)}$: Heat sink thermal resistance
P_D : Power loss

5.3 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. 6-11. 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. 6-10).

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

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

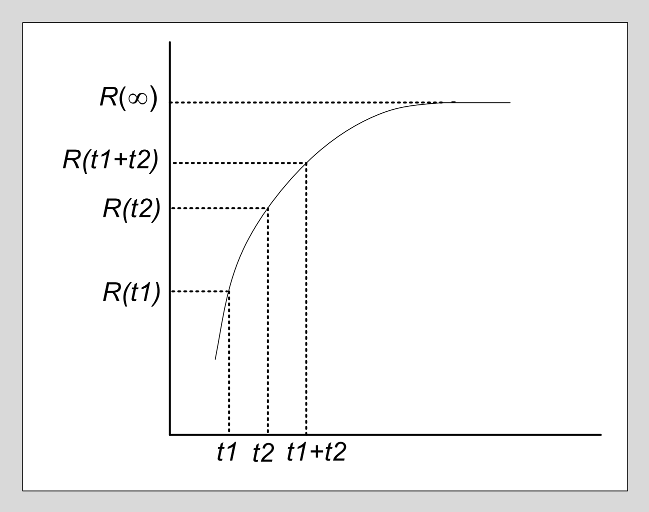


Fig. 6-10 Transient thermal resistance curve

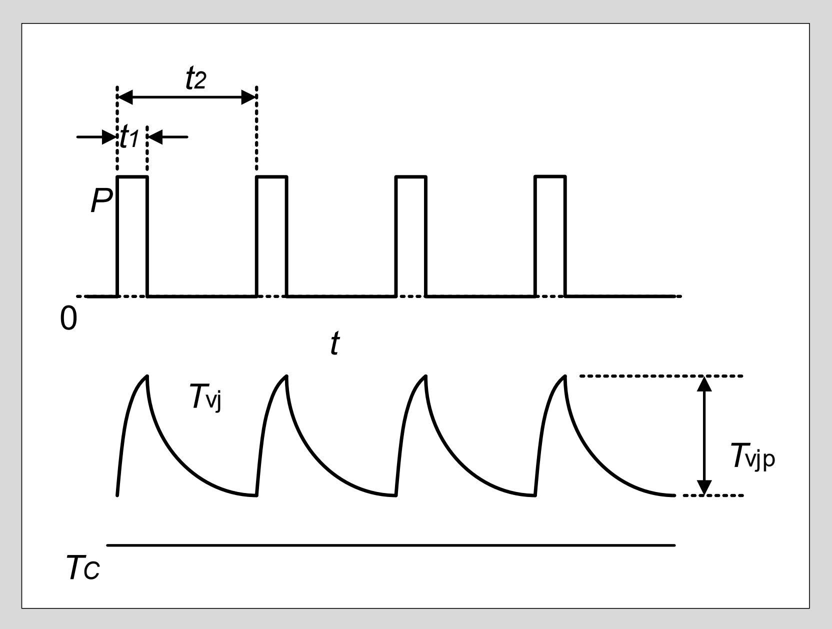


Fig. 6-11 Thermal ripples