Chapter 5 Thermal Design

This chapter describes the thermal design.

1. Types of Power Loss

There are two types of discrete IGBT: IGBT-only products and products with IGBT + FWD configurations. It is necessary to consider both IGBT and FWD power losses of the latter. Fig.5-1 shows the power loss factors. Cooling capability has to be designed to keep $T_{vj(max.)}$ below the max. rated value. Calculate the power loss with on-voltage and switching loss values when the junction temperature T_{vj} is high. These data are described in the specifications.

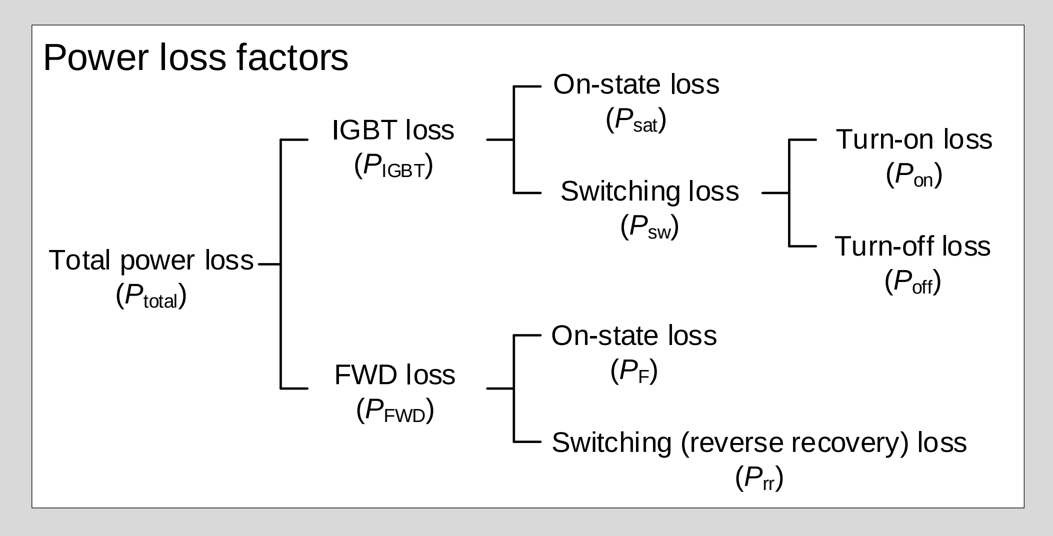


Fig.5-1　Power loss factors

2. DC Chopper Circuit Power Loss Calculations

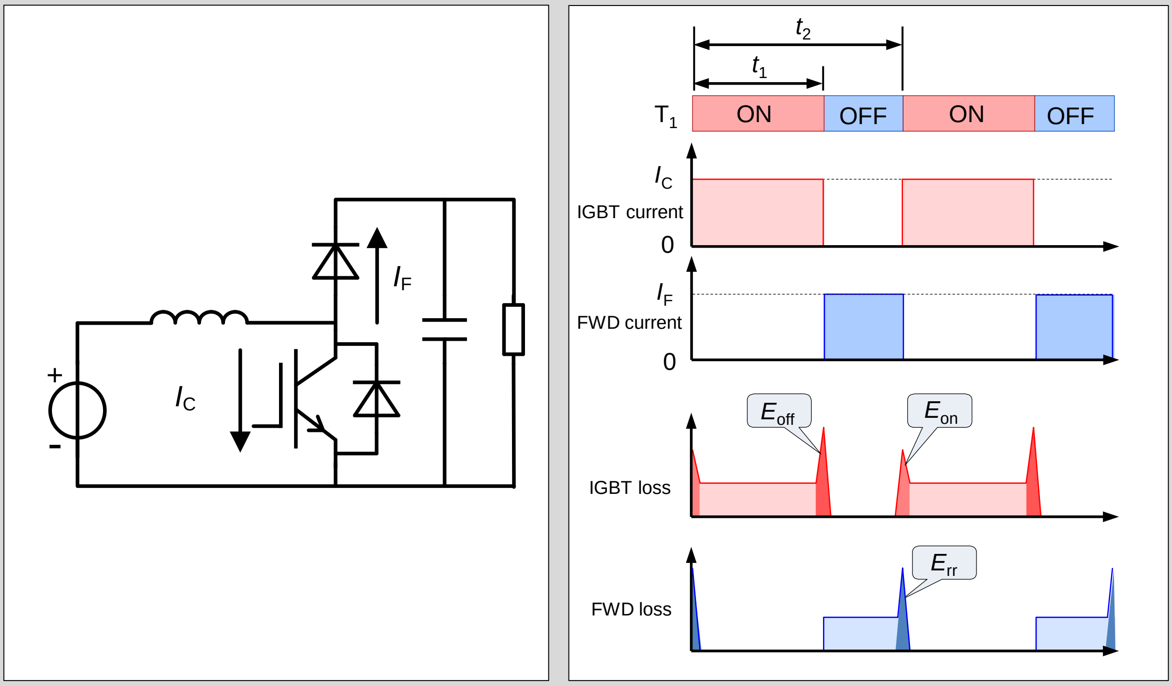
Approximate calculation can be performed by considering the current flowing through the IGBT or FWD as a series of square waves. Fig.5-2(a) shows an example of a chopper circuit. Fig.5-2(b) shows the approximate DC chopper waveforms, and the loss generated is calculated as follows.

IGBT loss (W)
= On-state loss + Turn-on loss + Turn-off loss

$$=V_{CE(sat)} \cdot I_C \cdot \frac{t_1}{t_2} + E_{on} \cdot f_C + E_{off} \cdot f_C$$

FWD loss (W)
= On-state loss + Reverse recovery loss

$$=V_F \cdot I_F - \left(1-\frac{t_1}{t_2}\right) + E_{rr} \cdot f_C$$



(a) Chopper circuit example

(b) Operation waveform and power loss of chopper circuit

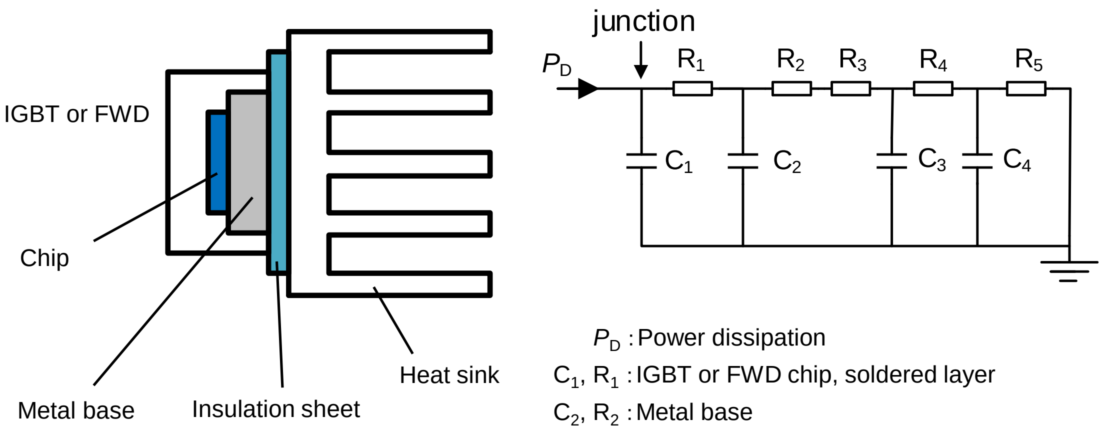
Fig.5-2 Power loss in chopper circuit

3. Concept of Heat Dissipation

During thermal design, the heat sink is selected so that the device temperature is below the permissible temperature based on the generated power loss. If the heat dissipation design is insufficient, problems such as device's failure due to temperature exceeding the permissible temperature may occur during actual operation.

＜Transient thermal impedance and steady-state thermal resistance＞

There are two types of heat dissipation method : mounting the device on a heat sink and only by the device itself. Fig.5-3 shows the former. The heat dissipation path is simulated by an electrical equivalent circuit for convenience.



P_D : Power dissipation

C_1, R_1 : IGBT or FWD chip, soldered layer

C_2, R_2 : Metal base

R_3 : Contact thermal resistance

C_3, R_4 : Insulation sheet (including a part of contact thermal resistance)

C_4, R_5 : Heat sink

Fig.5-3 Electric equivalent circuit showing thermal behavior

The transient thermal resistance is the thermal resistance as a function of time, which is affected by the heat capacities C_1 to C_4 shown in the equivalent circuit in Fig.5-3. The max. value of the transient thermal resistance characteristics of each device is specified in the data sheet, and the repetition rate D≅0 corresponds to it. The transient thermal resistance of the heat sink can be obtained by the following equation.

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

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

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

Table.5-1 lists the specific gravity of materials required for this calculation, and Fig.5-4 shows the steady-state thermal resistance of an aluminum heat sink (coated in black).

Table.5-1 Specific gravity and specific heat of each material

Material	Specific gravity γ [g/cm^3]	Specific heat [J/g• deg.]
Aluminum	2.71	0.895
Copper	8.96	0.383

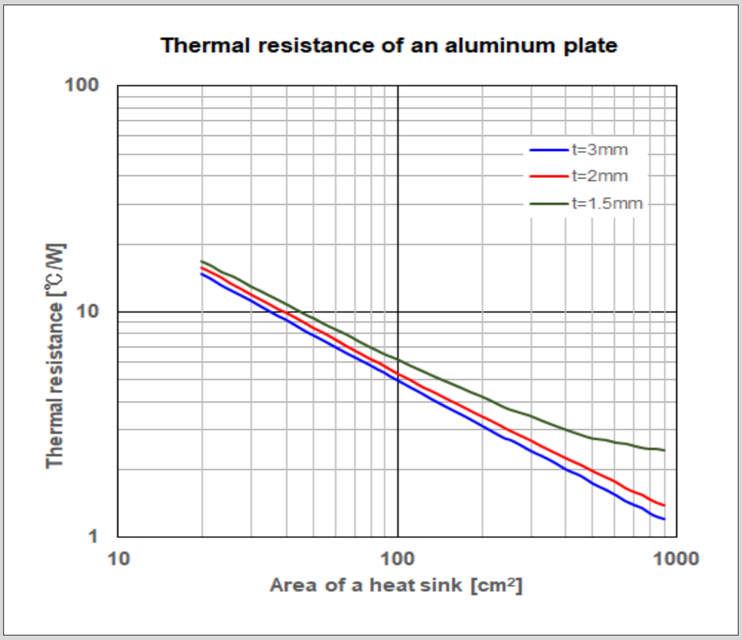


Fig.5-4 Steady-state thermal resistance of aluminum heat sink

4. Calculation of Junction Temperature

Since the steady-state thermal resistance is not affected by thermal capacitance, the junction temperature can be calculated easily.

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

T_{vj} : Junction temperature
T_a : Ambient temperature
$R_{th(j-c)}$: Thermal resistance between junction and case (IGBT or FWD thermal resistance)
$R_{th(i)}$: Insulation sheet resistance
$R_{th(c-i)}$, $R_{th(i-f)}$: Contact thermal resistance
$R_{th(f-a)}$: Thermal resistance of heat sink
P_D : Generated power dissipation

＜Thermal equation for transient power loss calculations＞

In general, it is sufficient to consider the steady-state T_{vj} based on the average power loss. However, practically, repetitive switching causes pulsed power loss and temperature ripples as shown in Fig.5-5. In this case, consider the power loss as a continuous constant cycles, constant-peak square wave pulses. Then the approximate peak value of the temperature ripples can be calculated using the transient thermal resistance curve given in the IGBT specification sheets as shown in Fig.5-6.

Be certain to select the heat sink that will also keep the T_{vjp} below $T_{vj\,(max)}$.

$$T_{vjp} - T_C = P \cdot [R_{(\infty)} \cdot \frac{t1}{t2} + R_{(t1+t2)} \cdot (1 - \frac{t1}{t2}) - R_{(t2)} + R_{(t1)}]$$

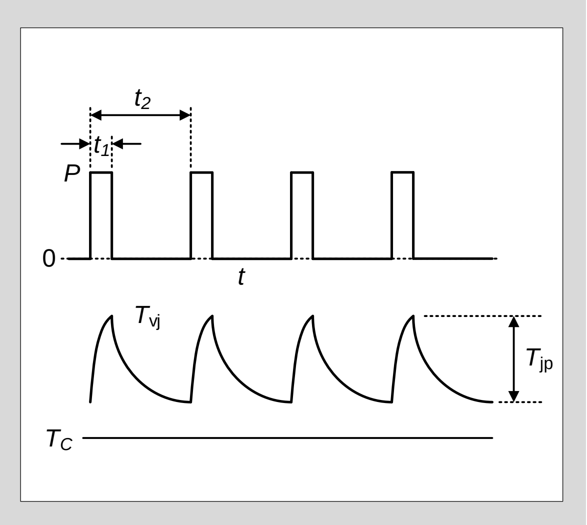


Fig.5-5 Thermal ripples

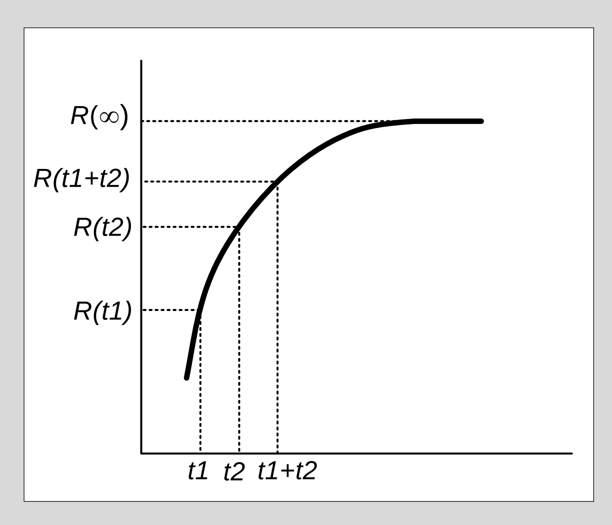


Fig.5-6 Transient thermal resistance curve

＜Transient thermal impedance characteristics of the device＞

Transient thermal impedance characteristics of the device is shown in the specification to assist in thermal designing. Fig.5-7 shows the transient thermal impedance characteristics of FGW40XS120C.

For example in Fig.5-7, in the case of a single pulse with a pulse width of 1ms, permissible power loss P_D when the device is mounted to a heat sink of 5 ℃/W under the condition of T_a=40℃ can be calculated by using the following formula:

$$P_D = \frac{T_{vj(max)} - T_a}{R_{th(f-a)} + R_{th(1ms)}}$$

$$= \frac{175\ [℃] - 40\ [℃]}{5\ [℃/W] + 0.2\ [℃/W]}$$

$$\cong 25.96\ [W]$$

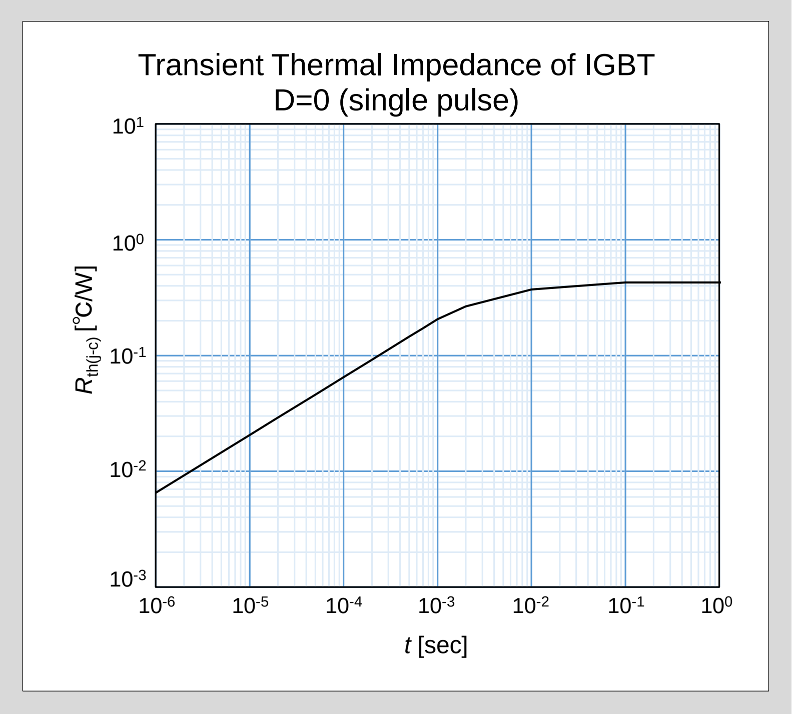


Fig.5-7 Transient thermal impedance characteristics of FGW40XS120C