Calculation of Power Consumption and Junction Temperature of IGBT Module in Inverter

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Abstract. Insulated Gate Bipolar Transistor (IGBT) is a fully controlled power electronic device with excellent comprehensive performance, which is widely used in various inverter units. At present, Infineon's IPOSIM simulation is usually used to obtain the power consumption and junction temperature fluctuation of IGBT modules, but it is only applicable to IGBT modules produced by Infineon. In this paper, the power consumption of IGBT and diode is calculated, and the expression of junction temperature fluctuation is obtained based on junction-shell transient thermal resistance, which is suitable for common IGBT modules. Finally, simulation verifies the correctness of the calculation method.

1. Introduction
Insulated Gate Bipolar Transistor (IGBT) is a fully-controlled power electronic device with excellent comprehensive performance, which has the advantages of easy driving and protection and high switching frequency. It is the mainstream product of power electronic devices and is widely used in various green energy inverter units such as wind power generation and photovoltaic power generation[1-2].

At present, the power consumption calculation of IGBT modules in inverter units is usually simulated by Infineon's IPOSIM, but this simulation process is difficult to understand its calculation principle and process, and it is only applicable to IGBT modules produced by Infineon. For common SPWM bipolar modulation, the on-state power consumption and switching power consumption of IGBT and diode are related to the manual given value and actual working value, while the junction temperature fluctuation of IGBT and diode is related to the transient thermal resistance and power consumption of junction-shell[3-4]. Therefore, it is of engineering and theoretical significance to calculate the total power consumption of IGBT module and the fluctuation of junction temperature.

In this paper, aiming at the IGBT module of two-level single-phase H-bridge inverter unit, the calculation of IGBT power consumption and diode power consumption are derived, and the total loss of IGBT module is obtained. Then, based on the transient thermal resistance analysis of IGBT junction-shell, the expression of junction temperature fluctuation between IGBT and diode is derived. At last, a certain IGBT module is selected and simulated by Infineon's IPOSIM. The simulation and calculation results of IGBT power consumption and junction temperature fluctuation are compared under two different operating conditions, and the causes of errors are analyzed.

2. Theoretical analysis

2.1. IGBT power consumption calculation
IGBT power consumption consists of three parts: on-state power consumption, switching loss and off-
state power consumption, which is usually ignored because of its small off-state power consumption. IGBT conduction power consumption is expressed as:

\[ P_{\text{cond, IGBT}} = \frac{1}{T} \int_0^{T/2} V_{CE}(t) \cdot i(t) \cdot \tau'(t) \, dt \]  

(1)

Where: \( i(t) = I \sin(\omega t) \) is the sinusoidal output current. \( V_{CE}(t) = V_{T0} + R_{CE} \cdot i(t) \) is the linearized representation of IGBT conduction voltage drop, where \( V_{T0} \) is threshold voltage and \( R_{CE} \) is the slope resistance when conducting, which is usually selected near the working current point.

\( \tau'(t) \) is the duty cycle of the inverter bridge output, which can be described as

\( \tau'(t) = \frac{1}{2} \left( 1 + m \sin(\omega t + \varphi) \right) \). \( m \) is the modulation index, \( \varphi \) is the phase difference between the output signal and the current.

Therefore, IGBT conduction loss is:

\[ P_{\text{cond, IGBT}} = \frac{1}{2} \left( V_{T0} \cdot I_p \cdot \pi + R_{CE} \cdot \frac{I_p^2}{4} \right) + m \cdot \cos \varphi \cdot \left( V_{T0} \cdot I_p \cdot \frac{1}{8} + \frac{1}{3} \pi \cdot R_{CE} \cdot I_p^2 \right) \]  

(2)

Where: \( I_p = \sqrt{2} I_0 \) is the amplitude of the output current.

IGBT switching loss is usually determined by the energy and switching frequency of single turn-on and turn-off, which is expressed as:

\[ P_{\text{SW, IGBT}} = f_{SW} \cdot \frac{T_e}{T} \int_0^{T/2} \left( E_{\text{on}} + E_{\text{off}} \right)(t, I) \, dt \]  

(3)

Where: \( E_{\text{on}}, E_{\text{off}} \) is the energy of single turn-on and turn-off respectively, and \( f_{SW} \) is the switching frequency.

The single switching energy of IGBT is related to the working state, which is expressed as:

\[ E_{\text{SW, IGBT}} = \left( E_{\text{on, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) + E_{\text{off, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) \right) \times \frac{I}{I_{\text{nom}}} \times \frac{V_{dc}}{V_{\text{nom}}} \]  

(4)

Where: \( I_{\text{nom}}, V_{\text{nom}}, E_{\text{on, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) \) and \( E_{\text{off, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) \) are the current and voltage of IGBT given in the manual, and the on-off energy under this given condition.

Switching loss is expressed as:

\[ P_{\text{SW, IGBT}} = \frac{1}{\pi} \cdot f_{SW} \cdot \left( E_{\text{on, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) + E_{\text{off, IGBT}}(I_{\text{nom}}, V_{\text{nom}}) \right) \cdot \frac{I}{I_{\text{nom}}} \cdot \frac{V_{dc}}{V_{\text{nom}}} \]  

(5)

Therefore, the power consumption of IGBT is expressed as:

\[ P_{\text{IGBT}} = P_{\text{cond, IGBT}} + P_{\text{SW, IGBT}} \]  

(6)

### 2.2. Power consumption calculation of diode

Similar to the conduction loss of IGBT, the conduction loss of diode is:

\[
\left\{ \begin{array}{l}
P_{\text{cond, Diode}} = \frac{1}{T} \int_0^{T/2} V_p(t) \cdot i(t) \cdot \tau'(t) \, dt \\
\tau'(t) = \frac{1}{2} \left( 1 - m \sin(\omega t + \varphi) \right)
\end{array} \right.
\]  

(7)

Derived from the above formula:

\[ P_{\text{cond, Diode}} = \frac{1}{2} \left( V_{T0} \times \frac{I_p}{\pi} + R_{CE} \times \frac{I_p^2}{4} \right) - m \times \cos \varphi \times \left( V_{T0} \times \frac{I_p}{8} + \frac{1}{3} \pi \times R_{CE} \times I_p^2 \right) \]  

(8)

Turn-on loss in diode switching loss is negligible, and turn-off loss, i.e. reverse recovery loss, is
expressed as:

\[
P_{SW,Diode} = \frac{1}{\pi} \times f_{SW} \times \left(E_{eff,Diode}(I_{nom}, V_{nom}) \right) \times \frac{I}{I_{nom}} \times \frac{V_{dc}}{V_{nom}}
\]  

(9)

Where: \(I_{nom}, V_{nom}\) and \(E_{eff,Diode}(I_{nom}, V_{nom})\) are the current and voltage of the diode given in the manual and the turn-off energy under this given condition.

Because \(E_{eff,Diode}\) is not proportional to the reverse recovery energy of the diode, it is usually equivalent by the following formula:

\[
E_{eff,Diode} = E_{rec}(I_{nom}) \times (0.45 \times \frac{I}{I_{nom}} + 0.55)
\]  

(10)

The switching loss of diode is expressed as:

\[
P_{SW,Diode} = \frac{1}{\pi} \times f_{SW} \times \left(E_{rec}(I_{nom}) \times (0.45 \times \frac{I}{I_{nom}} + 0.55) \right) \times \frac{V_{dc}}{V_{nom}}
\]  

(11)

Therefore, the loss of the diode is expressed as:

\[
P_{Diode} = P_{cond,Diode} + P_{SW,Diode}
\]  

(12)

2.3. Calculation of total loss of IGBT module

Each IGBT module consists of two IGBTs and anti-parallel diodes, and the total loss of a single module can be expressed as:

\[
P_{tot} = 2 \times (P_{IGBT} + P_{Diode})
\]  

(13)

2.4. Calculation of IGBT junction temperature fluctuation

The junction-shell thermal resistance model of IGBT chip is composed of four parts, and the thermal resistance and time constant of each part are given on the thermal resistance curve. The analytical model of local thermal network is shown in Figure 1.

![Figure 1. Thermal network](image)

Transient thermal resistance of junction-shell of IGBT is expressed as:

\[
\left\{ \begin{array}{l}
Z_{th,R_c} = R_{th,c}(1 - e^{-\frac{t}{\tau_{c}}}) \\
Z_{th,c}(t) = Z_{th,R_c1} + Z_{th,R_c2} + Z_{th,R_c3} + Z_{th,R_c4}
\end{array} \right.
\]  

(14)

The output current of IGBT is sinusoidal, and the power consumption curve is considered to be approximately sinusoidal. The power consumption expressions of IGBT and diode in the module are obtained as follows:

\[
\left\{ \begin{array}{l}
P_{IGBT}(t) = \pi \times P_{IGBT_{av}} \times \sin(\omega t) \\
P_{Diode}(t) = \pi \times P_{Diode_{av}} \times \sin(\omega t - \pi)
\end{array} \right. \quad 0 \leq t \leq \frac{T}{2}
\]  

(15)

Where: \(P_{IGBT_{av}}\) is the average power consumption of IGBT part, \(P_{Diode_{av}}\) is the average power consumption of diode part, and \(T\) is the period.
Taking IGBT as an example to calculate transient junction temperature, diode is similar. For the fourth-order equivalent junction-shell thermal resistance model shown in Figure 1, the temperature fluctuation of each order is calculated step by step, and the total temperature fluctuation is obtained by adding. For one of RC thermal resistance models, there are:

\[
P_{IGBT} \times R_{th(k)} = \Delta T_k + \tau_k \times \frac{d \Delta T_k}{dt}
\]

(16)

The expression of junction temperature fluctuation is obtained by bringing IGBT and diode power consumption into the above formula:

\[
\Delta T_{IGBT}(t) = \sum_{k=1}^{4} \frac{\pi \omega P_{IGBT} R_{th(k)}}{\tau_k (\frac{1}{\tau_k^2} + \omega^2)} \times \left( \frac{e^{-\frac{T}{\tau_k}}}{1 - e^{-\frac{T}{2\tau_k}}} - \cos \frac{\omega t}{\tau_k} + \sin \frac{\omega t}{\tau_k} \right)
\]

(17)

\[
\Delta T_{Diode}(t) = \sum_{k=1}^{4} \frac{\pi \omega P_{Diode} R_{th(k)}}{\tau_k (\frac{1}{\tau_k^2} + \omega^2)} \times \left( \frac{e^{-\frac{T}{\tau_k}}}{1 - e^{-\frac{T}{2\tau_k}}} - \cos \frac{\omega(t - \frac{T}{2})}{\tau_k} + \sin \frac{\omega(t - \frac{T}{2})}{\tau_k} \right)
\]

(18)

The calculation formula of junction temperature of IGBT and diode is:

\[
T_j = \Delta T(t) + T_C = \Delta T(t) + P \times R_{th,ch} + T_h
\]

(19)

3. Simulation verification and analysis

IGBT module FF1000R17IE4D-B2 is selected, and the simulation parameters are shown in Table 1. Infineon's IPOSIM is used for simulation, and the results are compared with those obtained by calculation method, as shown in Table 1.

Table 1. Comparison between simulation value and calculation value

| No. | m   | \(f_0(\text{Hz})\) | Category | IPOSIM simulation          | calculated value          |
|-----|-----|-------------------|----------|---------------------------|---------------------------|
|     |     |                   |          | Switching loss(W)         | Conduction loss(W)         | Switching loss(W)         | Conduction loss(W)         |
| 1   | 0.95| 20                | IGBT     | 505.7                     | 151.3                     | 541.6                     | 166.1                     |
|     |     |                   | Diode    | 273.7                     | 23.7                      | 302                        | 26.8                      |
| 2   | 0.1 | 2                 | IGBT     | 502.5                     | 95.6                      | 541.6                     | 104.8                     |
|     |     |                   | Diode    | 278.3                     | 72.1                      | 302                        | 80.8                      |

It can be seen from Table 1 that the calculated values of conduction loss and switching loss of IGBT and diode are basically consistent with the simulation values, and the error of conduction loss is small, while the error of switching loss is large. Error reason analysis mainly includes: the temperature is off-line during calculation, and the default value is 125°C during calculation, while the value of junction temperature coupling or low junction temperature is considered in simulation, and the conduction loss obtained is the value of actual junction temperature.

The calculation results of junction temperature fluctuation under two working conditions in Table 1...
are shown in Figure 2.

![Figure 2. IGBT junction temperature fluctuation curve](image)

(a) No.1  
(b) No.2

The simulation value of Infineon IPOSIM is compared with the calculated value, as shown in Table 2.

| No. | m  | f₀(Hz) | Category | IPOSIM simulation | Calculated value |
|-----|----|--------|----------|-------------------|------------------|
| 1   | 0.95 | 20     | IGBT     | 68.3°C            | 68.366°C         |
| 2   | 0.1  | 2      | IGBT     | 83.1°C            | 83.088°C         |

It can be seen from Table 2 that the calculated maximum junction temperature is in good agreement with the value simulated by Infineon IPOSIM.

4. Summary
The calculation method of IGBT and diode power consumption in this paper is basically consistent with Infineon's IPOSIM simulation results, and the junction temperature fluctuation calculated by substituting junction-shell transient thermal impedance is basically consistent with Infineon's IPOSIM simulation results. Therefore, the correctness of this calculation method is verified.

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