An Efficient Method to Estimate the Maximum Junction Temperature of IGBT Modules

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Abstract
The heat generated by power losses of IGBT modules must be conducted away from the power chips to the environment. If an appropriate thermal system is not used, the IGBT modules will overheat which can lead to failure. The paper introduces an efficient method to estimate the maximum junction temperature. The calculation of IGBT module’s power loss, the thermal conducting model and the calculation of thermal rise are explained.

1. Introduction
The power loss of IGBT modules contains conduction power losses and switching power losses. The power losses would cause the thermal rise of IGBT chips. If the temperature exceeds the maximum junction temperature, the IGBT modules will be damaged by over temperature. In many applications, the maximum usable output power is determined by the system’s thermal design.
To avoid the failure of the IGBT modules, it’s very important to estimate its junction temperature. Now there’re many methods to calculate the average temperature of IGBT modules, so the power loss calculation and the average temperature of IGBT modules are introduced in brief. The paper focuses on the estimation of the maximum temperature of IGBT modules. The varied power losses of IGBT modules are equivalent to rectangle model, so the detailed thermal rise calculation becomes convenient.

2. The calculation of IGBT module’s power loss

2.1. Constitution of IGBT module’s power loss
The first step in thermal design is the estimation of total power loss. The IGBT power losses contain conduction power loss and switching power loss which contains switching on power loss and switching off power loss. The freewheeling diode power losses contain conduction power loss and reverse recovery power loss.

\[ P_{IGBT} = P_{DC (IGBT)} + P_{SW (IGBT)} \]  
\[ P_{diode} = P_{DC (diode)} + P_{SW (diode)} \]  
\[ P_{total} = P_{IGBT} + P_{diode} \]
In equation (1) (2) (3), \( P_{(IGBT)} \) is the power loss of IGBT; \( P_{DC \ (IGBT)} \) is the conduction power loss of IGBT; \( P_{SW \ (IGBT)} \) is the switching power loss of IGBT; \( P_{(diode)} \) is the power loss of the freewheeling diode; \( P_{DC \ (diode)} \) is the conduction power loss of diode; \( P_{SW \ (diode)} \) is the reverse recovery power loss of diode; \( P_{(total)} \) is the total power loss of IGBT modules.

2.2. Calculation of IGBT module’s power loss

As showed in Fig. 1 and Fig. 2, it’s the typical switching waveforms of turn on, turn off and reverse recovery. Here \( I_c \) is current conducting the IGBT; \( V_{ce} \) is the voltage between IGBT module’s collector and emitter, \( i_E \) is the current conducting the freewheeling diode, \( V_{EC} \) is the voltage between IGBT module’s emitter and collector. We can see the \( P_{DC \ (IGBT)}, P_{SW \ (IGBT)}, P_{DC \ (diode)}, P_{SW \ (diode)} \) in each pulse.

Conduction losses are the losses that occur while IGBT or diode is on and is conducting current. The total power losses during conduction are computed by multiplying the on-state saturation voltage by the on-state current. As a result, we can get the equation as below:

\[
P_{DC \ (IGBT)} = \frac{1}{2\pi} \int_{0}^{t} \left[ I_c \times V_{ce\ (sat)@Ic} \times D(on) \right] dx
\]

\[
P_{DC \ (diode)} = \frac{1}{2\pi} \int_{0}^{t} \left[ I_e \times V_{ec@Ie} \times D(on) \right] dx
\]

In above equations: \( x \) means \( \omega t \), \( I_c/I_e \) means the collector/diode current, \( V_{ce \ (sat)@Ic}/V_{ec @Ie} \) means the saturation voltage of IGBT/diode, \( D \ (on) \) means on-state duty; If we can get \( I_c=f_1(x), V_{ce \ (sat)}=f_2(x), D \ (on)=f_3(x) \), we put these parameters into the equation (4), and we can easily calculate the IGBT on-state power losses. The same method can be used to calculate the diode on-state power losses.

Switching power loss is the power dissipated during the turn-on and turn-off switching procedure. If we sum up all the \( E_{SW \ (on)} \) and \( E_{SW \ (off)} \) in a period of time, and then divided by the period \( T \), we can get the average switching power loss as below functions:

\[
P_{SW \ (IGBT)} = \frac{1}{2\pi} \int_{0}^{T} \left[ E_{on@Ic} + E_{off@Ic} \right] \times fc \ dx
\]

\[
P_{SW \ (diode)} = \frac{1}{2\pi} \int_{0}^{T} \left[ E_{ron@Ie} \times fc \right] \ dx
\]
Here fc is the switching frequency, Eon(@Ic)/ Eoff(@Ic) is the turn on and turn off energy at collector current=Ic. Err (@Ie) is the reverse recovery energy at diode current=Ie;

3. Estimation of IGBT module’s average junction temperature

If the total average power losses of IGBT modules are known, the average junction temperature can be estimated by using thermal resistance concepts.

Fig. 3 shows the thermal conduction model of IGBT modules. From the chart, we can easily estimate the average junction temperature by using the following equations:

\[ T_c = T_f + (P_{IGBT} + P_{diode}) \times R_{th(c-f)} \]  \hspace{1cm} (8)

\[ T_{jave-IGBT} = T_c + P_{IGBT} \times R_{th(j-c)IGBT} \] \hspace{1cm} (9)

\[ T_{jave-diode} = T_c + P_{diode} \times R_{th(j-c)diode} \] \hspace{1cm} (10)

Where: \( T_c \) = IGBT module case’s temperature; \( T_f \) = heat sink’s temperature; \( R_{th(c-f)} \) is the thermal resistance of case to heat sink; \( R_{th(j-c)IGBT} \) is the IGBT’s thermal resistance of junction to case; \( R_{th(j-c)diode} \) is the diode’s thermal resistance of junction to case; All these parameters can be obtained in the datasheet.

Fig. 3. Thermal conduction model of IGBT modules

4. Estimation of IGBT module’s maximum junction temperature

4.1. Principle introduction

The newest IGBT chips can have a maximum rated junction temperature of 175°C. This rating should not be exceeded under any normal operating conditions. To keep high reliability, in actual application, we’d better limit the highest junction temperature to 150°C or less. Especially in the working of low frequency output, the thermal rise of the IGBT junction is very big, it needs us can have an efficient way to estimate the IGBT module’s maximum junction temperature.

As we all know, the junction temperature is in direct proportion to the power loss, and the power loss is in direct proportion to the current which pass the IGBT modules. Because the
diode model is the same to IGBT model, we use the IGBT as the example.

In Fig.4, the first diagram is current conducting IGBT modules. The second diagram is the power loss containing IGBT conduction power loss and switching power loss in every PWM pulse. The third diagram is the average power loss in a cycle, and it’s a constant power loss in steady running conditions, here we suppose it as \( P_{\text{ave}} \).

The last diagram, because the power loss in little current is also very little (such as: \( 0 \sim \pi/6 \) & \( 5\pi/6 \sim \pi \)), we can ignore the power loss during this period. As a result, the power loss of a cycle can be equivalent to a rectangle power loss, and it’s also a constant power loss, here we suppose it as \( P_{m} \). According to the area equivalent principle, we can easily get \( P_{m}=3 \times P_{\text{ave}} \).

In the last diagram of Fig.4, we suppose the time of equivalent rectangle as ‘tp’, and the cycle time as ‘T’. We can use the following equation to estimate the maximum temperature of IGBT chips.

\[
\Delta T_{j,max} = P_{m} \times \left[ \frac{tp}{T} \times R_{\text{th(j-c)}} + \left( 1 - \frac{tp}{T} \right) \times Z_{\text{th(0)+T}} + \frac{Z_{\text{th(D)}}}{2} \right]
\]  

(11)

Where, \( R_{\text{th(j-c)}} \) means the stable thermal resistance, \( Z_{\text{th(0)}} \) means the transient thermal resistance in time \( t \), we can get these values from the IGBT performance curves in datasheet.

4.2. Actual estimation of an example

For example, We use Mitsubishi IGBT module CM1500HC-66R in 3 phase inverter, DC bus voltage \( V_{CC}=1800V \), \( I_{O-RMS}=750A \), PF=0.85, Modulation ratio=1, switching frequency= 0.5kHz,
output frequency= 50Hz, heat sink temperature=80°C, \( R_{g(on)}/R_{g(off)} = 1.6\Omega / 5.6\Omega \).

By using the equations (4)-(7) and (9), we can get the power loss as Table.1:

<table>
<thead>
<tr>
<th>IGBT module</th>
<th>( P_{DC} ) (IGBT)</th>
<th>( P_{SW} ) (IGBT)</th>
<th>( P_{IGBT} )</th>
<th>( \Delta T_{J-IGBT-ave} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1500HC-66R</td>
<td>678.92W</td>
<td>698.20W</td>
<td>1377.12W</td>
<td>11°C</td>
</tr>
</tbody>
</table>

Table.1. Power loss calculation results of CM1500HC-66R

From the above description, we can know:

\[ P_m = 3P_{ave} = 3P_{IGBT} = 4131.36W \]

Fig.5 is the transient thermal resistance curve of CM1500HC-66R. Output frequency =50Hz, \( T=0.02s \), \( tp=0.02/3=0.0067s \), we can check from Fig.5, \( Z_{th(tp+T)} = 0.36 \times 8 = 2.88kW \); \( Z_{th(T)} = 0.32 \times 8 = 2.56kW \); \( Z_{th(tp)} = 0.17 \times 8 = 1.44kW \); We put all the parameters in the equation (15), and we get: \( \Delta T_{J-IGBT-max} = 13.99°C \).

Table.2. Estimation results

<table>
<thead>
<tr>
<th>Output frequency</th>
<th>1Hz</th>
<th>10 Hz</th>
<th>50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation results</td>
<td>28.3°C</td>
<td>18.07°C</td>
<td>13.99°C</td>
</tr>
<tr>
<td>Software results</td>
<td>27.89°C</td>
<td>17.69°C</td>
<td>13.71°C</td>
</tr>
<tr>
<td>Deviation</td>
<td>0.41°C</td>
<td>0.38°C</td>
<td>0.28°C</td>
</tr>
</tbody>
</table>

Fig.5. Transient thermal impedance of CM1500HC-66R

Table.2 is the comparison results of the estimation results and the Melcosim 5.1 results under different output frequencies. From it, we can see the estimation results are almost the same to the software results.

5. Maximum junction temperature estimation at overload

5.1. Maximum junction temperature estimation

Firstly, we need to separate the different overload, such as 1ms @ 200% overload, 1s @ 150% overload, 1minute @ 120% overload. For 1 minute overload, we can take it as the stable working status and calculate the thermal rise by using the stable thermal resistance \( R_{th(j-c)} \). But for 1ms or 1s overload, this method is improper.

In actual applications, it’s difficult to evaluate the transient temperature. If IGBT modules had
been run in a high temperature, overload happens, the maximum junction temperature may exceed the IGBT module’s maximum temperature, so it’s necessary for us to estimate the maximum thermal rise at overload, and we’d better leave some margin in design.

We can use the following equation to estimate the thermal rise of IGBT chips:

\[
\Delta T_{j,\text{IGBT}-\text{max}} = P_{\text{ave}} \times R_{\text{th}(j-c)} + P_{\text{sc}} \times \left[ \left( \frac{t_{p}}{T} - \frac{P_{\text{ave}}}{P_{\text{sc}}} \right) \times Z_{\text{th}(\text{toL})} + \left( 1 - \frac{t_{p}}{T} \right) \times Z_{\text{th}(T)} + Z_{\text{th}(p)} \right] \tag{12}
\]

In which, \( P_{\text{ave}} \) means the average power loss of normal working conditions, \( P_{\text{sc}} \) means the equivalent power loss of overload, \( Z_{\text{th}(\text{toL})} \) means the transient thermal resistance of overload.

5.2. Actual estimation of an example

For example, we use Mitsubishi IGBT module CM1500HC-66R in 3 phase inverter, the working conditions are same as the above 3.2. Now we calculate the thermal rise of 1ms 200% overload.

By using the equations (4)-(7), we can get the 200% overload power loss as Table.3:

<table>
<thead>
<tr>
<th>IGBT module</th>
<th>( P_{\text{DC}(\text{IGBT})} )</th>
<th>( P_{\text{SW}(\text{IGBT})} )</th>
<th>( P_{\text{IGBT}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1500HC-66R</td>
<td>1886.8W</td>
<td>1344.6W</td>
<td>3231.4W</td>
</tr>
</tbody>
</table>

Table.3. Power loss calculation results of CM1500HC-66R @ 200% overload

\( P_{\text{ave}}=1377.12W, P_{\text{sc}}=3 \times 3231.4W=9694.2W, t_{\text{toL}}=1\text{ms}, \) from the equation (16), we can get:

\( \Delta T_{j,\text{IGBT}-\text{max}}=11°C +8.5°C =19.5°C \)

6. Conclusion

The paper introduces an efficient method to estimate the maximum junction temperature of IGBT modules. The power loss calculation and the average junction temperature calculation are also talked. According to the area equivalent principle, the power loss of a cycle can be equivalent to a rectangle power loss. The maximum thermal rise calculation becomes easy and convenient. It’s a simple and useful method in engineering applications.

7. References