Consideration on IGBT Module Lifetime for Electrical Vehicle (EV) Applications

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Abstract
Considering the effects of start and stop, acceleration and deceleration, motor outputs maximum torque at low speed and uphill or motor yields minimum torque at maximum speed on IGBT life, an analysis of IGBT power cycling and thermal cycling capability is made in this paper. It can be summarized that traditional industrial module has the potential risk of life expiration in electric vehicles. EV IGBT T-PM (Transfer-molded Power Module) which focuses on improving power cycling capability and thermal cycling capability can completely satisfy the life requirement of electric vehicle. It provides a reference for the EV inverter design engineers to choose the appropriate IGBT module.

1 Introduction
Energy-saving and environment-protection by adopting EVs has become important development trend for major automobile companies, and many countries have realized the sustainable development of automobile industry. Inverter is one of the most important parts for EV system, and the harsh application conditions such as higher running temperature and frequent start and stop have higher requirements on inverter reliability especially the core components IGBT reliability. Lifetime is one of the important factors of IGBT reliability and mainly decided by the IGBT power cycling and thermal cycling capability.

The start and stop, acceleration and deceleration, motor outputs maximum torque at low speed and uphill or motor yields minimum torque at maximum speed of EV, correspondingly junction temperature fluctuation, when the IGBT module temperature is changing. Repetitive junction temperature fluctuation of IGBT will cause thermal stress between Al wires and power chip bonded surface, which gradually produces crack and finally Al wires breaks away from the power chip, power cycling life expires. Repeated base plate temperature change of IGBT will cause thermal stress between substrate and base plate, which gradually produces crack and results in thermal resistance increasing, cooling capability decreasing, and lead to higher junction temperature failure and thermal cycling life ends.

2 The difference between industrial and EV T-PM structures
Industrial IGBT module and Mitsubishi EV T-PM structures are illustrated as in Fig.1 and Fig.2 respectively:

Fig.1 shows that industrial IGBT module is made up of multilayer, Al wires are bonded on power chip, power chip is soldered on DCB(Direct Copper Bonding) and DCB is soldered on
copper base plate. Different layers use different materials, their coefficients of thermal expansion are also different, as shown in Table 1:

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficient of thermal expansion (CTE) @ T=25°C (298K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum wire</td>
<td>24×10⁻⁶/K</td>
</tr>
<tr>
<td>Silicon chip</td>
<td>2.5×10⁻⁶/K</td>
</tr>
<tr>
<td>Insulation substrate</td>
<td>4.3×10⁻⁶/K</td>
</tr>
<tr>
<td>Copper base plate</td>
<td>16.9×10⁻⁶/K</td>
</tr>
</tbody>
</table>

Table 1 Coefficient of thermal expansion of different materials

Fig. 2 shows that EV T-PM has just lead-to-chip and chip-to-heat spreader structures, the TCIL (thermally conductive electrically insulated layer) and Cu foil layers. Lead-to-chip introduces Direct Lead Bonding (DLB) technology, enlarging bonding surface and increasing power cycling capability. Power chip is soldered on heat spreader, and molded structure can effectively reduce thermal stress of the solder layer and increase thermal cycling capability.

3 The calculation of IGBT power cycling and thermal cycling capability

3.1 Power loss calculation

IGBT module power loss calculation is written as formula (1), (2), (3):

\[ P_{loss} = \sum_{i=1}^{n} P_{loss,IGBT_i} + \sum_{i=1}^{n} P_{loss,Diode_i} \]  

\[ P_{loss,IGBT} = I_C \times V_{CE(sat)} + F_s \times (E_{on} + E_{off}) \]  

\[ P_{loss,Diode} = I_F \times V_F + F_s \times E_{rec} \]

where \( I_C \) is collector current, \( V_{CE(sat)} \) is collector-emitter saturation voltage, \( F_s \) is switch frequency, \( E_{on} \) is turn-on switch loss, and \( E_{off} \) is turn-off loss.

The relationship among IGBT junction temperature \( T_j \), power loss \( P_{loss} \), heat sink temperature \( T_f \) and thermal resistance \( R_{th(j-f)} \) can be given as formula (4):

\[ T_j = T_f + P_{loss} \times R_{th(j-f)} \]

3.2 Power cycling life calculation

Repetitive junction temperature fluctuation of IGBT will cause thermal stress between Al wires and IGBT silicon bonded surface, which gradually produces crack and finally Al wires breaks away from the IGBT chip, power cycling life expires. The calculation of IGBT power cycling life can be written as formula (5):

\[ N_{f1} = C1 \times \Delta T_j^{-m1} \]

where \( N_{f1} \) is power cycling life time, \( \Delta T_j \) is IGBT junction temperature swings, and \( C1, m1 \) are both constants and gained by experiments.
3.3 Thermal cycling life calculation

Repeated base plate temperature change of IGBT will cause thermal stress between substrate and IGBT baseplate, which gradually produces crack and results in thermal resistance increase, cooling capability decreases, and leads to higher junction temperature failure and thermal cycling life ends. The calculation of IGBT thermal cycling life is as follows (6):

\[ N_{f2} = C2 \times \Delta T_{c}^{-m2} \]  

where \( N_{f2} \) is thermal cycling lifetime, \( \Delta T_{c} \) is IGBT copper base plate temperature swings, and \( C2, m2 \) are both constants and gained by experiments.

4 The lifetime comparison between industrial IGBT and EV T-PM

4.1 EV T-PM concept

Based on EV application requirements, Mitsubishi designs EV power module J-series T-PM as Fig.3:

Fig.3 Concept of J-series T-PM

EV T-PM highlights on improving power cycling capability and thermal cycling capability. At 50°C, EV T-PM power cycling life is more than 30 times of industrial IGBT module. The base plate temperature varies from -40°C to 150°C, EV T-PM thermal cycling life is more than 30 times of industrial IGBT module.

4.2 The lifetime comparison

Industrial IGBT module and EV T-PM power cycling life are shown in Fig.4, where blue line represents industrial IGBT module power cycling life curve, and red line represents EV T-PM power cycling life curve. At \( \Delta T_{j}=100°C \), EV T-PM power cycling life is more than 10 times longer than that of industrial IGBT module.

The thermal cycling lifetimes of industrial IGBT is illustrated as in Fig.5. From Fig.5, we can see that the thermal cycling life and base plate temperature swing \( \Delta T_{c} \) relation curve of industrial IGBT, at \( \Delta T_{c}=80°C \), thermal cycling life is 7000 cycles. Fig.6 shows that molded structure can reduce the stress of the solder between the power chips and heat spreader significantly, and then the strain of the solder declined to approximately 25% and increases the power chip bonding reliability. Fig.7 indicates that after 2000 cycles of thermal cycling test (-40°C ~ 125°C), no solder crack was observed. And after 7000 cycles of thermal cycling test (-40°C ~ 150°C), the T-PM has no deteriorating in electrical characteristics.
5 Design Notes on IGBT for EV application

This paper gives a type of EV inverter topology structure as shown Fig.8:

Battery voltage: 250V-400V; Rated power: 30kW; Peak power: 60kW;
Rated current: 200Arms; Peak current: 320A&60s;
Motor rated rotation speed: 1350rpm, peak rotation speed: 2700rpm;
Motor rated torque: 210N.m, peak torque: 420N.m;
Motor stall current: 450APeak&8s.

The inverter adopts water-cooling method, and cooling water flow is 18l/min; the inverter uses industrial IGBT module whose block voltage $V_{CES}$ is 600V, rated current $I_C$ is 600A and maximum operation junction temperature is 125℃.

The paper simulated IGBT and Diode junction temperature at different operation working conditions with Mitsubishi simulation software Melcosim Ver.5.

5.1 IGBT and Diode junction temperature at low frequency with peak current

When EV inverter runs at low output frequency and peak current, and carrier frequency keeps constant, it will cause a IGBT unit operation time with load is longer in a period compared with high output frequency. Therefore, the IGBT maximum operation junction temperature is far beyond average junction temperature. Given output frequency 2Hz, output peak current 320Arms, IGBT and Diode junction temperature are shown as in Fig.9, the IGBT maximum operation junction temperature exceeds allowed 125℃. Large IGBT junction temperature swing will cause much bigger thermal stress and significantly affect IGBT life.

Fig.9 IGBT and Diode junction temperature

5.2 IGBT and Diode junction temperature at peak speed with peak current

When EV inverter runs at peak output frequency 90Hz and peak output current 320Arms, IGBT and Diode junction temperatures are shown as in Fig.10.

Fig.10 IGBT and Diode junction temperature
From Fig. 10, when EV inverter runs at peak frequency, moreover, the motor outputs peak current, IGBT and Diode junction temperature basically keeps constant and within allowed operation junction temperature and swings are also very small.

5.3 IGBT and Diode junction temperature at motor stall condition.

When the motor runs at stall working condition, EV inverter operates at DC chopper working condition, which is also inverter’s worst state. In this case, the inverter is in current-limited state, which limits the current in a stable value by controlling the duty ratio. Then the motor impedance determines the duty cycle. IGBT junction temperature is determined by switching frequency and equivalent duty ratio to a great extent. The paper analyses how equivalent duty ratio affects IGBT and Diode junction temperature.

When EV inverter runs at stall conditions, inverter current, IGBT switching frequency and the motor characteristics decide the IGBT junction and Diode junction temperature. From Fig. 11, when motor equivalent duty ratio is small, such as duty = 0.1, IGBT junction temperature is within the permitted scope of operation temperature, but the parallel diode junction temperature is far more than its maximum junction temperature; From Fig. 12, when motor equivalent duty ratio is bigger as duty = 0.5, IGBT junction temperature rises, the diode junction temperature drops, if inverter current and carrier frequency can be limited in a reasonable scope, IGBT and diode junction can be within permitted operation junction temperature. But in actual operation, except carrier frequency, other factors are difficult to control. Therefore stall conditions greatly affect the power cycle life of IGBT module. Meanwhile, IGBT thermal cycle life will be affected to a certain extent with change of EV working conditions.

6 Industrial IGBT failure analysis for EV application

<table>
<thead>
<tr>
<th>Application Condition</th>
<th>ICES</th>
<th>VCE(sat)</th>
<th>VEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCE=600V</td>
<td>-IC=600A</td>
<td>IC=600A</td>
<td>VGE=15V</td>
</tr>
<tr>
<td>Measurement Value</td>
<td>≤1.0mA</td>
<td>1.7V</td>
<td>1.95V</td>
</tr>
<tr>
<td>Specification</td>
<td>≤1.0mA</td>
<td>≤2.2V</td>
<td>≤2.6V</td>
</tr>
</tbody>
</table>

Table 2 Measurement results of basic electrical properties parameters

When industrial IGBT is applied in EV, on-site running total time is about 3.2 years. The IGBT is checked thoroughly, the measurement results of electrical properties parameters are normal as Table 2.
Ultrasonic testing results show that serious crack appears in solder layer edge between substrate and the base plate, as shown in Figure 13. It can be inferred that on-site EV operation condition will result in repetitive temperature change of IGBT baseplate; repeated base plate temperature change of IGBT will cause thermal stress on solder layer between substrate and IGBT base plate, so significantly affects IGBT thermal cycling life. Thermal resistance $R_{th(j-c)}$ increasing shows that the IGBT thermal cycling life ends, and it’s just about 3-year thermal cycling life in EV application.

When uncovering the industrial IGBT, although the electrical properties parameters are normal, just touching the Aluminum wires, they break off from the IGBT chip as Fig.14, which explains the IGBT power cycling life expires. It can be inferred that on-site EV operation condition will result in repetitive IGBT junction temperature fluctuation and also has big affluence on IGBT power cycling life.

![Fig.13 Solder layer edge cracks between substrate and the base plate](image1)

![Fig.14 IGBT Aluminum wires break off from the IGBT chip](image2)

### 7 Conclusion

From the analysis of the theoretical simulation and on-site application results, the special EV application condition has much higher requirements for IGBT power cycle life and thermal cycle life. Industrial IGBT modules have rather limited life when being used in EV. Usually, if the EV with industrial IGBT modules is expected to the same long life span as traditional fuel vehicles, the IGBT modules used should be replaced regularly. With the advanced Transfer-molded technology Mitsubishi EV T-PM has very high power cycling life and thermal cycling life, which can guarantee power module reliability for EV application.

### 8 References

