Effect of Asymmetric Layout of IGBT Modules on Reliability of Motor Drive Inverters

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Abstract—Power electronics inverters are one of major failure sources in motor drive systems and power devices are one of the main causes of the power electronics inverter failures. Typically, an IGBT module has multiple power devices due to some technical and cost advantages. This kind of configurations could have an asymmetric internal layout, which may lead to different thermal loadings and thereby lifetime difference of the power devices. Therefore, both the power rating and the lifetime of inverters are limited by the most stressed device. However, generally a common data is provided for all devices in the datasheet and this may cause improper design of the inverters in terms of the lifetime and the power rating. In this paper, an effect of an asymmetric layout of IGBT modules on the reliability of motor drive inverters is studied based on a 3-phase motor drive application with a 600 V, 30 A, 3-phase transfer molded IGBT module. The thermal impedances of 6 IGBTs are investigated and its effect on thermal loadings of power devices is studied under the given mission profile. Then, their lifetimes are estimated and compared. Finally, this effect is verified by the experiments.

Keywords—Motor drives, inverter, reliability, IGBT module.

I. INTRODUCTION

Motor drive systems have been widely used in various applications such as ship propulsion, rail traction, steel mills, water pump system, home appliance and nowadays their use has been extended to aerospace, electric vehicle and etc [1]-[2]. As roles of motor drive systems have gradually increased, the reliability of motor drive systems is getting important issue because it is very closely related to the cost aspect as well as the safety aspect. According to [3], power electronics inverters are one of major failure sources in motor drive systems and power devices are one of main causes of power electronic inverter failures [4]. Therefore, much research has been performed on the reliability of power devices such as condition monitoring, fault detection and fault-tolerant controls [5]-[10]. Further, recently, the lifetime prediction of power devices in power electronic inverters is one of major concerns and possibilities for Design for Reliability (DFR) [11]-[12].

Wire-bonded IGBT modules are one of the most widely used of their kind for various applications in a power range from several hundreds of watts (W) to several megawatts (MW) [13]. The wire-bonded IGBT module consists of different materials and it is well known that thermal stress is a main cause of package-related failures because the thermomechanical stress is applied to the point of contact of different materials under temperature variation due to the Coefficient Thermal Expansion (CTE) mismatch between different materials [14].

There are typically multiple power devices inside an IGBT module for some advantages [15]. However, this kind of configurations could have an asymmetric layout and thus results in thermal impedance differences among power devices. Thereby, they have different thermal loadings in real applications that might lead to discrepancy in the lifetime of the power devices. Therefore, both the lifetime and the power rating of an inverter are limited by the most stressed device. However, typically a common data for all power devices are provided in the datasheet and it causes the improper design of inverters in terms of the lifetime and the power rating.

In this paper, an effect of an asymmetric layout of IGBT modules on the reliability of power inverters is studied based on a 3-phase motor drive application using 600 V, 30 A, 3-phase transfer molded IGBT module. The thermal impedances of 6 IGBTs are investigated and its effect on the thermal loadings of the power devices is studied under the given mission profile of the motor drive system. Then, the lifetimes of power devices are estimated from the thermal loadings and compared. Finally, this effect is verified by the experiments.

II. TRANSFER MOLDED IGBT MODULE FOR MOTOR DRIVE INVERTERS

A. Molded power IGBT module

Transfer molded IGBT modules are widely used in low power motor drive applications such as water pumps and home appliances due to their advantages like compactness, low cost, and high reliability [16]. In the case of inverter modules for low power 3-phase motor drives, they generally consist of 6 IGBTs and 6 diodes. Such kind of configurations could have an asymmetric internal layout and thereby leads to thermal impedance differences among devices.

Fig. 1. Transfer molded IGBT module (a) physical appearance (b) cross section structure.
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Fig. 2. Internal layout of the molded IGBT module shown in Fig. 1.

Fig. 3. Transient thermal impedances of the 6 IGBTs in the molded IGBT modules.

Fig. 4. Lifetime estimation procedure of IGBT modules in power converter applications [17].

III. LIFETIME OF MOLDED POWER IGBT MODULE IN MOTOR DRIVE SYSTEM

In order to investigate the effect of the thermal impedance difference on the reliability of the upper and lower IGBTs, a case study is carried out with a specific mission profile of a motor application. $T_{VL}$ and $T_{UL}$ are considered in this case study because they have the largest thermal impedance mismatch and the thermal impedances of $T_{UL}$, $T_{VL}$ and $T_{WH}$ are almost the same. The thermal loadings of $T_{VL}$ and $T_{UL}$ are investigated and then the lifetimes are estimated based on their thermal loadings.

Fig. 4 shows the whole procedure to estimate lifetimes of power devices in an IGBT module [17].

In the first step, loss profiles of power devices are obtained from input data such as device characteristics, converter characteristics and mission profiles of power converter applications. Then, the loss profiles of power devices are converted to temperature profiles by thermal models of power devices. In step 3, the different temperature stress factors such as junction temperature swing ($\Delta T$) and mean junction temperatures ($T_{jm}$) are counted from the temperature profiles by using a Rainflow counting method [18]. Finally, lifetimes of power devices in the IGBT module are predicted based on a Linear Damage Accumulation rule by putting the accounted temperature stress factors into a lifetime model, which are typically developed by power cycling tests.

A. Motor drive system

Fig. 5 shows a configuration of a 3-phase motor drive system with Permanent Magnet Synchronous Motor (PMSM) for the case study and related parameters for the motor drive inverter and PMSM are listed in TABLE I.

Fig. 6 shows a mission profile composed of information on torque and speed profiles. The maximum torque is 24 Nm and the maximum speed is 2000 rpm. The motor is operated for 15 s with the maximum torque and the maximum speed with 2 s ramp-up time and it is stopped for 15 s.
Thus, the one period of the mission profile is 30 s. This is one of typical start-run-stop processes in motor drive applications. The corresponding output currents and reference voltages of the motor drive under the given mission profile are shown in Fig. 7.

B. Power loss profiles

In order to get the thermal loadings of \( T_{VH} \) and \( T_{VL} \), the power loss profiles of \( T_{VH} \) and \( T_{VL} \) should be obtained first.

The total power loss of the IGBT is composed of a conduction loss (\( P_{\text{cond}} \)) and a switching loss (\( P_{\text{sw}} \)).

The average conduction loss in one switching cycle can be represented as

\[
P_{\text{cond}}(T_{v}/T_{j}) = V_{CE\_ON}(T_{v}/T_{j}) \cdot I \cdot d
\]

(1)

where \( I \) is the collector current, \( d \) is the duty cycle and \( V_{CE\_ON}(T_{v}/T_{j}) \) is the on-state collector-emitter voltage at the certain reference junction temperature \( T_{H} \) or \( T_{L} \).

The switching loss of the IGBT is calculated as

\[
P_{\text{sw}}(T_{v}/T_{j}) = f_{\text{sw}} \cdot E_{\text{sw}}
\]

(2)

where \( f_{\text{sw}} \) is the switching frequency and \( E_{\text{sw}} \) is the switching energy of the IGBT at the certain reference junction temperature \( T_{H} \) or \( T_{L} \).

Fig. 8 shows \( V_{CE\_ON} \) and \( E_{\text{sw}} \) of the IGBTs when the junction temperatures are 125 °C (\( T_{H} \)) and 25 °C (\( T_{L} \)).

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Fig. 8 shows \( V_{CE\_ON} \) and \( E_{\text{sw}} \) of the IGBTs when the junction temperatures are 125 °C (\( T_{H} \)) and 25 °C (\( T_{L} \)), respectively. Those values can be found in the datasheet or by experiments.

It is known that both switching and conduction losses are dependent on junction temperature and thus junction temperature information of power devices should be included when power losses are calculated.

Consequently, the conduction loss and the switching loss of the IGBT at the certain junction temperature can be computed as

\[
P_{\text{cond}}(T_{v}/T_{j}) = \frac{P_{\text{cond}}(T_{v}/T_{j}) - P_{\text{cond}}(T_{v}/T_{j})}{T_{H} - T_{L}} (T_{j} - T_{L}) + P_{\text{cond}}(T_{v}/T_{j})
\]

(3)

Fig. 9 shows the loss profiles of \( T_{VH} \) and \( T_{VL} \) under the given mission profile shown in Fig. 6.
C. Thermal profile and lifetime estimation

The thermal loading of each device can be obtained from the power loss profiles and a thermal model with thermal impedances. In this paper, the thermal model proposed in [19] are used as shown in Fig. 10 in order to translate the power loss profiles into the thermal loadings of the devices. This thermal model has two thermal paths.

The first thermal path is used for the junction temperature estimation. In this path, the multi layer RC Foster thermal network is used. The RC Foster thermal network is represented as

$$Z_{th\left(j-c\right)}(t) = \sum_{i=1}^{n} R_i (1 - e^{-t/\tau_i})$$  \hspace{1cm} \text{(4)}$$

where $Z_{th\left(j-c\right)}$ is the junction to case thermal impedance, $\tau_i = R_i * C_i$ and $i$ means the different layers of power module for the Foster model. The related parameter can be obtained from datasheet or experiments. In this path, only the reference temperature $(T_{ref})$ is connected, where the $T_{ref}$ is determined by the case temperature $T_c$ from the other thermal path.

The second thermal path is used for the temperature estimations outside IGBT module such as case and heat-sink temperatures. In this path, the filtered power loss by a low pass filter (LPF) is used to model the loss behaviors flowing out of the device, where the parameters for the LPF can be extracted from the RC Foster thermal network in the first thermal path. The filtered loss can help to obtain correct temperature behavior outside the IGBT module.

The thermal impedances of $T_{VIH}$ and $T_{VL}$ and the related thermal impedances for this study are listed in the TABLE II. In this simulation study, it is assumed that the heat-sink temperature is 35 °C.

<table>
<thead>
<tr>
<th>Impedance</th>
<th>IGBT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{dij-c}$ (Junction to case)</td>
<td>$T_{VIH}$</td>
<td>$R$</td>
<td>0.6667</td>
<td>0.4060</td>
<td>0.3720</td>
</tr>
<tr>
<td></td>
<td>$T_{VL}$</td>
<td>$C$</td>
<td>0.2419</td>
<td>0.0583</td>
<td>1.3502</td>
</tr>
<tr>
<td>$Z_{dij-kc}$ (Case to heat-sink)</td>
<td>$R$</td>
<td>0.4221</td>
<td>0.8770</td>
<td>0.3717</td>
<td>0.0820</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C$</td>
<td>1.1793</td>
<td>0.1937</td>
<td>0.0642</td>
</tr>
</tbody>
</table>

Fig. 11 shows the thermal loadings of $T_{VIH}$ and $T_{VL}$ under the given mission profile of the motor drive system shown in Fig. 6.

In the LDA rule [17], [20], In the LDA rule, if there are $k$ different stress levels and a certain material is exposed to $a_i$ stress for a certain number of cycles $n_i$ and the number of cycles to failure at $a_i$ stress is $N_i$, a damage $(D)$ can be represented as

$$D_i = \frac{n_i}{N_i}$$  \hspace{1cm} \text{(5)}$$

where $n_i$ is the number of cycles accumulated at $a_i$ stress, $D_i$ is damage of life consumed by exposure to the cycles at $a_i$ stress level.
The total damage at different stress levels can be added up for a total Accumulated Damage (AD) as given in (6) if different stress levels lead to the same failure mechanism.

\[
AD = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_{k-1}}{N_{k-1}} + \frac{n_k}{N_k}
\]  

Finally failure occurs, when a total accumulated damage is reached to 1.

In this paper, the Semikron lifetime model presented in [15] is used since there is no existing lifetime model for the target IGBT module. Therefore, the lifetime value should be considered only for the purpose of the lifetime comparison between \( T_{VH} \) and \( T_{VL} \). 

Fig. 12 shows the accumulated damage of \( T_{VH} \) and \( T_{VL} \) based on the Semikron lifetime model during a period of the mission profile. The lifetime can simply be calculated as below

\[
\text{Lifetime} = \frac{\text{Period of mission profile(s)}}{\text{Operating time(s)} \times \text{Accumulated damage}}
\]  

If it is assumed that the motor system is operated for 12 hours per day, based on (7), the corresponding estimated lifetimes of \( T_{VH} \) and \( T_{VL} \) are about 9 years and 5.6 years, respectively. The lifetime of \( T_{VL} \) is about 38 % shorter than that of \( T_{VH} \). In other words, the IGBTs in the lower group \( (T_{UL}, T_{VL}, T_{WL}) \) are the most reliability-critical devices and thus the lifetime of the inverter could depend on the lower group of IGBTs.

IV. EXPERIMENTAL RESULTS

Experiments have been carried out in order to verify the effect of asymmetric layout of IGBT modules on the reliability of motor drive inverters.

The same IGBT module with the simulation study, which is 600 V, 30 A 3-phase transfer molded IGBT module has been used for the experiments. The IGBT module is opened as shown in Fig. 13 and painted by black paint in order to measure junction temperatures of \( T_{VH} \) and \( T_{VL} \) by high-resolution Infra-Red camera (FLIR X8400sc) when it is operated under the given mission profile of the motor drive system.

Fig. 14 shows the output current of the phase-V when the motor drive inverter is operated under the given mission profile as shown in Fig. 7 and TABLE I. The heat-sink temperature is controlled as 25 \( ^\circ{}C \) and 68 \( ^\circ{}C \). The reason that \( T_{VL} \) has a higher junction temperature than \( T_{VH} \) in terms of junction temperature swing and the mean junction temperature due to the unbalance of the thermal impedance, which is caused by the internal asymmetric layout. Therefore, it can be expected that \( T_{VL} \) has a shorter lifetime than \( T_{VH} \). 

Fig. 16(a) and (b) show the figures of \( T_{VH} \) and \( T_{VL} \) taken by the Infra-Red camera when they have the maximum temperatures, respectively. It can be clearly seen that \( T_{VL} \) has a higher junction temperature than \( T_{VH} \). 

Furthermore, the power cycling test has been performed in order to verify that the IGBTs in the lower group \( (T_{UL}, T_{VL}, T_{WL}) \) have shorter lifetimes than the IGBTs in the upper group \( (T_{UL}, T_{VL}, T_{VH}) \). The power loading that output current \( (I) = 29 \) A, peak output voltage \( (V_{out}) = 140 V_{peak} \) and output frequency \( (f_{out}) = 1 \) Hz is applied to the IGBT module, where the heat-sink temperature is controlled as 25 \( ^\circ{}C \). The reason that \( f_{out} \) is set to 1 Hz is to get the thermal loading in a second range easily by the output current and also to get the high thermal loading in order to get the test result in a reasonable testing time.
The end-of-life (EOL) criterion of the IGBT module is 5% increase of $V_{CE\_ON}$ from its initial value. $V_{CE\_ON}$ of the 6 IGBTs are measured in real-time per temperature cycle when the current is $\pm 20 A_{peak}$. More detailed information on power cycling test can be obtained in [10], [21].

Fig. 17 shows the power cycling test result of the IGBT module. As expected, $V_{CE\_ON}$ of the IGBTs in the lower group ($T_{UL}$, $T_{VL}$, $T_{WL}$) increases earlier where $V_{CE\_ON}$ of $T_{UL}$ is reached to the end-of-life criterion first at about 420800 cycles. It can also be expected that the other lower IGBTs will be reached to EOL criterion soon. However, in the case of the IGBTs in the upper group ($T_{UH}$, $T_{VH}$, $T_{WH}$), there are no any visible increases in $V_{CE\_ON}$.

The power cycling test with another 600 V, 30 A 3-phase transfer molded IGBT module also has been performed under the same condition as shown in Fig. $V_{CE\_ON}$ of $T_{WH}$ is reached to the end-of-life criterion first at about 303527 cycles and it is also expected that $V_{CE\_ON}$ of $T_{UL}$ will increase to the end-of-life criterion. On the other hand, the increases in $V_{CE\_ON}$ of the upper IGBTs ($T_{UH}$, $T_{VH}$, $T_{WH}$) is not observed during the power cycling test.

These two test results clearly show that the IGBTs in the upper group ($T_{UH}$, $T_{VH}$, $T_{WH}$) have longer lifetimes than the IGBTs in the lower group ($T_{UL}$, $T_{VL}$, $T_{WL}$) because the lower IGBTs have higher thermal loadings than the upper IGBTs due to the differences of the thermal impedances.

It is worth to mention that the initial $V_{CE\_ON}$ of the lower IGBTs are higher than that of the upper IGBTs. This is because the lower IGBTs have the higher internal resistance due to longer current path in this module and also higher junction temperature at the point of $V_{CE\_ON}$ measurement due to the different thermal impedance between the upper and lower IGBTs.

More detailed information on the internal resistance of the target IGBT module can be obtained in [22]. Furthermore, the effect of asymmetric layout of another type of IGBT module on the reliability of inverters has been validated with a small-scaled Modular Multilevel Converter (MMC). A full-bridge IGBT module manufactured by Infineon (F4-50R12KS4) is used for a sub-module of the MMC. Junction temperatures of upper and lower IGBTs of one leg in the full-bridge IGBT module are measured. In this paper, the sub-module of the MMC is operated under the following conditions; DC-link voltage ($V_{DC}$): 100 V, output current ($I$) = 40 $A_{peak}$, modulation index = 0.8, switching frequency ($f_{SW}$) = 2 kHz and output frequency ($f_{out}$) = 50 Hz. The upper IGBT is represented as $S_1$ and the lower IGBT is denoted as $S_2$.

Fig. 18 shows the average junction temperatures of $S_1$ and $S_2$ measured by the Infra-Red camera for 120 s. The junction temperatures of $S_1$ and $S_2$ increase continuously because the heat-sink temperature is not under the steady-state condition. However, it can be clearly seen that $S_1$ has a higher junction temperature than $S_2$ due to the different thermal impedance caused by the asymmetric layout of the IGBT module. Therefore, they have the different thermal loadings in real applications and thus it can be expected that $S_1$ has a shorter lifetime than $S_2$.

Fig. 20(a) and (b) show the figures of $S_1$ and $S_2$ taken by the Infra-Red camera when they have the maximum temperatures, respectively. It can be clearly seen that $S_1$ has a higher junction temperature than $S_2$. 
This study has been performed with 600 V, 30 A, 3-phase full-bridge IGBT module in the sub-module of the small-scaled Modular Multilevel Converter. Due to the asymmetric layout of the IGBT module, the upper and lower IGBTs in one leg also have different junction temperatures. From above result, it can be expected that other kinds of IGBT modules can have an asymmetric internal layout and therefore, they can affect the reliability of inverters for other different power electronic applications such as PV inverter, wind turbine converter, electric vehicle and so on.

This study can provide a feedback to module designers on optimizing module’s internal geometry such as a layout of a DBC so that power devices in power modules have thermal impedances as similar as possible for even lifetime distributions. Further, it can also give suggestions for application engineers when inverter is designed with the target lifetime and the power rating.

V. CONCLUSION

In this paper, an effect of asymmetric layout of IGBT modules on the reliability of power inverters has been studied. This study has been performed with 600 V, 30 A, 3-phase molded IGBT modules under the 3-phase motor drive application.

Due to the asymmetric internal layout of the IGBT module, the 6 IGBTs have the different thermal impedances and especially the lower IGBTs have higher thermal impedances than the upper IGBTs. Because of this, the IGBTs have the different thermal loadings under the given mission profiles of the motor drive application and finally leads to mismatched lifetimes. The lifetime of $T_{IL}$ is shorter about 38 %, which is 5.6 years than that of $T_{UH}$, which is 9 years. Consequently, the lower IGBTs ($T_{UL}$, $T_{VL}$, $T_{VH}$) are the most reliability-critical devices. Thus, the lifetime and the power rating of the inverter may be limited by the lower group of the IGBTs. However, generally a common data is provided for all devices in datasheet and this may cause improper design of the inverter in terms of the lifetime and the power rating.

This effect has been verified by the experiments. As expected, the lower IGBTs have higher thermal loadings than the upper IGBTs and therefore have shorter lifetimes.

Furthermore, this effect has also been validated with the full-bridge IGBT module in the sub-module of the small-


