Junction temperature estimation method for a 600 V, 30 A IGBT module during converter operation

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This paper proposes an accurate method to estimate the junction temperature using the on-state collector-emitter voltage at high current. By means of the proposed method, the estimation error which comes from the different temperatures of the interconnection materials in the module is compensated. Finally, it leads to satisfactory estimated results. The proposed method has been verified by means of an IR (Infra-Red) camera during power converter operations when the loading current is sinusoidal.

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1. Introduction

Power devices are one of the most fragile components in overall power electronic systems, and thermo-mechanical stresses due to temperature and temperature cycling in power device modules are the main causes of failure [1–3]. Therefore, the junction temperature is a prime parameter to be concerned about for reliability, when converters are designed and operated. Typically, there are two main approaches in junction temperature measurement which are direct and indirect methods. The junction temperature measurement by direct methods such as Infra-Red cameras and optical fibers require the modification of the power device module structure. Therefore, this approach is not suitable for real converters. On the other hand, the indirect methods using Thermo-Sensitive Electrical Parameters (TSEPs) could be useful for real-time junction temperature measurement in converter operation because it does not need to modify the power device module structure. Therefore, many researchers have proposed methods to estimate the junction temperature using Thermo-Sensitive Electrical Parameters (TSEPs) [4–6]. In [7], the main methods used to estimate junction temperature with TSEPs have been presented and compared considering seven comparison criteria. In such a paper, it is concluded that the on-state collector-emitter voltage \( V_{CE,ON} \) calibrated at low currents seems to be the most suitable TSEP. However, this method is unsuitable for converter applications because the converter operation has to be interrupted in order to do that [8]. If the \( V_{CE,ON} \) at high currents is used as TSEP, the junction temperature could be estimated without any interruptions during normal operations. In addition, it could be a good indicator to determine the wear-out condition of the power device modules.

Along this research track, a junction temperature estimation method using a short circuit current has been proposed recently [9]. However, its applicability is quite debatable because the related repetitive short circuit stress can accelerate the degradation of the device.

Among the other difficulties, it is worth to point out that there is also a major drawback of the method using \( V_{CE,ON} \) at high current: the different voltage drops on the electrical connections due to non-homogeneous temperature distribution during real converter operation cause also large estimation errors [10].

In this paper, a novel principle to estimate the junction temperature using the \( V_{CE,ON} \) in converter operation is proposed. The adopted topology and switching sequence for an I–V characterization of power devices are described first. Then, a technique to compensate the influence of the temperature of interconnection materials in the module is proposed. Finally, a proof-of-concept of the proposed method is given.

2. Preliminary I–V characterization

A preliminary calibration is necessary to estimate the junction temperature from TSEPs. The purpose is to obtain the dependence of temperature on the \( V_{CE,ON} \) and \( V_f \) for the IGBTs and diodes, respectively. Of course, the data for the calibration can be obtained from the manufacturer’s data sheet, but it is not accurate enough to this aim. The test equipment such as V/I curve tracer can be used to get more
precise and various data. However, such equipment is considerably expensive.

In this section, an I–V characterization method of the power devices under test is presented. Fig. 1 shows a schematic of the proposed topology and switching sequences for low side switch TL and high side diode DH in the tested module. The tested module, i.e., a bridge leg is connected with the load module through an inductor.

From the simple switching sequences with on-line on-state VCE measurement [11], the I–V characterization curves for the junction temperature estimation can be obtained. The heat-sink temperature is controlled by an external system. After a while, once the thermal steady-state condition is reached, the junction temperature becomes equal to the heat-sink one and the TL and TH₁ are turned on as shown in Fig. 1(a). The current level can be changed by varying the dwell time of turn-on state of TL and TH₁. Then, the TH₁ is turned off so that the current flows through TL and DL₁ as shown in Fig. 1(b). The VCE_ON of TL and the current are measured at this point. After the VCE_ON and the current are measured, the TL is turned off in order to reduce the current to zero as shown in Fig. 1(c). In the case of DH, TL is turned off. The current flows through DH and TH₁ as shown in Fig. 1(d). The forward voltage of DH and the current are measured at this point and then TH₁ is turned off to make the current zero. This switching sequence is performed by changing the current level from the minimum value to the rated current value under the same temperature and then it is performed again in different temperature levels. Each switching sequence is performed in a short period (less than 200 us in this paper). During this period, thermal impedance and the loss of the device are very small. Therefore, the Tj increase during the switching sequence is negligible. In the present work, a 600 V, 30 A, Smart Power Module (SPM) from Fairchild Corp. is used for the case study. The low side IGBT of the phase V among the 3 phases U–V–W of the module is the target device.

3. Junction temperature estimation from I–V characterization curves

It is needed to derive the $V_{CE,\text{ON}}$ as a function of the temperature at a given current level in order to estimate the junction temperature ($T_j$) from the I–V characteristic curves of Fig. 2. To derive the relation between the $V_{CE,\text{ON}}$ and $T_j$, the $V_{CE,\text{ON}}$ should be formalized as a function of current. This can be achieved by a polynomial fitting method. Then, the temperature can be represented as a function of the $V_{CE,\text{ON}}$ at a given current. The temperature variation according to the $V_{CE,\text{ON}}$ can be represented by a Slope Factor (SF) as shown in Fig. 3. From the above relations, $T_j$ can be estimated from the measured current and the $V_{CE,\text{ON}}$ as follows

$$T_{j,\text{est}} = SF(I) \times (V_{CE,\text{M}} - V_{CE,\text{B}(I)}) + T_B$$

where $SF(I)$ is the slope factor as a function of the current, $V_{CE,\text{M}}$ is the measured on-state $V_{CE}$ in real time, $V_{CE,\text{B}(I)}$ is the base on-state $V_{CE}$ as a function of current which can be chosen among the characterization curves. $T_B$ is the base temperature corresponding to base on-state $V_{CE}$. 

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However, it is worth to note that packaged devices do not permit to solely measure the $V_{CE\_ON}$.

In fact, each device is connected to the output pins through a series of interconnections, like bond wire and traces. Furthermore, in SPMs, control Integrated Circuits (ICs) with Printed Circuit Board (PCB) are embedded inside the module. Therefore, the measured $V_{CE\_ON}$ definitely includes the voltage drops on various interconnections elements as follows

$$V_{CE\_ON} = V_{CE\_Chip} + R_{int} \times I$$  \hspace{1cm} (2)

where $V_{CE\_Chip}$ is the real on-state collector-emitter voltage of the chip, $R_{int}$ is the equivalent resistance of the interconnections elements and $I$ is the collector current.

4. Proposed junction temperature estimation method

4.1. Resistance change in an IGBT module according to temperatures

To investigate the effect of temperature on the resistance in the IGBT module, the resistance of the interconnection materials in the IGBT module is measured using a four-point probing approach. The open module is used to contact the probe to the emitter and collector of the device.

Fig. 4 shows the four-point probing method to measure the interconnection resistance. The resistances from negative DC-link input pin to emitter and collector to output pin of low side IGBT and from positive DC-link input pin to collector and emitter to output pin of high side IGBT are measured by applying a DC current.

Two different currents (1A and 5A) have been used to check the effect of self-heating during the measurement. Moreover, two IGBT modules have been used for measurements. Fig. 5 shows the total resistance values of high and low side IGBTs. No big differences are observed in the resistances between the cases 1 A and 5 A and between two modules. From the results, it can be concluded that the self-heating effect by the applied current is negligible. Further, the Resistance Variation Factor (RVF) according to temperature can be obtained. Measurements of Fig. 5 yield 0.036 mΩ/°C and 0.0234 mΩ/°C for low side and high side IGBTs, respectively.

4.2. Compensation of the effect of interconnection resistance

As analyzed above, the interconnection resistances are significantly changed by temperatures, affecting the measured voltage drop.

Fig. 6 shows the qualitative time diagram temperatures in the modules corresponding to an AC current, where $T_{J\_real}$ is the real junction temperature, $T_{J\_est}$ is the estimated junction temperature using $V_{CE\_ON}$ and $T_{R\_int}$ is the average temperature of the interconnection materials in the modules. The interconnection materials are represented by one equivalent resistor with an average temperature. If the $T_{R\_int}$ is the same as $T_{J\_real}$, $T_{J\_est}$ would be the same as $T_{J\_real}$. However, $T_{R\_int}$ is not the same as $T_{J\_real}$ under converter operation and it leads to lower $V_{CE\_ON}$ measurement than the one under the characterization condition, even though, the junction temperatures are the same. Consequently, the estimated junction temperature by the $V_{CE\_ON}$ at high current is smaller than the real one. Therefore, it is necessary to compensate the voltage drop caused by the different temperature of interconnection materials.

However, it is very challenging to know the temperature of each part of interconnection materials during real operations.

A reasonable assumption which has been supported by the experimental observation is that the temperature difference between $T_{J\_real}$ and $T_{R\_int}$ during one fundamental period of the output current has the similar trend with the temperatures as shown in Fig. 6. Therefore,
it can be expressed as Eq. (3) and the resistance variation can be represented as Eq. (4). Therefore, on-state voltage compensation $V_{CE\_comp}$ can be expressed as Eq. (5)

$$T_{J,\text{real}} - T_{Rint} = \frac{\alpha}{C_2} \left( T_{J,\text{test}} - T_H \right) C_0/C_1$$

$$\Delta R_{int} = \frac{\alpha}{C_2} \left( T_{J,\text{test}} - T_H \right) \times \text{RVF}$$

$$V_{CE\_comp} = \frac{\Delta R_{int}}{I} = \frac{\alpha}{C_2} \left( T_{J,\text{est}} - T_H \right) \times \text{RVF} \times I$$

where $T_H$ is the heat-sink temperature, $\alpha$ is the scaling factor, RVF is the resistance variation factor and $I$ is the output current. Finally, the junction temperature can be corrected as

$$T_{J,\text{est\_comp}} = SF(I) \times \left( V_{CE,A\_est} - V_{CE,B\_est} + V_{CE\_comp} \right) + T_B.$$  

To find the scaling factor for the test module, an IR (Infra Red) camera and a black-painted open module have been used. By comparing the measured junction temperature by IR camera with the estimated one, the scaling factor $\alpha$ can be found. $\alpha$ and RVF factors are different according to the types of modules because they have different resistance and different structures. For this reason, it is difficult to generalize both factors for all modules. Therefore, efforts to find $\alpha$ and RVF are still needed. Further, if the scaling factor $\alpha$ and RVF for each type of modules are provided from the manufacturer based on the proposed approach, the user can estimate the junction temperature more precisely with the proposed method.

5. Experimental results

Experiments have been carried out in order to verify the validity of the proposed method. The junction temperature ($T_J$) has been measured by an IR camera in order to compare it with the estimated value. The $V_{CE\_ON}$ has been measured by the circuit proposed in [11]. It is worth to point out as a non-uniform temperature distribution is typically observed in the chip surfaces [6,7]. Therefore, the average temperature of the chip area has been used for comparison.

Fig. 7(a) shows the $T_J$ measured by the IR camera when the converter is operated under the following conditions: $I = 30$ A, $V_{DC} = 400$ V, $f_{sw}$ (switching frequency) = 10 kHz, $f_{OUT}$ (output frequency) = 3 Hz, $T_H$ (Heat-sink temperature) = 50 °C, RVF = 0.036 m$\Omega$/°C, $\alpha = 0.85$. The maximum $T_J$ is about 119 °C and the minimum is about 70.2 °C. Fig. 7(b) shows the estimated $T_J$ before and after the compensation whose difference is about 16.9 °C. The maximum compensated $T_J$ is about 117.5 °C, yielding an error of less than 2 °C with respect to the measured value. The estimated temperature agrees well with the measured value.

The junction temperature estimations have also been performed at different operating conditions. Fig. 8 shows the measured and estimated junction temperatures when the $T_H = 65$ °C and $I = 30$ A. The measured maximum

![Image](https://via.placeholder.com/150)

Fig. 9. Junction temperature when $I = 25$ A, $f_{OUT} = 3$ Hz and $T_H = 50$ °C (a) IR camera measurement and (b) estimation.

![Image](https://via.placeholder.com/150)

Fig. 10. Junction temperatures when $I = 30$ A, $f_{OUT} = 5$ Hz and $T_H = 50$ °C (a) IR camera measurement and (b) estimation.

![Image](https://via.placeholder.com/150)

Fig. 11. Junction temperatures when $I = 30$ A, $f_{OUT} = 20$ Hz (a) $T_H = 50$ °C and (b) $T_H = 65$ °C.

<table>
<thead>
<tr>
<th>$f_{OUT}$</th>
<th>$T_H$ (°C)</th>
<th>$I_{peak}$ (A)</th>
<th>Method</th>
<th>$T_J$ (°C)</th>
<th>Error (°C)</th>
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<tr>
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<td>Estimation</td>
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<td>25</td>
<td>IR camera</td>
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<td>-1.3</td>
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<td></td>
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<tr>
<td></td>
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<td>25</td>
<td>IR camera</td>
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<tr>
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<td>0.6</td>
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<tr>
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<td>50</td>
<td>30</td>
<td>IR camera</td>
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<td>2.3</td>
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<td>30</td>
<td>Estimation</td>
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<td></td>
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<td>IR camera</td>
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<td>1.2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Estimation</td>
<td>83.5</td>
<td></td>
</tr>
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</table>

Table 1 Comparison of the junction temperature estimation at different operating conditions.

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temperature is about 137.1 °C and estimated one is about 134.8 °C. The error is about 2.3 °C.

The measured and estimated temperature when I = 25 A and T_H = 50 °C are shown in Fig. 9. The estimated and measured values are 100.8 °C and 102.1 °C, respectively. As the above results, the junction temperature is estimated well under the different current and heat-sink temperature conditions.

Fig. 10 shows the measured and estimated junction temperatures when f_OUT = 5 Hz, I = 30 A, and T_H = 50 °C. The measured temperature is about 111.5 °C and the estimated one is about 113.5 °C. The estimated results when the T_H = 65 °C and I = 25 A, respectively, are listed in Table 1. In all cases of 5 Hz, the errors are less than 2 °C.

Fig. 11 shows the estimated results when I = 30 A, f_OUT = 20 Hz with different heat-sink temperatures. When T_H = 50 °C, the estimated temperature is about 100.2 °C and the measured value is 97.5 °C. The junction temperature is a little bit over estimated in this case. The error is about 2.7 °C. In the case of 65 °C, the estimated value is also over estimated by 2.5 °C.

Fig. 12 shows the junction temperature estimation results when f_OUT = 50 Hz and T_H = 50 °C with different currents. Even in this case, the estimation errors are about 3 °C and 1.2 °C when I = 30 A and 25 A, respectively.

All estimation results are summarized in Table 1.

As shown in Table 1, the estimated junction temperatures by the proposed method are in good agreement with the measured temperatures by the IR camera at various operating conditions. It is worth to point out that uncertainties come also from the IR measurement technique. First, the response of IR camera is not fast enough to measure the correct maximum temperature when the output frequency goes beyond several tens of Hz. Therefore, the maximum temperatures under these conditions are little bit higher than the measured values leading to a smaller error than current values. Second, the measured temperatures are the average ones. For this reason, according to the area that is considered for mean temperature, the measured value can be slightly changed. Furthermore, the black paint and the shading effect of the bond wire can also affect to the measured temperature value. Nevertheless, it can be seen from the results that the accuracy of the junction temperature estimation using the V_CE_ON at high currents is significantly improved by the proposed method.

6. Conclusion

In this paper, an accurate method to estimate the junction temperature using the V_CE_ON at high current has been proposed. A topology and the related switching sequences for the characterization of power devices have been introduced first. By the proposed topology and the simple switching sequence with online V_CE_ON measurement, the power devices can be characterized regarding V_CE_ON without any expensive equipment. Then, the junction temperature estimation method using V_CE_ON at high currents and its limitation has been discussed. Finally, the method to improve the accuracy of the junction temperature estimation accounting for the interconnection resistance has been proposed. By the proposed method, the junction temperature can be estimated well. Further, the proposed method does not interrupt the converter operation, thus, it is suitable for online junction temperature monitoring in real converter applications.

The feasibility and effectiveness of the proposed method has been verified by the experimental results.

References