An online V_{ce} measurement and temperature estimation method for high power IGBT module in normal PWM operation

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***Abstract*—An on-state collector-emitter voltage (V_{ce}) measurement and thereby an estimation of average temperature in space for high power IGBT module is presented while power converter is in operation. The proposed measurement circuit is able to measure both high and low side IGBT and anti parallel diode voltages for a half bridge module which are also used to monitor the electrical degradation of the module. The V_{ce} load current is proposed to estimate the variation of average temperature in space at every fundamental cycle of sinusoidal loading current. Initially, the calibration of voltage and junction temperature for load current level is presented and a trend of change in calibration factor for the IGBT is presented. Finally, the variation in temperature for sinusoidal variation of current is presented at initial stage and after an ageing of the IGBT. The measurement technique is simple and easy to implement into a gate driver for field applications.**

Keywords*—*IGBT power module, junction temperature, real time monitoring, reliability.

I. Introduction

A real time monitoring of electrical and thermal characteristics during conduction and switching of power electronic devices are still a challenge in order to improve reliability of power converters. A physical architecture of standard multichip power IGBT consists of multi-layers of materials with mismatched coefficient of thermal expansion (CTE), which is a major drawback for the device because the operating temperature and thermal cycling severely affects its performance [1]. Specially for traction and wind power converter applications, large temperature oscillation occurs at low modulating frequencies even in normal operation [2]. In normal operation, the semiconductor power devices shows ageing due to both electrical and thermal degradation after certain number of cycles of operation. An electrical degradation changes the electrical resistance which is monitored by observing the on-state V_{ce} drop or on-state resistances. However the thermal degradations changes the thermal resistance which can be monitored by observing the junction temperature or thermal impedance of the device. For example, in the electrical degradation the rise in on-state electrical resistance can be the effect of wire bonding degradations or aluminum reconstruction which increases sheet resistance of the aluminum layer. On the other hand the thermal degradation increases the thermal resistance by increasing the temperature inside the power module. Hence, a real time estimation of junction temperature during normal PWM operation of power module is in priority to improve the overall reliability of power converters [3] [4] [5]. In practice, the junction temperature T_j of an IGBT can be measured using optical methods, physical contacting methods and electrical methods. In case of a real time application, the optical methods have limitations to implement physically in field applications. Similarly, the physical contacting methods have slow response in the measurement [6] [7]. Therefore, the temperature sensitive electrical parameter (TSEP) such as an on-state V_{ce} is preferable to measure the T_j and ageing of IGBT power module in real time operation [8]. It has been proven that the IGBT chip itself can be used as a temperature sensor [9] [8] .

IGBT has negative temperature coefficient (NTC) at lower current level whereas positive temperature coefficient (PTC) at higher current level. The estimation of T_j using V_{ce} requires an accurate calibration of $V_{ce}(T_j)$. Therefore, to avoid a temperature rise on chip due to self-heating, the $V_{ce}(T_j)$ calibration is conducted at small current mainly at 100mA [9], where IGBT posses the NTC characteristics. On the other hand, a very accurate calibration of $V_{ce}(T_j)$ is required at load current calibration method [10], where IGBT shows both NTC and PTC characteristics. The T_j estimation method is proposed using offline characterization method of the module [11]. The on-state V_{ce} is influenced by the collector current, coolant temperature and the gate voltage. Excluding the collector current, every other parameters are kept constant during the characterization at load current method in this paper.

This paper presents a measurement of real time on-state V_{ce} and thereby an estimation of average T_j in space at V_{ce} load current while converter is in operation. In this method, the $V_{ce}(T_j)$ calibration is conducted at load current level for both IGBT and free-wheeling diode. A calibration factor (K-factor) [12] is obtained at different current levels by increasing the load current up to the nominal rated value in a very short period of time. Finally,

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the average temperature rise after 5.1 million cycles of operation is presented for both sigh side and low side of the IGBT. However, this paper only deal with the temperature estimation for IGBT. A measurement set up and the (V_{ce}) measurement methods are also briefly described. The rise in V_{ce} due to electrical degradation is also presented.

II. THE CONVERTER SETUP

An H-bridge topology is used as a test converter [13] as shown in Fig. 1, where half bridge modules are used on each half leg as a device under test (DUT) and control side of the converter. Two control IGBT modules are used in order to ensure the slower wear-out of the control side. In Fig. 1,

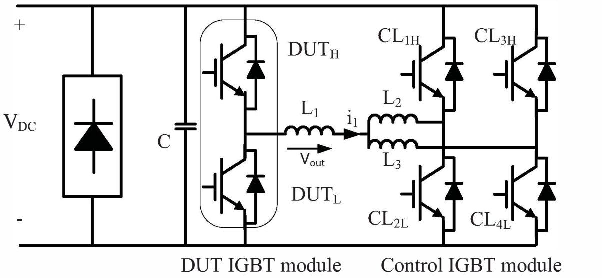

Fig. 1. The power converter set up for testing IGBT modules

DUT_H: High side IGBT device under test
DUT_L: Low side IGBT device under test
L_1, L_2 and L_3: Load inductors

A separate DC supply is used to charge DC link capacitor bank in the converter. Eventually, a $890A_{peak}$ peak current is circulated through the inductors during normal operation of the converter, where the major power loss is dissipated through the power modules such as DUT. The converter operating parameters are given in Table I.

TABLE I. THE CONVERTER OPERATING PARAMETER

Symbol	Meaning	Value
V_{DC}	DC link voltage	$1000V$
V_{DUT}	Forward voltage reference	$253V_{rms}$
I_L	Load current	$890A_{peak}$
F	Fundamental frequency	$6Hz$
F_{SW}	Switching frequency	$2.5kHz$
C	DC link capacitance	$4mF$

III. VOLTAGE MEASUREMENT METHOD

The on-state voltage of the IGBT module is measured using double diode circuit as shown in Fig. 2. The circuit is able to measure the voltages for both IGBT and free wheeling diode of a half-bridge module with

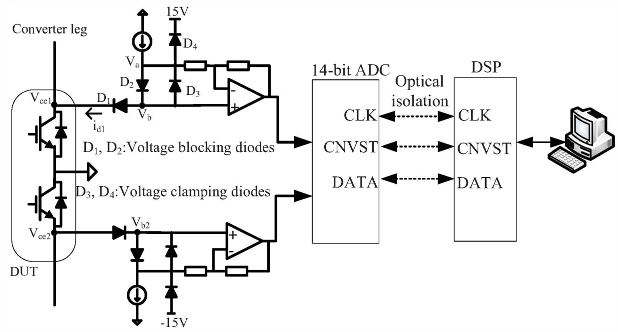

Fig. 2. The power converter test set up

1mV accuracy [14]. Equation (1) shows V_{ce} measurement formulation for high side IGBT as shown in Fig. 2.

$$V_{ce1} = V_b - V_{D2} = V_b - (V_a - V_{b)} = 2V_b - V_a \qquad (1)$$

The measurement circuit is connected to kelvin terminals of the device and is directly connected on top of a IGBT gate driver. The measurement technique has no influence in the switching and operation of the converter during operation [15].

IV. VOLTAGE-TEMPERATURE CALIBRATION

In order to transfer knowledge about current and V_{ce} into temperature an initial calibration is needed. Therefore, the output characteristics of the DUT is calibrated in the same converter and the measurement set up as shown in Fig. 1 and Fig. 2. Each calibration is completed for all

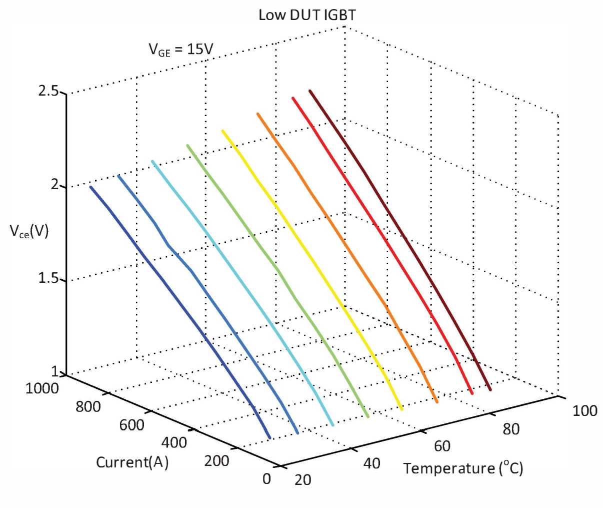

Fig. 3. The IV characteristics for the low side IGBT

four IGBTs and free-wheeling diode keeping the steady baseplate temperature and ramping up the current until 890A$_{peak}$ through the load inductors within $340\mu S$. The calibration is started at room temperature normally 22^oC and the converter is then operated to increase the coolant temperature using self-heating until 85^oC. As the coolant content a mixture of water and glycol, the calibration process stopped at 85^oC due to safety issues. Prior to the calibration, all PWM signals are disabled for a minute

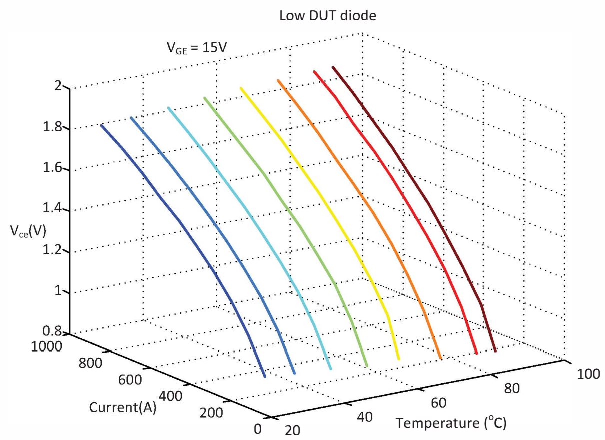

Fig. 4. The IV characteristics for the low side free wheeling diode

to maintain the homogeneous temperature distribution across the baseplate and thereby in the chips. Then after, the calibration is conducted for each temperature by switching the DUT and the control side IGBT in a controlled fashion.

The $V_{ce}(T_j)$ calibration at high current is shown in Fig. 3 and Fig. 5 for low side IGBT and the corresponding free-wheeling diode respectively. The calibration is completed in $680\mu S$ to minimize the error due to self heating for both sides of the half bridge module. Just before the calibration the surface of the chip temperature inside power module is maintained at the same level by running the cooling water continuously without applying the load for a minute. The homogeneous distribution of temperature is also confirmed by the finite element modelling as described in paper [16].

Although the calibration is conducted very fast, because

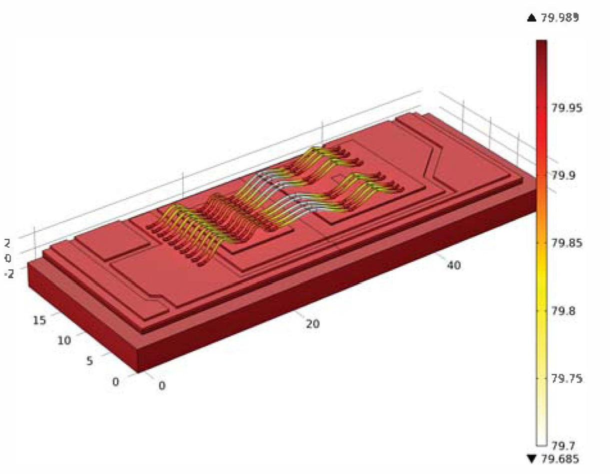

Fig. 5. The temperature distribution on surface of the chip before applying load current

of the high load current surface of the chip experiences small energy loss which will increase the surface temperature above than the cooling temperature. Therefore, the calibration factor is corrected by using thermal impedance to estimate the chip temperature on the surface of the module [5].

The calibration factor is calculated at different current level as given in Equation (2).

$$K = |\frac{T_{J2} - T_{J1}}{V_{CE2} - V_{CE1}}|^{o}C/mV \quad (2)$$

The gain of the calibration factor at crossover point from

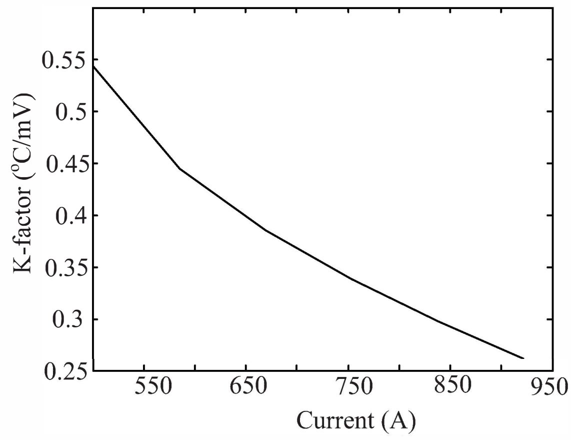

Fig. 6. The calibration factor

NTC to PTC is infinite which cannot be used to calculate the average T_j of the device. In fact, the major interest of study is also at higher current level, hence the K-factor for the higher current level is considered for the temperature estimation. The IGBT and diode has NTC to PTC crossover point at 152A and 419A respectively for the DUT. A 1700V/1000A P3 IGBT module is used in the DUT, which consists of six identical sections of half bridge structure. Fig. 6 shows the corrected calibration factor which is used to estimate the average junction temperature of the IGBT.

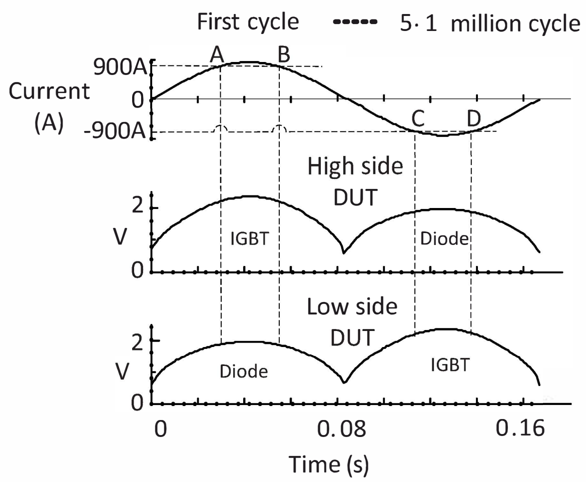

Fig. 7. The on-state voltage measurement

V. EXPERIMENTAL RESULTS

A. Online voltage monitoring

An online measurement is conducted at every five minutes in normal operation to limit the amount of data. In every single measurement, slightly above 2 fundamental cycles of collector current and corresponding conductive voltage drops are recorded as exhibited in Fig. 7 [5]. As given in Table I, the cooling temperature is kept steady with 80 ± 0.5^oC throughout the test as exhibited in Fig. 8. At 6Hz sinusoidal current loading

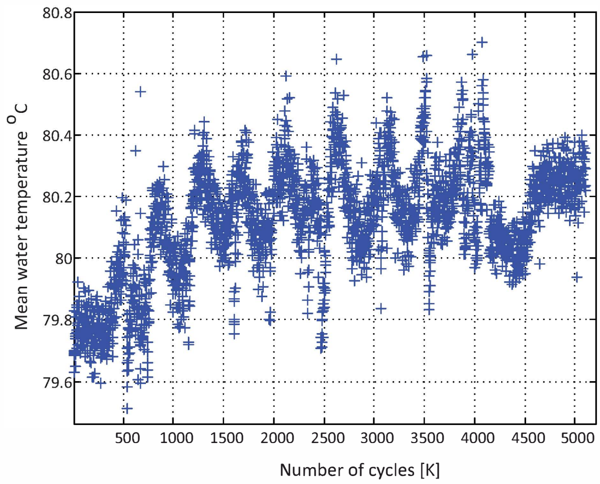

Fig. 8. The variation in water cooling temperature during the test

the power module is failed after 5.1 million cycles of operation due to ageing. The real time voltage measurement shows that the trend of on-state voltage increment is different for IGBTs and free-wheeling diodes. The IGBT has nearly linear increment in on-state V_{ce} drop until the module fails, on the other hand the corresponding free wheeling -diode has minimal change in on-state V_{FD} drop until certain cycles of operation. For instance, in this case only above around 3.5 million

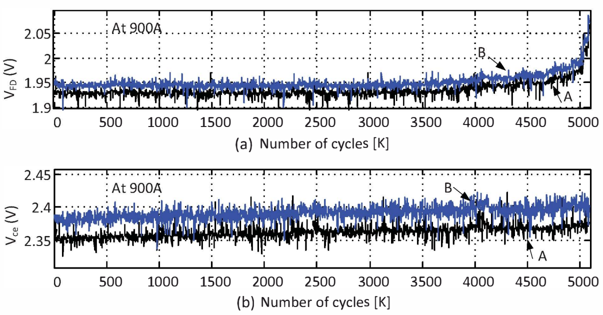

Fig. 9. The on state voltage variation at 900A (a)The on state V_{FD} drop for low side diode at point A and B from Fig. 7 and (b)The on state V_{ce} drop for high side IGBT at point A and B as shown in Fig. 7

cycles the rate of rise of V_{FD} is increasing until the module fails. After the degradation has been started the rate of rise of voltage is also increasing. In the measurement, the step increment of nearly 7mV in the on-state V_{FD} is also witnessed due to bond wire lift-off. The on-state V_{FD} of low side diode is increased in total by 132mV from the beginning before it fails at 900A as shown in Fig. 9(a) and Fig. 10. However, the on state V_{ce} of high side IGBT is only increase by 22mV after the 5.1 million cycles.

The fig. 9 exhibits the trend of change in on-state V_{ce} and V_{FD} for low side diode and high side IGBT at $900A$. The on state voltage drops at the rising edge and falling edge of the sinusoidal current are compared at $900A$. Although the electrical parameters are similar at the same current level, the on-state voltage drop is higher at the falling edge of the sinusoidal current because the temperature rises slowly in comparison to the load current due to thermal impedance of the chip and the module. Assuming similar electrical degradation for a half cycle of the loading current, the voltage gradient is mainly due to the rise of the surface temperature.

Fig. 10 exhibited an extended plot of the rate of increase

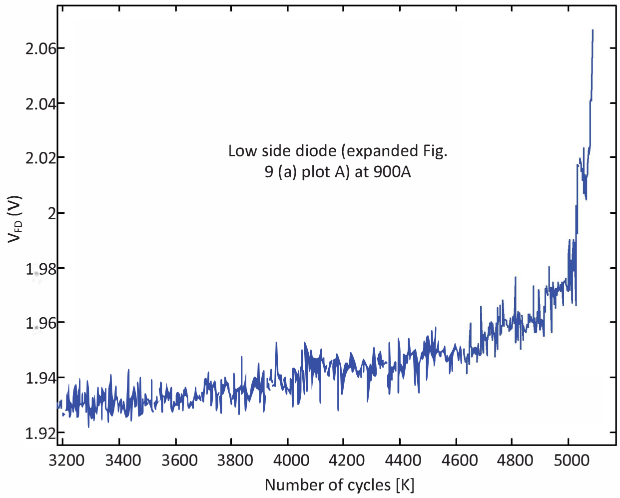

Fig. 10. An extended figure of on state V_{FD} for low side diode from 9 at point

in on-state V_{FD} with respect to number of cycles after for above 3.3 million cycles of operation. As mentioned above, the on state V_{ce} and V_{FD} gradient at $900A$ are calculated as follows from fig. 7;

High side IGBT V_{ce} at rising side point A = $A(V_{ceRise})$
High side IGBT V_{ce} at falling side point B = $B(V_{ceFall})$
High side IGBT V_{ce} gradient (ΔV_{ceHIgh})= $B(V_{ceFall}) - A(V_{ceRise})$
Low side IGBT V_{ce} at rising side point C = $C(V_{ceRise})$
Low side IGBT V_{ce} at falling side point D= $D(V_{ceFall})$
Low side IGBT V_{ce} gradient (ΔV_{ceLow})= $D(V_{ceFall}) - C(V_{ceRise})$

Similarly for corresponding free-wheeling diode;
High side diode V_{FD} at rising side point C = $C(V_{FDRise})$
High side diode V_{FD} at falling side point D = $D(V_{FDFall})$
High side diode V_{FD} gradient (ΔV_{FDHIgh})=

$D(V_{FDFall}) - C(V_{FDRise})$
Low side diode V_{FD} at rising side point A = $A(V_{FDRise})$
Low side diode V_{FD} at falling side point B= $B(V_{FDFall})$
Low side diode V_{FD} gradient (ΔV_{FDLow})= $B(V_{FDFall}) - A(V_{FDRise})$

In fig. 11,

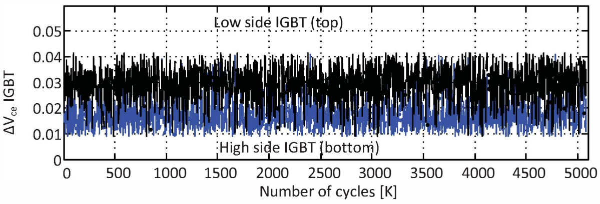

Fig. 11. The rise in V_{FD} gradient at $900A$ for diode

Low side IGBT (top)= $D(V_{ceFall}) - C(V_{ceRise})$
High side IGBT (bottom) = $B(V_{ceFall}) - A(V_{ceRise})$

In fig. 12,

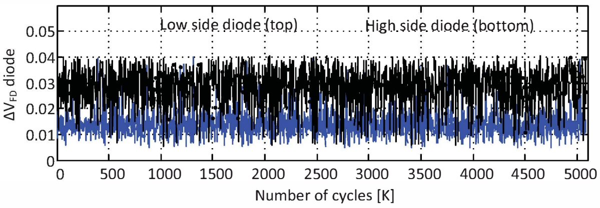

Fig. 12. The rise in V_{ce} gradient at 900A bentween for IGBT

Low side diode (top)= $B(V_{FDFall}) - A(V_{FDRise})$
High side diode (bottom) = $D(V_{FDFall}) - C(V_{FDRise})$

Fig. 11 and fig. 12 shows that the change of rise in gradient voltage drop between falling and rising edge of sinusoidal voltage at $900A$ for IGBT and diode in all cycles. In both IGBT and diode, the trend of change in gradient voltage is nearly constant throughout the cycles, even though the rate of rise of on state voltage drops are different at different number of cycles. Hence, it can be predict that the voltage increment in Fig. 9 is mainly due to electrical degradation.

B. *Temperature estimation*

As shown in Fig. 6, the voltage sensitivity is in between 2mV/^{o}C to 3mV/^{o}C for the current range 550A to 922A. Hence, for an accurate estimation of average T_j in space, the measurement circuitry should have mV accuracy in the real time operation. Similarly, the current measurement should have higher accuracy. The voltage measurement circuitry requires some settling time which is fulfilled by measuring at the switching pulse. In addition this makes the implementation into control simple. Actually, the measurement could be beneficailly made at the end of the switching period, but this complicates the implementation [5].

As mentioned in previous section, because of the thermal impedance of the chip the rise in temperature takes longer than the electrical signals. The average T_j is calculated based on the real time measurement and $V_{ce}(T_j)$ calibration as given in equation (3).

$$T_j = T_{ref} + K \times (V_{cemeas} - V_{ceref}) \tag{3}$$

Where,
T_{ref}: reference temperature taken during calibration process
T_{cemeas}: real time on-state V_{ce} measurement
V_{ceref}: on-state Vce measured at given reference temperature which is at 30^oC in this paper

Fig. 13 demonstrates the T_j variation at different

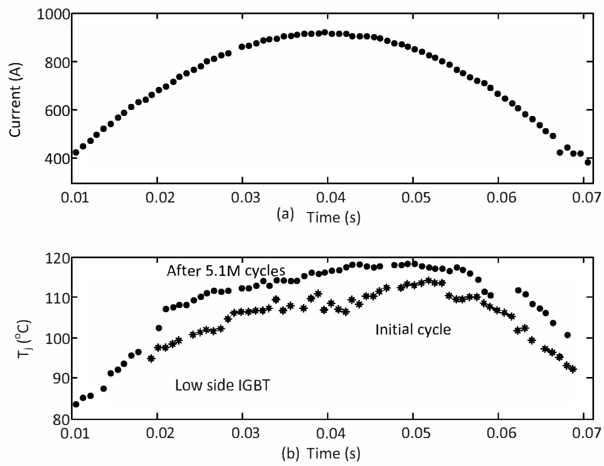

Fig. 13. The average T_j estimation (a)The collector current flowing through the IGBT (b) The Tj variation on low side IGBT

current during half fundamental cycle at initial and after 5.1 million cycles of operation. In both cases the collector currents are same. The initial calibration factor measured for the low side IGBT is used to obtain the T_j in both cases for the comparison. But for the final cycle the new V_{ceref} which is measured at 5 million cycles is used in equation (3). The peak temperature is raised by close to 5^oC from the beginning of the cycle cycle until module fails due to ageing process. Fig. 14 demonstrates the calculated T_j variation of the high side IGBT during half fundamental cycle of the current in the beginning and after 5.1 million cycles of operation where the peak of calculated T_j is increased nearly by 9^oC. The calibration factor measured at the beginning of the high side IGBT is used to compare the calculated T_j for both initial cycle and final cycle, but for this side also the new new V_{ceref} which is measured at 5 million cycles is used in equation (3). At the initial cycle the peak of calculated T_j is higher by close to 10^oC in the low side than the high side. The cooling temperature is maintained at 80^oC as shown in fig. 8 through out the test period. As exhibited in the figures 13 and 14, high peak temperature is observed in low side IGBT than the high side IGBT at the beginning and at the end of the

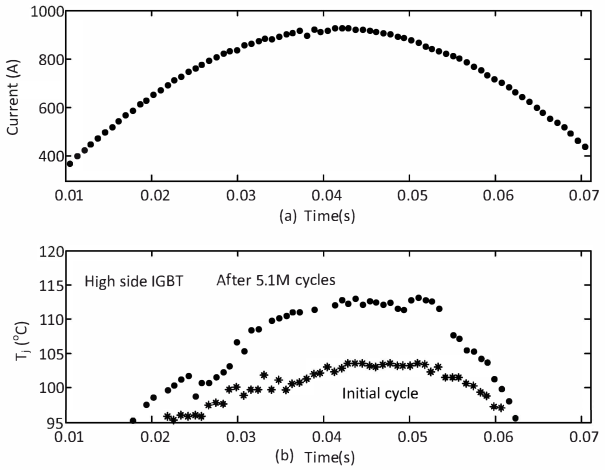

Fig. 14. The average T_j estimation (a)The collector current flowing through the IGBT (b) The Tj variation on high side IGBT

cycles but the temperature rise is higher in high side IGBT in comparison to the initial state of both sides. On the voltage measurement, the trend of rise in V_{FD} is higher in the low side diode leading to the failure of the DUT.

VI. CONCLUSIONS

This paper describes a potential method for real time measurement of on state collector emitter and forward voltage drop in continuous sinusoidal loading of the current. The proposed V_{ce} load current method which is used to estimate the average junction temperature in space shows that a good agreement between voltage and temperature measurement. The proposed method is able to detect the mean junction temperature variation for the low side and high side IGBT separately in every fundamental cycle of the current. As observed in the measurement result, the lower side of the tested IGBT module is failed earlier during the test. The verification of the accuracy of temperature estimation by this method is in progress using direct measurement technique. The proposed technique could be a potential method for the field application such as for wind power converter, automotive application etc.

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