Improving Power Converter Reliability

Online Monitoring of High-Power IGBT Modules

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The real-time junction temperature monitoring of a high-power insulated-gate bipolar transistor (IGBT) module is important to increase the overall reliability of power converters for industrial applications. This article proposes a new method to measure the on-state collector–emitter voltage (V_{ce}) of a high-power IGBT module during converter operation, which may play a vital role in improving the reliability of the power converters. The measured voltage is used to estimate the module average junction temperature of the high and low-voltage side of a half-bridge IGBT separately in every fundamental cycle of the current by calibrating them at V_{ce} load current. The V_{ce} measurement is very accurate and also measures the voltage at the middle of a pulse-width modulation (PWM) switching. A major objective is that this method is designed to be implemented in real applications. The performance of this technique is measured in a wind power converter at a low fundamental frequency. To illustrate more, the test method as well as the performance of the measurement circuit are also presented. This measurement is also useful to indicate failure mechanisms such as bond wire lift-off and solder layer degradation. The measurements of V_{ce} and rise in the junction temperature after five million cycles of normal operation of the converter are also presented.

Since its first commercial demonstration in 1983, the IGBT has been very popular and has improved significantly [1]. Specifically, high-voltage and high-current IGBT

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modules such as 1,700 V and 1,000 A are popular for traction, industrial, and wind power converter applications. As power converters are exposed to intermittently varying harsh environmental conditions in several applications, the power modules suffer stresses due to the thermal gradient, ambient temperature, and electrical power loss during operation.

In the case of wind power converters, the multimegawatt wind turbines are emerging as new market trend. Despite consisting of several components, the power converters for these turbines need to be considered seriously because they need to fulfill grid codes' compatibility, reliability, high-power density, and voltage rating [2]. In addition, the large turbines for both offshore and onshore applications will be exposed to harsh ambient conditions due to fluctuations in temperature and intermittently varying wind velocity. Furthermore, especially for a power converter with a doubly fed induction generator, the power modules experience severe thermomechanical stress at low frequencies of less than 16-Hz operation [3]. As a result, the power modules fail in a short period of time because of package-related failures [2]. The construction of the IGBT power module consists of several layers of materials with different coefficients of thermal expansion, which varies from 2.6×10^{-6}/K for silicon to 22.3×10^{-6}/K for aluminum [4]. As a result, a considerable thermomechanical stress during their operations leads to aging and, ultimately, failures in those layers. The package-related failures, such as bond wire fatigue, bond wire lift-off, bond wire heel cracking, and aluminum reconstruction, predominantly occur due to thermomechanical stress [5], [6]. Also, the power modules are the weakest components in the converter due to temperature limitations in Si-based IGBT power modules [7].

The junction temperature of power IGBT modules can be measured using either the direct or indirect method. However, the direct measurement method requires close physical contact with the chip, which is not practical for field applications. Hence, indirect methods, such as temperature-sensitive electrical parameter (TSEP), are more preferable. To overcome these limitations, online monitoring of TSEPs such as on-state V_{ce} is necessary [8]–[11]. The voltage can be measured either online or offline. An offline measurement can be used to measure the V_{ce} evolution due to wearout of the power module. This technique can be used while the converter is not in operation, whereas the online method shows the on-state voltage variations while the converter is in action. Hence, this method is useful for various purposes such as real-time junction temperature variation in the chip, fast overload protection, desaturation protection, and wear out monitoring. The proposed online method is easier to implement in the current systems because no special measurement routine is required, and it is also invisible to the other parts of the system.

Reliability in Power Electronic Converters

The reliability of power electronic converters is a major concern in industrial applications because of the use of high-power semiconductor devices, which have high-power density and higher failure rates [12], [13]. Real-time monitoring plays a vital role not only to increase the reliable operation of the system during adverse situations but also to avoid the higher maintenance cost. Every failure of the power devices may cause catastrophic damages in high-power applications such as automotive, aerospace, motor drives, and wind power. However, the real-time monitoring methods, as well as the monitoring parameters, vary with the type of application

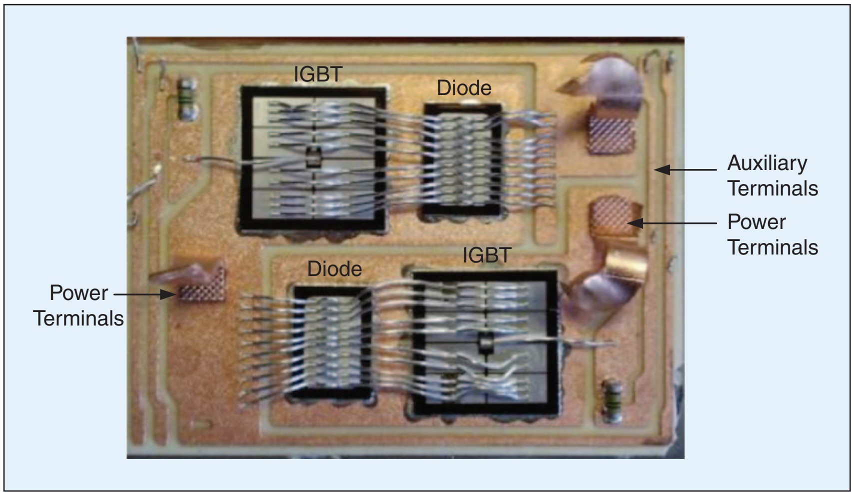

FIGURE 1 – An image of a section inside a power module after a power cycling test. The bond wires are moved during the removal of power module housing.

TABLE 1 – MATERIALS USED FOR THE IGBT MODULE CONSTRUCTION.

ELEMENTS	MATERIAL	THICKNESS (μm)
Wire	Al	400
Metallization	Al	4
Chips	Diode/IGBT	300
Chip solder	Ag based	50
Direct bonded copper (DCB)	Cu	300
	Ceramic	700
	Cu	300
DCB solder	Ag based	100
Baseplate	Cu	3,000

and also with the type of semiconductor device used in the converter. Hence, a better design approach and high-temperature susceptible devices are emerging on the market to improve the overall reliability. In addition, priority is also given to the real-time monitoring of the wear out status of new power devices [14], [15].

There are different stresses and factors that provoke the failure of power converters such as thermal stresses, overload transients, extreme ambient temperature, moisture, and mechanical vibration. Usually, the junction temperature swings between 30 °C and 110 °C for these kinds of application [12]. But today, the requirement of T_j has been increased to around 200 °C in some applications. Regarding the total reliability approach, the power devices experience early failures, random failures, and end-of-life failures. Even though the nature and cause of failures are different, the real-time monitoring may play a vital role in warning of failures due to aging. Thus, this article proposes an on-state V_{ce} measurement as one of the potential methods for a high-power IGBT module with higher accuracy during converter operation.

Wearout in IGBT Module

The wearout in the IGBT power module develops more slowly in normal PWM switching operations than in accelerated lifetime tests [16]. The accelerated power cycle test is time saving and is also suitable for investigating bond wire failures, degradation of the solder layer, and aluminum reconstruction, including other failure mechanisms. Although the normal PWM switching operation takes longer to wear out the device than the accelerated test, the test outcome gives realistic information about the aging of the power devices. However, an accurate measurement of the electrical parameters is essential to precisely define the aging status. The possible wear out processes that can be seen in a multichip module by measuring a certain quantity are [6]:

- delamination of the solder joints: V_{ce}, I_c, T_j, T_{case}
- degradation of the gate-oxide characteristics: V_{geth} variation
- bond wire heel crack initiation: V_{ce}, I_c, T_j, T_{case}
- chip metallization degradation: V_{ce}.

Generally, three major electrical parameters are measured in power devices, such as the junction to baseplate thermal resistance (R_{thjc}), the gate threshold voltage (V_{geth}), and the on-state V_{ce} [16]. The R_{thjc} is calculated by measuring the collector current (I_c), junction temperature (T_j), and case temperature (T_{case}). Except for the gate oxide-characteristics, the on-state V_{ce} variation can be used as a wearout indicative parameter and can also be considered for estimating the variation in the mean junction temperature of the power module. However, the

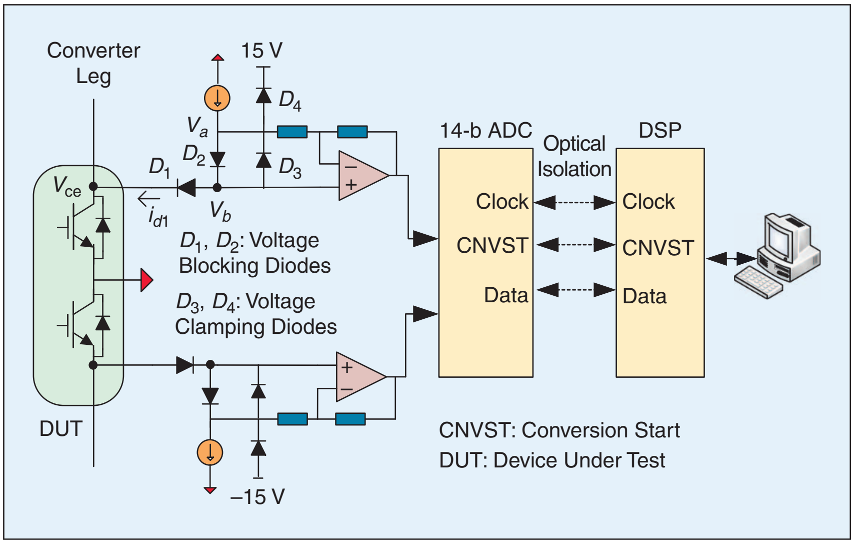

FIGURE 2 – A new V_{ce} measurement circuit.

on-state V_{ce} measurement and current must be measured at the same time with a high level of accuracy.

Failures in IGBTs

The causes of early life failures are electrothermal overload and component weaknesses. Although the deviation in the real-time measurement parameters creates an alert before the failure occurs, random failures may also arise from external sources and are not device specific [8]. The end-of-life failures are mainly due to wearout of the power module, which can be monitored and diagnosed using suitable strategy and measurement techniques.

IGBT Parts

The tested IGBT module has six identical sections, each consisting of two IGBTs, two diodes, and ten bond wires in parallel as shown in Figure 1. The materials and size of the physical parameters are listed in Table 1.

V_{ce} and I_e Measurement Technique

The on-state V_{ce} can be measured using either offline or online techniques. In the offline method, initially, the normal PWM switching operation is stopped and the switches are turned on in such a way that the current ramps up linearly until it reaches a maximum value through the inductor. Then, both the V_{ce} and I_c are measured at different levels of I_c. On the contrary, in the online measurement method, the V_{ce} is measured in the regular PWM switching operation of the converter continuously for the sinusoidal current. Although both techniques give an indication of the aging of the power module, the latter method is useful for the real-time health monitoring of the power module when the converter is in normal operation.

Voltage Measurement Circuit

A desaturation protection technique is popular in modern gate driver circuits to protect the transistors from short circuit and overload [15]. A similar approach is used in the online voltage measurement circuit as shown in Figure 2 [18]. Two diodes are connected in a series, and a weak current source is forward-biased to them during the transistor turn-on period of the IGBT. When the transistor is turned off, the diode blocks the V_{ce} voltage. An additional low-leakage diode is used antiparallel to D_2 to protect from transients. Two similar diodes, D_1 and D_2, are used, and the V_{ce} voltage is measured by subtracting the voltage drop on diode D_2 from V_b potential illustrated as

$$\begin{aligned} V_{ce} &= V_b - V_{D2} = V_b - (V_a - V_b) \\ &= 2V_b - V_a. \end{aligned} \tag{1}$$

A bipolar amplifier circuit and analogue to digital converter (ADC) are implemented so that the circuit will operate for both positive and negative V_{ce} and the voltage drop on free-wheeling diode (V_{FD}) can also be measured. As the V_{ce} measurement depends on the two diodes, the following criteria should be fulfilled during the selection of the measurement diodes:

1) The two diodes should be thermally coupled to keep the junction temperature at a similar level.
2) The two diodes need to have similar forward voltage temperature coefficients.

The measurement circuit is designed to have an accuracy close to 1 mV. To obtain this accuracy, a ±5-V 14-b ADC with a resolution of 0.61 mV has been chosen. Figure 3 shows the effect of ambient temperature variation on the output of the measurement circuit, which was kept inside a small box. In Figure 3(a), the intentional ambient temperature inside the box can be seen, and in Figure 3(b) the variation in input voltage to be measured is shown. Figure 3(c) shows the error voltage difference between the input and measured output voltage. The maximum variation is less than 4 mV at its peak when the ambient temperature is increasing from 80 °C to 95 °C. Normally, the ambient temperature does not reach this level. This experiment shows that the V_{ce} measurement circuit is less sensitive to ambient temperature variation. The I_c is measured using an LEM sensor and a 12-b ADC, which is available inside a floating point digital signal processing (DSP) Texas Instruments TMS320F28335. The linearity in the current measurement is checked prior to running the test.

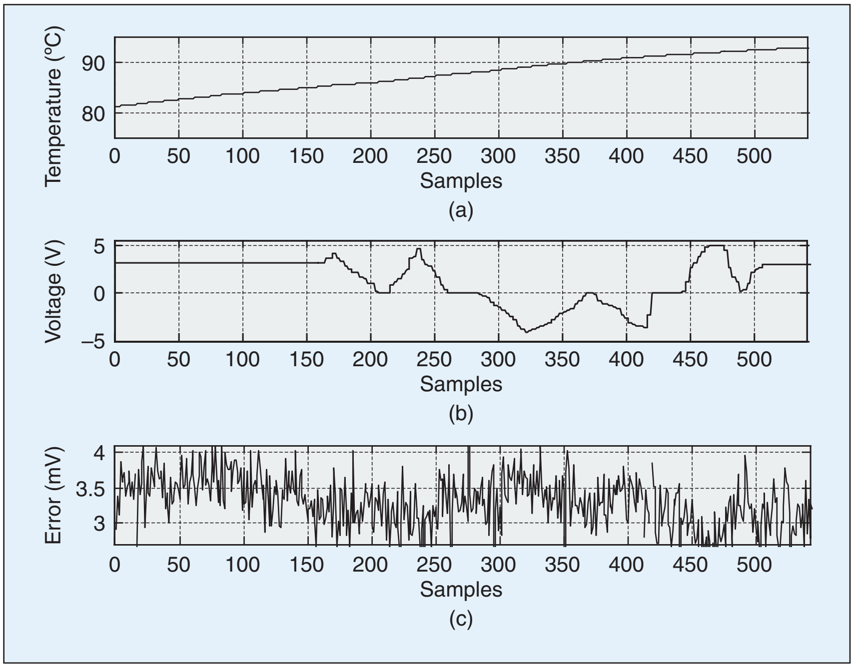

FIGURE 3 – The performance test of the V_{ce} measurement board: (a) the ambient temperature, (b) the input voltage variation, and (c) the error in the measured voltage (before ADC).

Online Implementation

The V_{ce} is measured when the IGBT is fully conducting in every PWM switching pulse. To avoid the effect of switching transients and the time constant to saturate the voltage, the on-state V_{ce} and I_c are measured at the middle of the

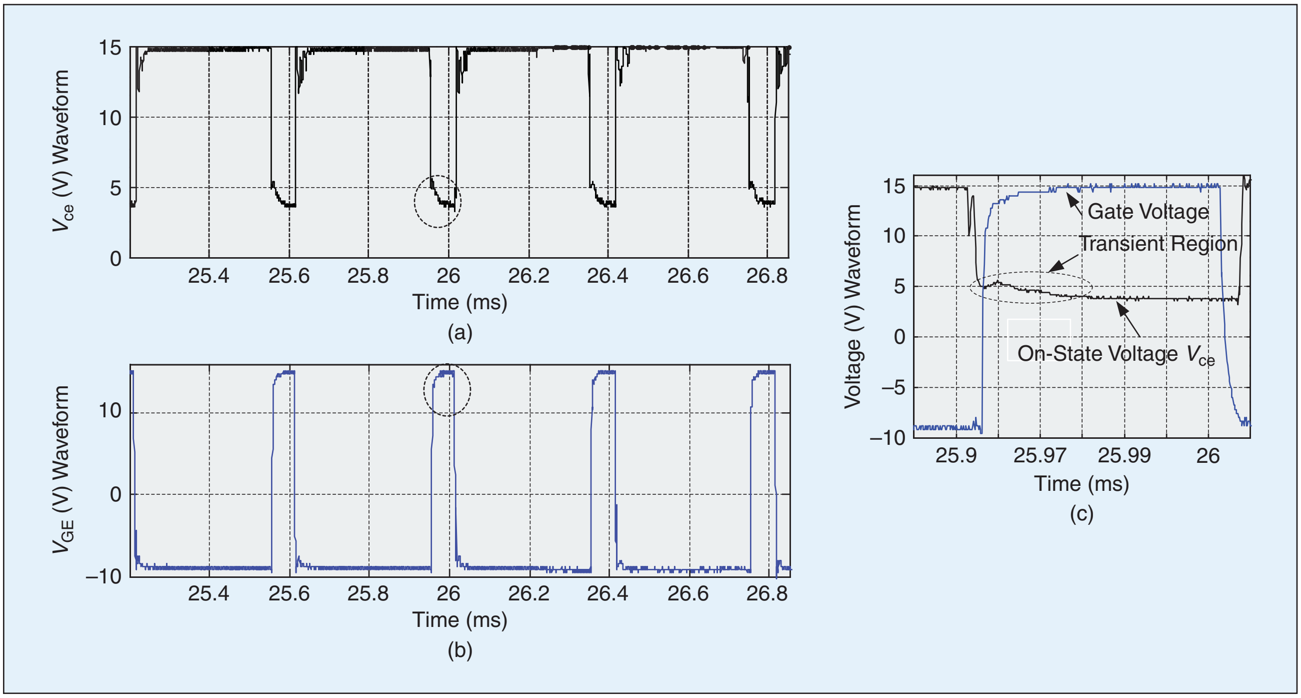

FIGURE 4 – The waveform at V_b of V_{ce} switching: (a) V_{ce}, (b) V_{GE}, and (c) both V_{ce} and V_{GE}.

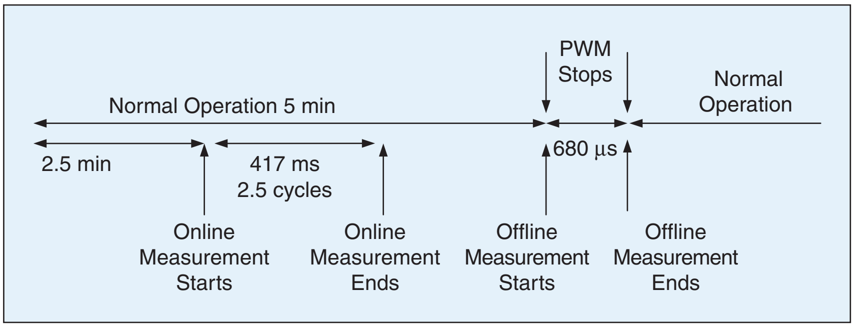

FIGURE 5 – The implementation of an online and offline measurement routine.

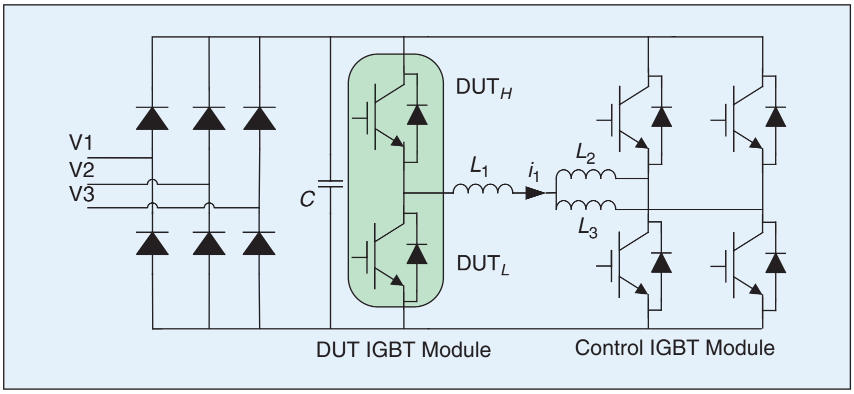

FIGURE 6 – A converter test topology.

turn-on time as shown in Figure 4, which is probed at V_b of Figure 2. However, this does not give the actual on-state V_{ce} drop. Figure 4(a) shows the switching V_{ce} waveform and in Figure 4(b), the corresponding V_{GE} waveform and in Figure 4(c) the expanded on-state voltage and V_{GE} waveform can be seen. As demonstrated in Figure 4(c), the V_{ce} waveform has a slower response to saturate the voltage mainly due to the slow response of the connected passive probes despite the time constant associated with the power module packaging and the measurement circuit. However, the time constant of the measurement circuit is small because of the usage of the SiC-based diode in comparison to the packaging of the Si-based power module. As the switching frequency is at 2.5 kHz, there will be approximately 416 measured data points in one fundamental cycle of the current. In this test, the fundamental frequency of the current is at 6 Hz. To avoid the large data handling process, the online measurement is conducted at every 5 min of the converter operation.

As the V_{ce} measurement board is mounted on top of the gate driver circuit, it experiences electromagnetic interference (EMI) and temperature fluctuations similar to the field application in the converter. Figure 5 shows both the online and offline measurement routine during the converter operations. The online measurement routine is activated after 2.5 min of normal operation, and it records close to 2.5 cycles in a single measurement. After every 5 min, the normal PWM switching is turned off to take the offline V_{ce} measurement. The offline measurement routine takes 680 µs to complete the measurement for both sides of the half-bridge module. After completing the offline routine, the normal operation starts again. In principal, this measurement method does not require stopping the converter operation in field applications.

Offline Implementation

The offline measurement is implemented to calibrate the V_{ce}-T_j during the operation of the system as well as to read the on-state V_{ce} evolution after the aging of the module. During the offline measurement, the normal PWM switching behavior of the IGBT is turned off and a high current is circulated through the power devices for a short period of time after every 5 min of the converter operation. The purpose of this test is to measure the rise in the on-state voltage due to aging. The V_{ce} is susceptible to the coolant temperature as well as the current for a fixed gate emitter voltage. This method does not need to apply for the field application. However, if necessary, it can be implemented while the power converter is stopped for several reasons such as during parking conditions for the wind power converter.

Test Setup

The measurement technique is tested in a high power converter, which is designed to act as a wind power converter [19]. An H-bridge topology is used with an open-loop control voltage output in the first leg, where a device under the test IGBT module is used as shown in Figure 6. The second leg is called the *control side,* which is switched in such a way that a sinusoidal current flows through an inductor. The inductor is used as a load where, together with the control side of the bridge, it acts like a current source. To reduce the thermo-electrical stresses in the control side, the power has been divided into two identical legs using the same PWM control signals for both high- and low-side IGBTs. A liquid cooling system is used to maintain the steady baseplate temperature during the measurement, which consists of a Danfoss Shower Power cooling plate to avoid the temperature gradient on the baseplate of the module. As the chip temperature is affected by the baseplate temperature and the temperature gradient causes thermal stress in the chip, it is mandatory to keep a homogeneous temperature distribution as much as possible across the baseplate during the measurement process.

Junction Temperature Measurement

The T_j measurement of the high-power module is of major interest for several reasons. For example, the rise in surface temperature due to thermal degradation, such as solder layer degradation, has a smaller influence on the V_{ce} for the detection. As the direct chip temperature measurement is not feasible, an indirect method, such as measurement of the TSEP, is chosen. Consequently, a proper measurement technique is required to calculate the average T_j using the on-state V_{ce} measurement. For this, a V_{ce}-T_j calibration at V_{ce} load current is proposed. The major challenges are that the measurement should be accurate, should be less sensitive to the ambient temperature fluctuations, and should block the high voltage.

V_{ce}-T_j Calibration

The IGBT has a negative temperature coefficient (NTC) and a positive temperature coefficient (PTC) at low and high currents, respectively. As the purpose of this work is to address the major interest for high-power industrial applications, priority is given to higher current levels. To increase the accuracy in the measurement, a similar measurement and setup are used for the calibration and the measurement. At the beginning, a V_{ce}-T_j calibration process is conducted. During the calibration, a paramount interest is to keep the baseplate temperature homogeneously distributed as well as to maintain a steady temperature on the surface of the module. Therefore, before conducting the measurement, the PWM signal is disabled and the converter is kept at the same liquid temperature level. In this way, initially, it is assumed that the baseplate temperature and the chip temperature will be at same level. Later, the calibration factor is corrected by considering a rise in T_j after applying the load current in the calibration. In one calibration

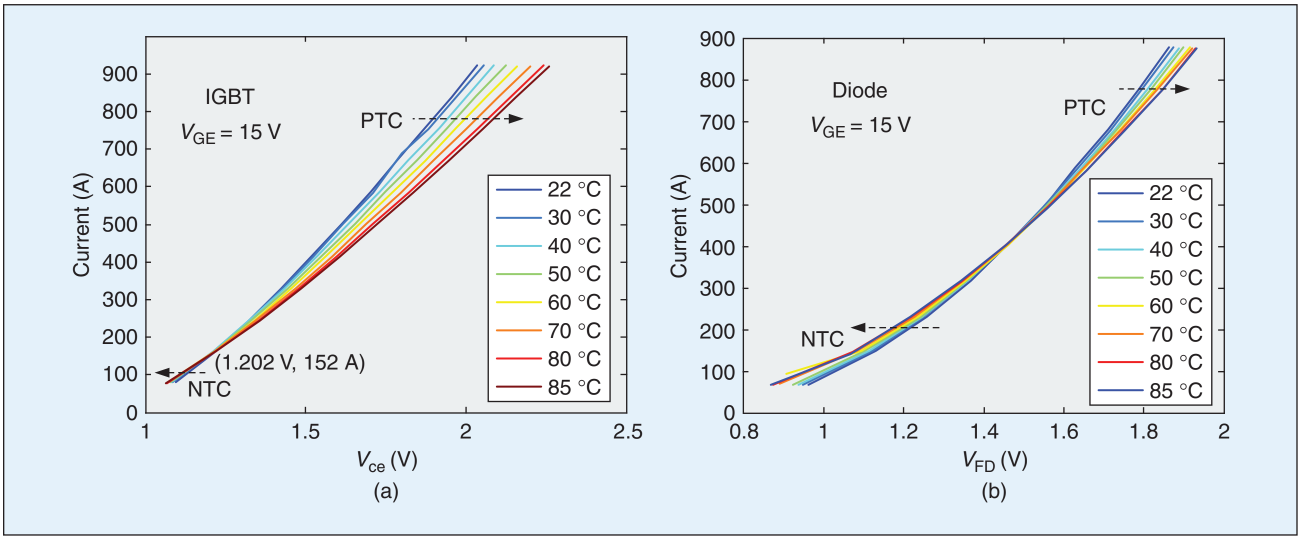

FIGURE 7 – The I-V characteristics at different temperatures (a) for a low-side IGBT and (b) for a low-side diode.

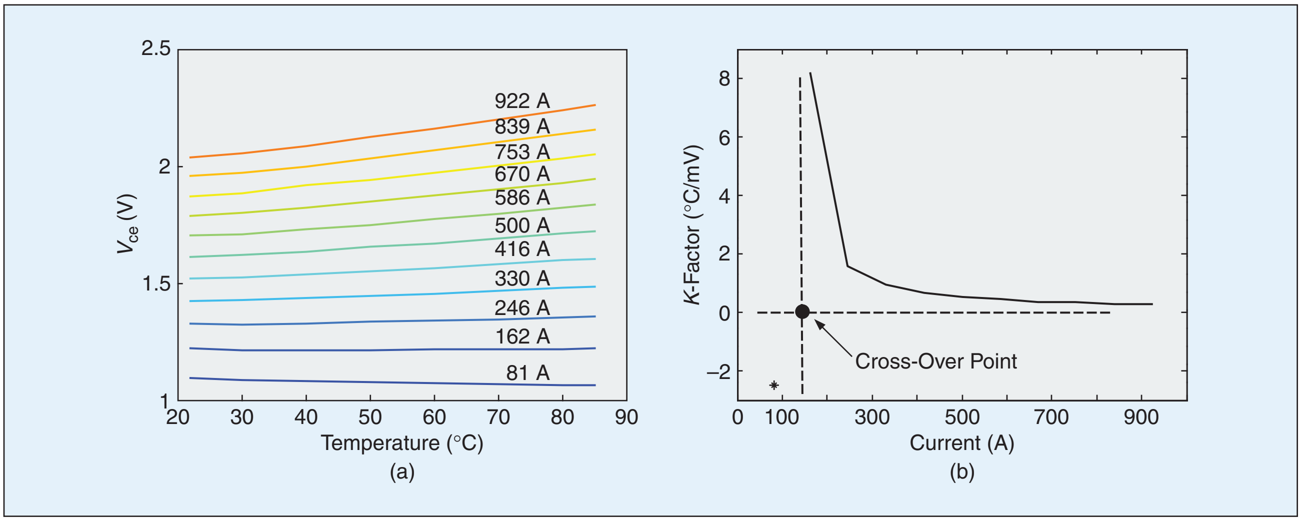

FIGURE 8 – A V_{ce}-T_j calibration for a low-side IGBT: (a) V_{ce}-T_j calibration and (b) a calibration factor.

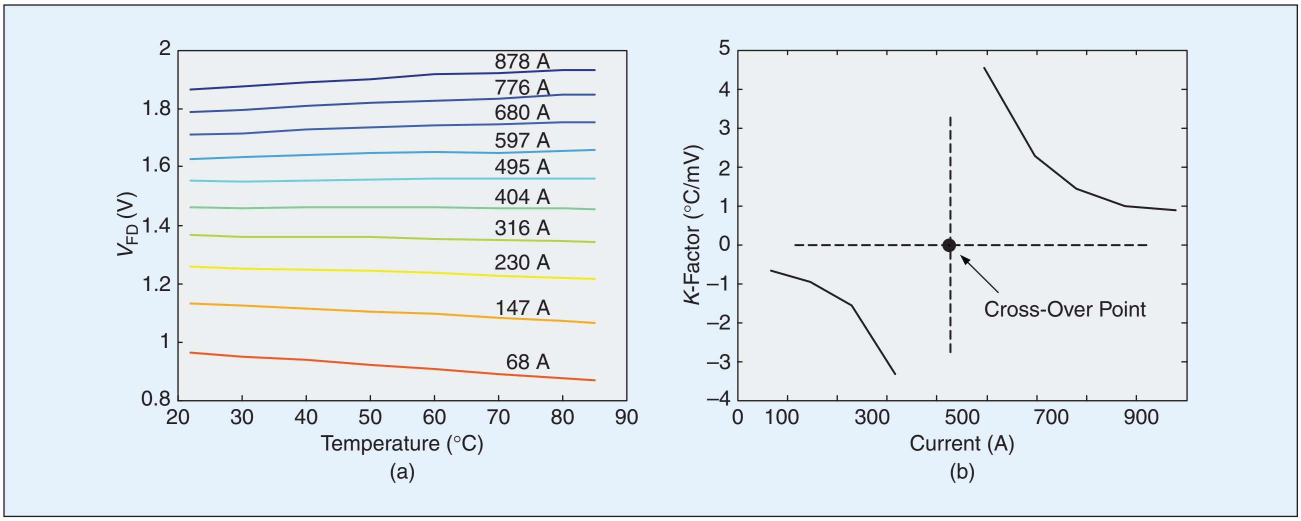

FIGURE 9 – A V_{ce}-T_j calibration for the low-side diode: (a) A V_{ce}-T_j calibration and (b) a calibration factor.

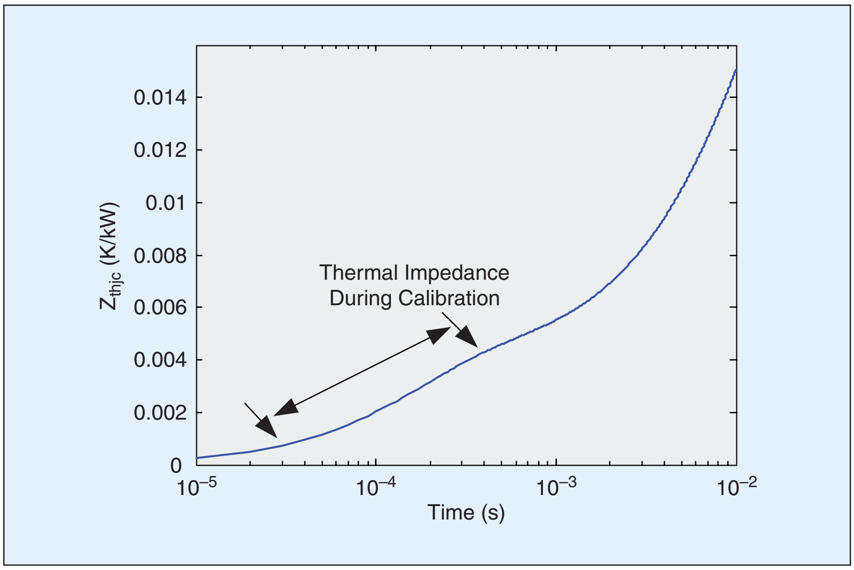

FIGURE 10 – The transient thermal impedance change during the calibration.

process, both the IGBT and the diode of the half-bridge module are measured. The calibration is conducted at different temperatures, increasing from a room temperature level up to 85 °C. During the calibration, I_c is ramped up to 890 A through the inductor by keeping the gate emitter voltage (V_{GE}) fixed at 15 V. The on-state V_{ce} and V_{FD} are recorded at different points until the current reaches the peak. The liquid temperature is kept steady during this measurement. The calibration factor (K) [20] is calculated as given in (2) to calculate the variation of T_j at different current levels. In (2), T_{j1} and T_{j2} are the corresponding junction temperatures for the on-state voltage drop V_{ce1} and V_{ce2} at a fixed current and baseplate temperature

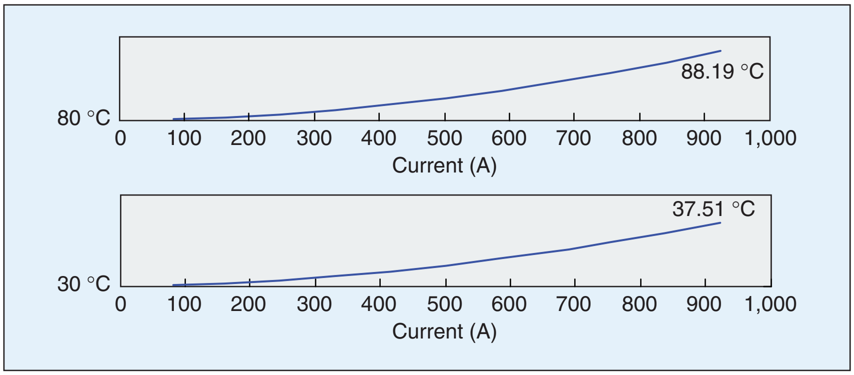

FIGURE 11 – The rise in T_j at different currents during the calibration.

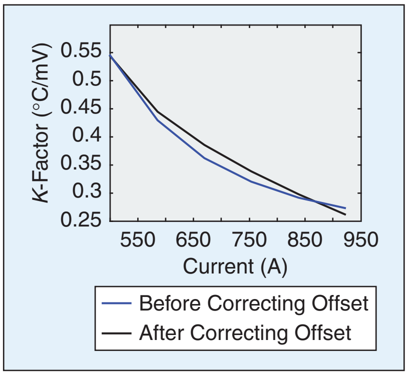

FIGURE 12 – The corrected calibration factor of the low-side IGBT to estimate the T_j.

$$K = \left| \frac{T_{J2} - T_{J1}}{V_{CE2} - V_{CE1}} \right|^{0} C/mV. \qquad (2)$$

Figure 7(a) shows the output characteristics for the IGBT, and Figure 7(b) shows the output characteristics for the diode at different temperatures. The calibration factor is calculated for the IGBT and diode separately. This IGBT has an NTC and PTC crossover at 152 A. The gain of calibration factor is more linear at a higher current level as shown in Figure 8(b).

The diode has an NTC and PTC crossover at higher current levels than the IGBT chip at 419 A. Figure 9(a) and (b) shows the V_{ce}-T_j calibration and calibration factor for the low-side free-wheeling diode, respectively. The change in gain of the calibration factor is higher in the diode than the IGBT.

Correction in Calibration Factor

Because of the high current, the T_j will differ from the baseplate temperature during the V_{ce}-T_j calibration even though the calibration duration is very short. But the module and the cooling liquid have their own thermal impedances, which do not allow a rise in T_j instantaneously. In addition to this, the calibration is conducted in a very short time, which has a small amount of energy to make a significant change in the T_j. A transient behavior of thermal impedance is considered to estimate the rise in T_j during the calibration process. The transient response of thermal impedance is derived from the thermal parameters provided by the manufacturer. Figure 10 depicts the change in the thermal impedance during the calibration period. Figure 11 shows the rise in T_j due to the higher current during the calibration. The calibration factor is corrected by updating a rise in T_j as indicated in Figure 12.

Measurement and Test Results

This section presents the measurement results for the online, offline, and module average temperature estimation of the power module in the test setup as shown in Figure 6.

Online Measurement Results

A real-time measurement is essential to calculate the T_j during a converter operation. Since the gain of V_{ce}-T_j calibration factor is sensitive, and also because it changes from 2 mV/°C to 3 mV/°C for the higher current above 500 A up to the load current level as shown in Figure 12, the accuracy of the real-time measurement is crucial.

Figure 13(a) and (b) illustrates the real-time measurement of the current and on-state voltage drop in the IGBT and diode on the lower side of the IGBT, respectively. The measurement is conducted at an 80 °C coolant temperature during the test period. Figure 13(b) shows the on-state V_{ce} drop by comparing the voltage at the initial cycle of the test with the voltage after 5.1 million cycles of operation at 6 Hz. Consequently, after continuous aging of the module until the end of its life, the on-state V_{ce} increases by 20 mV on the high side of the IGBT and 32 mV on the low side of the IGBT at 900 A at the rising side of the sinusoidal current. After this measurement, the junction temperature

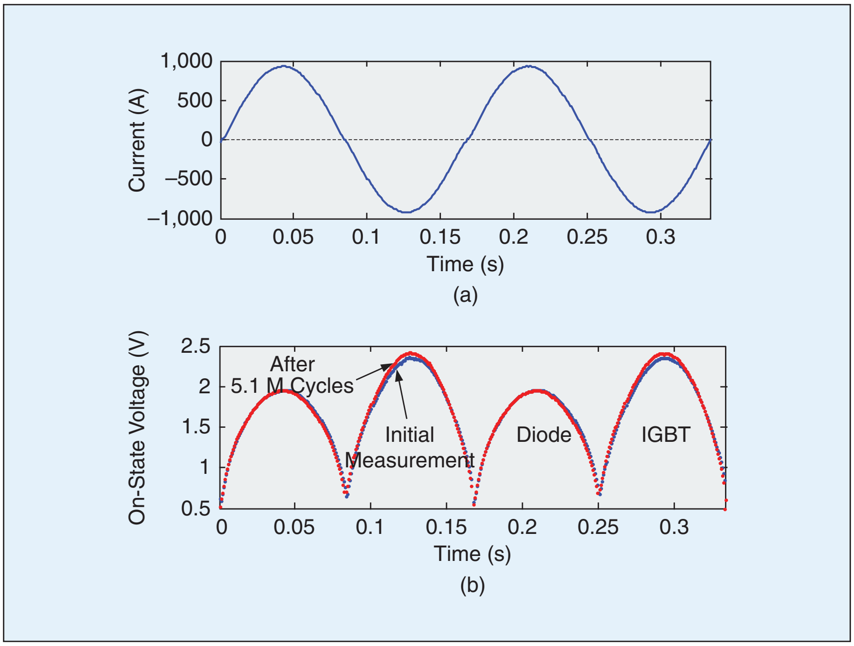

FIGURE 13 – A real-time measurement: (a) the current and (b) the on-state voltage drop for the low-side IGBT and diode.

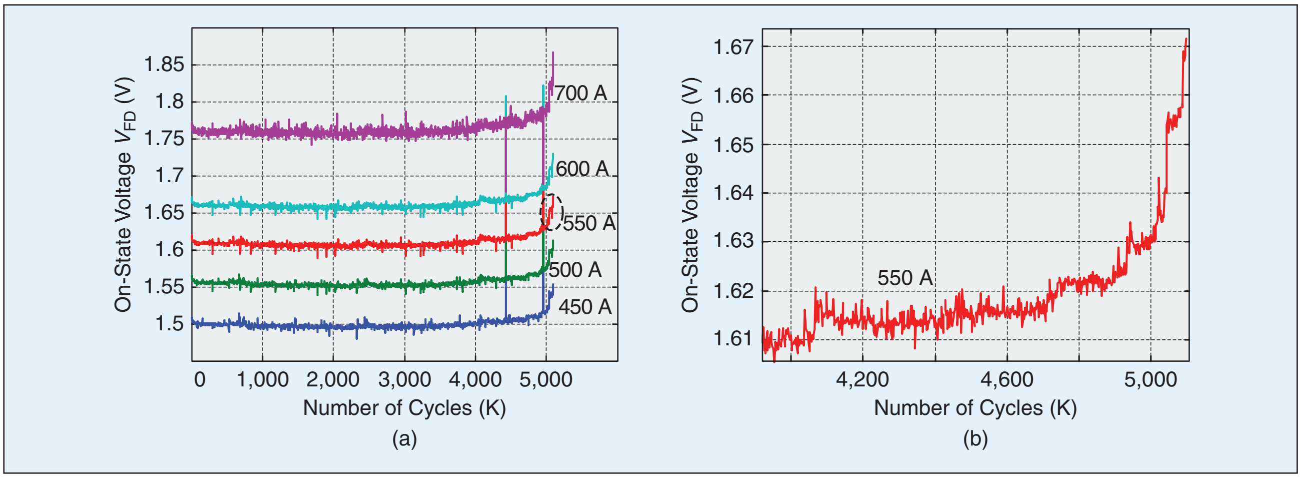

FIGURE 14 – An offline measurement: (a) the on-state V_{ce} evolution at different current levels and (b) a quick increment V_{ce} before failure occurs.

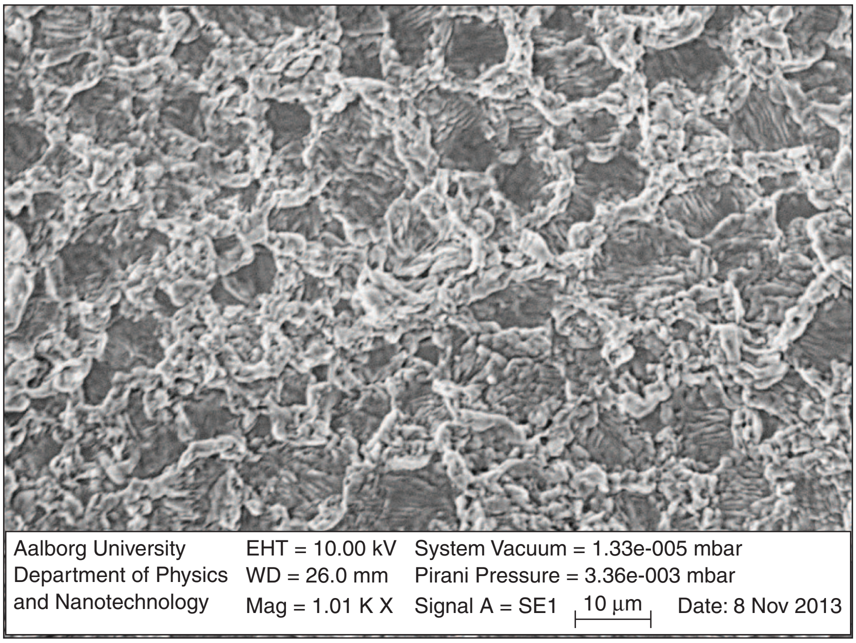

FIGURE 15 – An SEM image of Al reconstruction on the top of the diode after being subjected to 3.5 million cycles of operation.

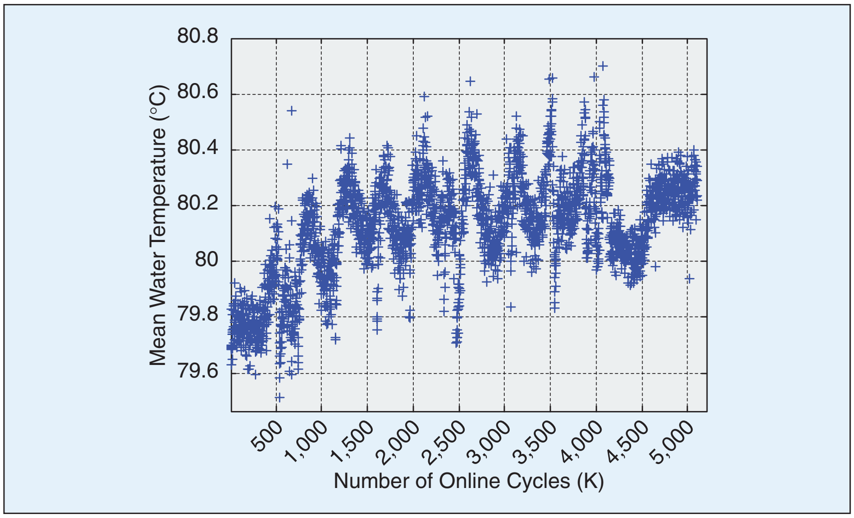

FIGURE 16 – The coolant temperature variation during the online measurement.

is calculated using the corresponding calibration factor. Finally, the estimated temperature reflects a variation of average T_j on each side of the IGBT module.

Offline Measurement

As described in the previous section, the V_{ce} is measured every 5 min during the normal operation of the converter. This method can be used to obtain the wearout status of the module when the converter is in the off state in field applications.

Figure 14(a) shows the V_{ce} evolution at different current levels on the low-side diode of the module. Figure 14(b) depicts the step increment in the voltage at some cycle due to bond wire lift-off. Furthermore, the voltage increases steadily because of the rise in the on-resistance from bond-wire degradation, aluminum reconstruction, and the increase in thermal resistance due to solder layer degradation. Figure 15 shows the scanning electron microscopic (SEM) image of metallization on the top surface of the diode chip after being subjected to 3.5 million cycles of operation, which is crude and irregular. After completing 4 million cycles of operation, the slope of the V_{ce} increases, and the first step increment appears after around 4.9 million cycles. Consecutively, the IGBT is tested for another 6.8 h until it fails. Finally, after 5 million cycles, three consecutive voltage increments are recorded within 3.2 h of operation. The V_{ce} increases by approximately 7–10 mV on each step because of the bond wire lift-off.

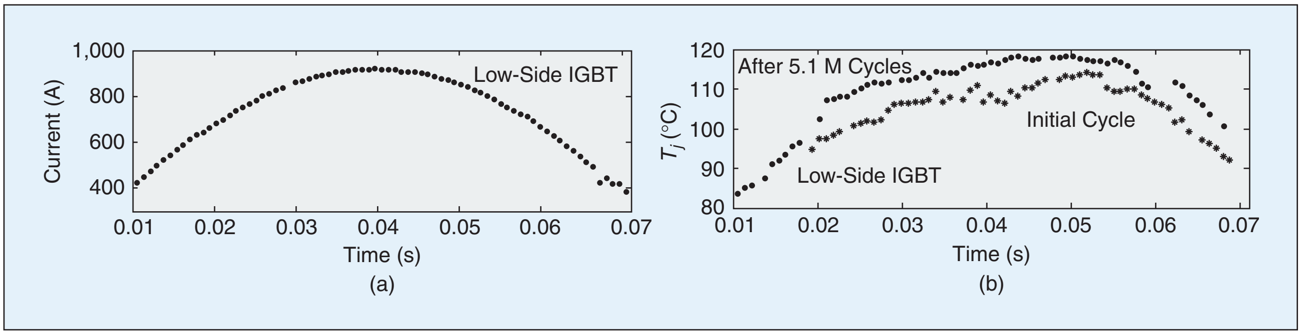

FIGURE 17 – The average T_j calculation of the low-side IGBT: (a) current and (b) average T_j at initiation and after wearout of the module.

Cooling Temperature Variation

The cooling liquid consists of glycol mixed with water to make the test conditions identical to the field applications, especially for wind power converters. The temperature of the liquid is monitored and recorded continuously together with the V_{ce} and I_c. A mean cooling temperature in every fundamental cycle of the I_c is calculated and shown in Figure 16, which shows that the coolant temperature is steady at 80 °C with a maximum of ±0.5 °C variation during the whole measurement.

Junction Temperature Calculation

The fundamental current varies sinusoidally, but, due to thermal impedance, the temperature does not change instantaneously as demonstrated in Figure 17. The average T_j in space is calculated as shown in

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

where T_{ref} is a reference temperature used during calibration (30 °C in this case), V_{cemeas} is a real-time on-state voltage measurement, and V_{ceref} is a real-time on-state voltage measured at the reference temperature.

In Figure 17(a), the current flowing through the low-side IGBT and in Figure 17(b), the calculated average T_j in space on this side at the beginning and after 5.1 million cycles of operation for half of a fundamental cycle can be seen. An updated calibration factor, as illustrated in the "Junction Temperature Measurement" section, is used for the temperature calculation at both the initial and final current cycle for the comparison. However, the change in V_{ceref}, because of the degradation of the module, is included to calculate the temperature for the final cycle as given in (3). This method allows for limiting error in the calculation of temperature because of electrical degradation in the module. Nearly 5 °C is increased at the peak temperature on the low-side IGBT before the module fails. Similarly, the average T_j in space is also calculated for the high-side IGBT using the calibration factor measured on the respective side. The current flowing through the high-side IGBT and calculated average T_j in space at the beginning of the cycle and after 5.1 million cycles are demonstrated in Figure 18(a) and (b), respectively. The change in V_{ceref} because of degradation on the high side of the IGBT is also included for the temperature calculation at the final cycle. In fact, the low-side IGBT has a peak temperature that is nearly 10 °C higher than the high-side IGBT at the beginning of the cycle, and the difference is lower after the aging of the module.

Conclusion

This article discussed and presented the experimental results of a new V_{ce} measurement method for real-time monitoring as well as a method to calculate the average junction temperature in the space of the IGBT module for a continuous sinusoidal loading operation. A long wearout test of the IGBT shows slow degradation by changing the on-state voltage as well as increasing the peak of the average junction temperature in space. A step change in the on-state voltage or a slower rise in the junction temperature can be used as a warning signal to protect from the failure of the device. A need for accurate measurement of the junction temperature estimation is emphasized. This technique is implemented in a high-power converter during operation, and the measurement result shows that this technique is adaptable

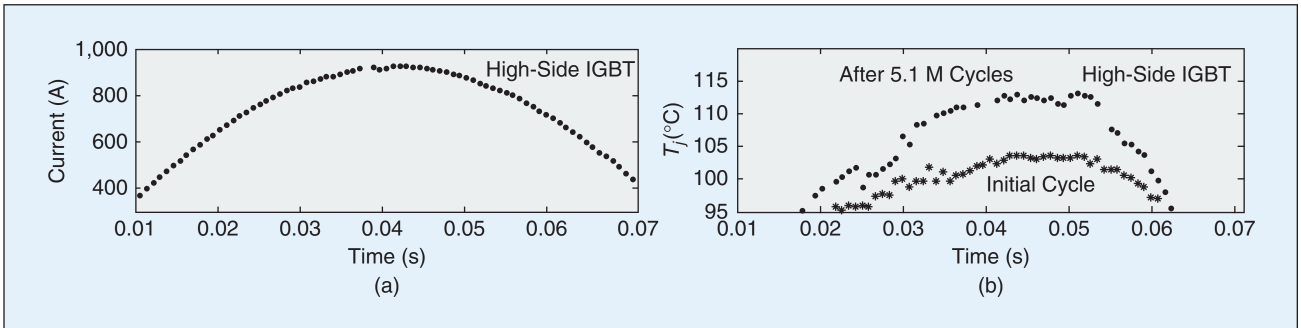

FIGURE 18 – The average T_j calculation of a high-side IGBT: (a) current and (b) average T_j at initiation and after wearout of the module.

in external field applications. Finally, finding the accuracy of this measurement technique using direct measurement is in progress.

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