Reliability Improvement of Power Converters by Means of Condition Monitoring of IGBT Modules

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***Abstract*—Power electronic systems have gradually gained an important status in a wide range of industrial applications such as renewable generation, motor drives, automotive, and railway transportation. Accordingly, recent research makes an effort to improve the reliability of power electronic systems to comply with more stringent constraints on safety, cost, and availability. The power devices are one of the most reliability-critical components in power electronic systems. Therefore, its condition monitoring plays an important role to improve the reliability of power electronic systems. This paper proposes a condition monitoring method of insulated-gate bipolar transistor (IGBT) modules. In the first section of this paper, a structure of a conventional IGBT module and a related parameter for the condition monitoring are explained. Then, a proposed real-time on-state collector–emitter voltage measurement circuit and condition monitoring strategies under different operating conditions are described. Finally, experimental results confirm the feasibility and effectiveness of the proposed method.**

***Index Terms*—Condition monitoring, insulated-gate bipolar transistor (IGBT), IGBT module, power converter, reliability, wear-out failure.**

I. INTRODUCTION

As POWER electronic systems still play a more important role in a wide range of applications such as renewable generation, automotive, motor drives, aerospace and railway transportation, recent research makes an effort to improve the reliability of power electronic systems to comply with more stringent constraints on safety, cost, and availability [1], [2].

Each component in power electronic systems affects the system reliability and robustness. Especially, reliability-critical components play a key role in the system robustness and reliability. Two surveys were performed to investigate the reliability-critical component in microelectronics and power electronics systems where the power devices account for 21% and 34% of total failure distribution in power electronic systems, respectively [2], [3]. It can be seen from the results that the power devices are one of the most reliability-critical components in power electronic systems.

The insulated-gate bipolar transistor (IGBT) is one of the most widely used of their kind for various applications in the power range from several hundred watt to several megawatt. In practical applications, power devices are used in a form of package such as discrete devices and modules, due to several reasons [4].

There are two types of IGBT modules; press-pack and wire-bonded IGBT modules. The press-pack packaging technology improves the connection of chips by the direct press-pack contacting. The press-pack IGBT module has an improved reliability, higher power density, and better cooling capability. However, the cost for this technology is higher compared with the conventional wire-bonded IGBT modules. Therefore, the wire-bonded IGBT modules are still widely used in various power electronic systems [5]–[7].

Much research on condition monitoring of the wire-bonded power IGBT module has been performed. Most of condition monitoring methods are dedicated to accelerated power cycling test [8]–[11]. In [8], an on-state collector–emitter voltage $V_{\mathrm{CE\_ON}}$ measurement circuit has been proposed using MOSFET connected in parallel with the device under test. This method has the risk that the failure of MOSFET for $V_{\mathrm{CE\_ON}}$ measurement circuit can lead to the short-circuit failure of the converter and circuit is relatively complex [9]. In [10], the $V_{\mathrm{CE\_ON}}$ measurement method using relay has been proposed. However, this method is not fast enough for the real-time $V_{\mathrm{CE\_ON}}$ measurement during converter operation. The saturation voltage measurement circuit using zener diode has been also proposed in [11]. However, this circuit is also not fast enough for applications, which have more than several kilohertz switching frequency due to long settling time for the measurement. The online V_{CE} measurement circuit using two diodes derived from typical desaturation protection circuit has been proposed in [12]. This method can measure $V_{\mathrm{CE\_ON}}$ and V_F under the converter operation but the deviation between two diodes could lead to the measurement error. The $V_{\mathrm{CE\_ON}}$ measurement for an electric vehicle has been proposed in [13]. The $V_{\mathrm{CE\_ON}}$ measurement is not activated during drive operations but activated during maintenance works or other certain modes such as red traffic light, stop and go traffic, as this circuit cannot block high dc-link voltage.

Besides the aforementioned methods, there are other condition monitoring methods for the IGBT modules [14], [15]. However, most of methods have limitations in applicability to

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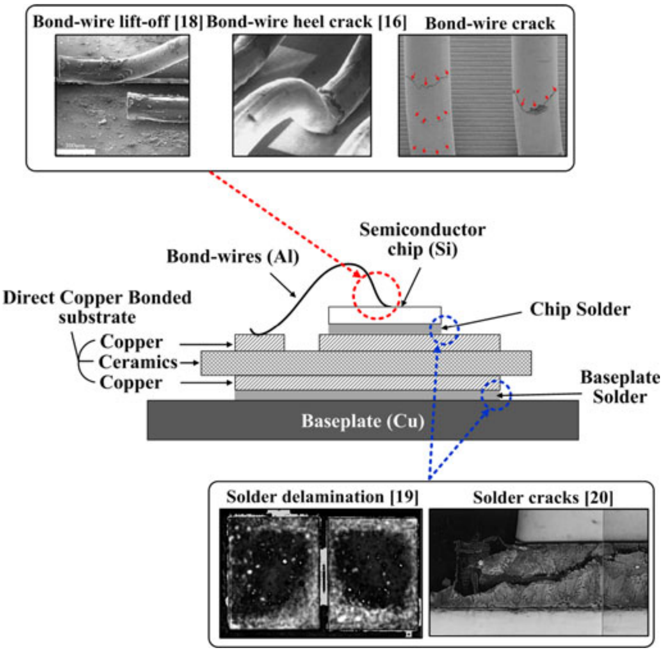


Fig. 1. Structure of a standard IGBT module and dominant package-related failure mechanisms.

various real applications because of sensitive measurement parameter or structure modification. Therefore, more intelligent condition monitoring methods are still needed.

In this paper, a condition monitoring method of IGBT modules is proposed. In the first section of this paper, a structure of a conventional IGBT module and related parameter for the condition monitoring are explained. Then, an intelligent on-state collector–emitter voltage measurement circuit and condition monitoring strategies depending on converter operating conditions are described. Finally, experimental results confirm the feasibility and effectiveness of the proposed method.

II. INSULATED GATE BIPOLAR TRANSISTOR (IGBT) MODULES

In this section, the basic structure of a conventional IGBT module is presented. Then, the major failure mechanisms of the IGBT module and the related parameters for the condition monitoring are discussed.

A. *Structure of Wire-Bonded IGBT Module*

In practical applications, power devices are used in a form of package such as discrete devices and modules in order to provide electrical connection between one or more semiconductor chips and the circuit and to reduce costs for high power applications by connecting several chips with internal insulation of individual components. Furthermore, the power device module can dissipate the heat generated during chip operation to a cooling system with electrical insulation and also can protect the semiconductor chip from harmful ambient influences [4].

Fig. 1 shows the structure of a standard IGBT module [4], [16]. A direct copper bonded (DCB) substrate is soldered to a base-plate. The DCB provides electrical insulation between power components and cooling systems. Further, it conducts the current via copper tracks and provides also good thermal connection to the cooling systems. In the lower power range, IGBT modules without base-plate are more frequently used, while in medium and high power range, IGBT modules have almost all a base-plate. The base-plate provides thermal capacity and helps for the thermal spreading by increasing the contact area to a heat-sink. IGBT and diode chips are soldered to DCB. Bond wires are commonly used in order to connect the emitter of the silicon chips to the substrate and in order to connect the substrate to the terminals. Finally, it is covered by silicone gel or epoxy resin for insulation.

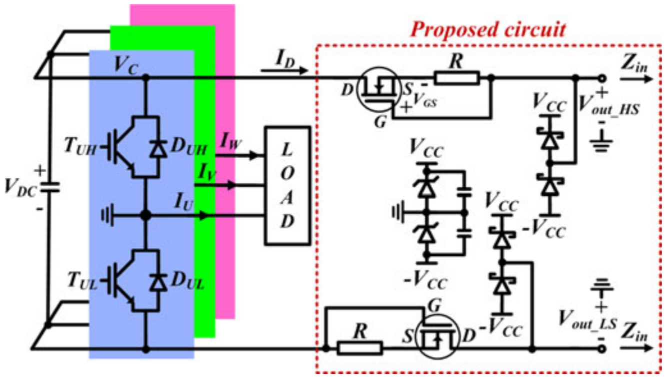


Fig. 2. Schematic diagram of the proposed $V_{\mathrm{CE\_ON}}$ and V_F measurement circuit using a depletion mode MOSFET.

B. *Wear-Out Failure Mechanisms and Monitoring Parameter*

Bond wire fatigue is one of the common failure mechanisms in power IGBT modules [16]. As shown in Fig. 1, IGBT module consists of various materials and each material has different coefficient of thermal expansion (CTE) [13]. The IGBT and diode produce the loss during switching and when conducting the electric currents and it appears as a heat source in the module. The converter load variation, the periodical commutation of power switching device, and the ambient temperature change cause the temperature variation in the IGBT module. The large CTE mismatch between the bond wires and chip under the temperature variation causes the thermomechanical stress in bond wires and, finally, leads to bond wire lift-off or crack failure as shown in Fig. 1 [16], [17].

Another dominant failure mechanism is solder joint fatigue [16]. There are two solder joints in the standard IGBT module between chip and DCB and between DCB and base-plate. Due to the CTE mismatch with temperature variation, the thermomechanical stresses are applied to the solder joints and cause the degradation of the solder interface like cracks, delamination and voids as shown in Fig. 1. The solder joint fatigue increases the thermal impedance. Consequently, the junction temperature of the power semiconductor devices may increase and it could accelerate other failure modes like bond wire fatigue. Furthermore, the increased junction temperature could induce hot spots and thermal runaway in the affected areas of the module [11], [12]. These two failure mechanisms are the dominant wear-out failure mechanisms in wire-bonded IGBT modules.

There are some electric parameters which can indicate the wear-out condition of the IGBT modules. Among them, on-state collector–emitter voltage ($V_{\mathrm{CE\_ON}}$) of IGBTs and forward

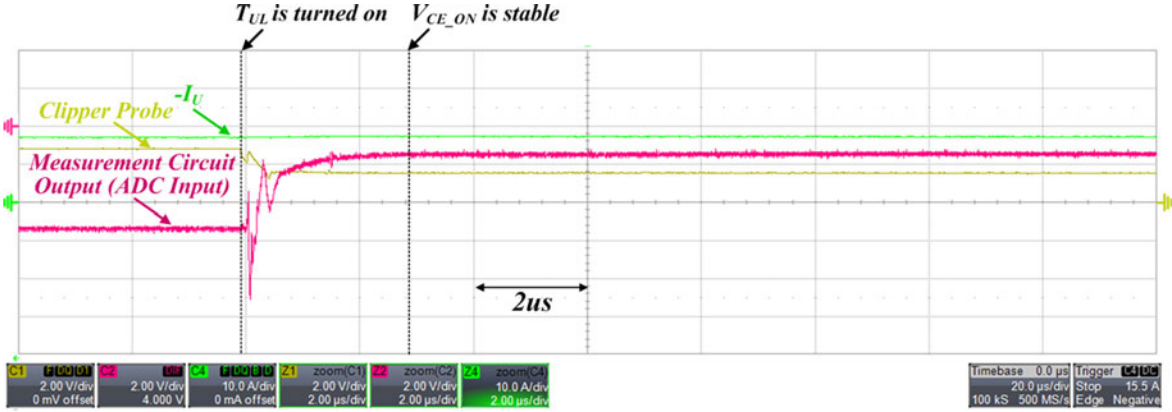


Fig. 3. Transient waveform of measured $V_{\mathrm{CE\_ON}}$ of T_{UL}; Y-axis of $V_{\mathrm{CE\_ON}}$: (2 V/div), Y-axis of I_U: (10 A/div).

voltage (V_F) of diodes can cover both failure mechanisms [21]. The bond wire fatigue increases the resistance of the electrical connection and results in increases of $V_{\mathrm{CE\_ON}}$ and V_F. Typically, 5% to 20% increase of $V_{\mathrm{CE\_ON}}$ and V_F from its initial values is considered as wear-out failure of the power device modules [16]. Further, this parameter is a temperature-sensitive electrical parameter (TSEP). Therefore, the junction temperature increase due to thermal impedance change can be estimated and it can be determined that the converter is in the safety-operating area. The detailed information for the junction temperature estimation using $V_{\mathrm{CE\_ON}}$ can be obtained in [21] and [22].

III. REAL-TIME ON-STATE COLLECTOR–EMITTER VOLTAGE AND FORWARD VOLTAGE MEASUREMENT CIRCUIT

Fig. 2 shows the proposed real-time measurement circuit of on-state collector–emitter voltage ($V_{\mathrm{CE\_ON}}$) of IGBTs and forward voltage (V_F) of diodes. The drain of N-channel small signal MOSFET in the measurement circuit is connected with the collector of high side IGBT (T_{UH}). In the case of the measurement circuit for low-side components, the gate of the MOSFET is connected to the emitter of low-side IGBT (T_{UL}) and it is connected to the source of the MOSFET through resistance (R). The MOSFET used in this circuit is a depletion mode MOSFET.

The depletion mode MOSFET has a negative threshold voltage ($V_{\mathrm{GS}} < 0$) and thus can be turned on when the gate–source voltage $V_{\mathrm{GS}} = 0$ V. In this circuit, the magnitude of clamping voltage ($\pm V_{\mathrm{CC}}$) should be larger than the magnitude of $V_{\mathrm{CE\_ON}}$ and V_F. Further, the input impedance (Z_{in}) for the $V_{\mathrm{CE\_ON}}$ and V_F measurements should be big enough.

The operating principle is explained considering the $V_{\mathrm{CE\_ON}}$ measurement of T_{UH}. When T_{UH} is tuned-on, the current I_D does not flow through the MOSFET because collector voltage $V_C = V_{\mathrm{CE\_ON}}$ is smaller than V_{CC} and thus $V_{\mathrm{GS}} = 0$. Consequently, the MOSFET is turned on and $V_{\mathrm{out}} = V_{\mathrm{CE\_ON}}$. As V_C increases above the clamping voltage V_{CC} by turning off T_{UH}, I_D starts to flow and makes the voltage drop in R. As I_D increases, V_{GS} becomes a negative value and then the MOSFET is turned off if V_{GS} becomes smaller than threshold voltage (V_T) of the MOSFET. Therefore, the clamping voltage V_{CC} is measured at the output during this period. $V_{\mathrm{CE\_ON}}$ of the IGBT is measured during a positive current period as a positive value and V_F of the diode is measured during a negative current period as a negative value where the current from the converter to load is a positive direction. The measurement of $V_{\mathrm{CE_{ON}}}$ and V_F for the low-side IGBT and diode also can be interpreted in a similar way. $V_{\mathrm{CE\_ON}}$ and V_F are measured during the negative current period as a negative value and the positive current period as positive value, respectively.

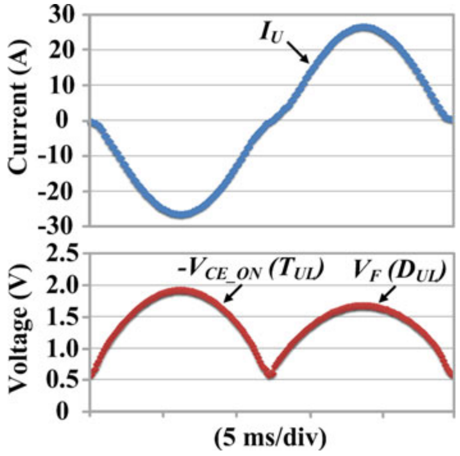


Fig. 4. Measured $-V_{\mathrm{CE\_ON}}$ and V_F of T_{UL} and D_{UL}, respectively, by the proposed circuit when the converter is operated under V_{DC}: 400 V, I_{peak}: 25 A, f_{OUT}: 50 Hz.

Fig. 3 shows the transient waveform of measured $V_{\mathrm{CE\_ON}}$ of T_{VL} by the proposed measurement circuit and clipper measurement probe (clp1500V15A1), respectively. When T_{VL} is turned off, the measured $V_{\mathrm{CE\_ON}}$ by the proposed measurement circuit is clamped to $-V_{\mathrm{CC}}$ as explained above. $V_{\mathrm{CE\_ON}}$ which is measured by the clipper probe as the positive value is also clamped to clamping voltage of the clipper probe. After T_{VL} is turned on, $V_{\mathrm{CE\_ON}}$ of T_{VL} becomes stable after the short settling time, less than 4 µs and then $V_{\mathrm{CE\_ON}}$ can be measured correctly by the proposed measurement which is almost the same with the measured $V_{\mathrm{CE\_ON}}$ by the clipper probe as shown in the result. Therefore, this circuit can be used for applications which have more than several kilohertz switching frequency. It is worth to note that the settling time of the measurement circuit could be varied depending on operating conditions of the IGBT module.

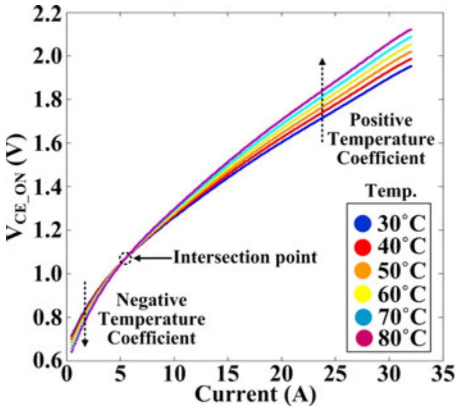
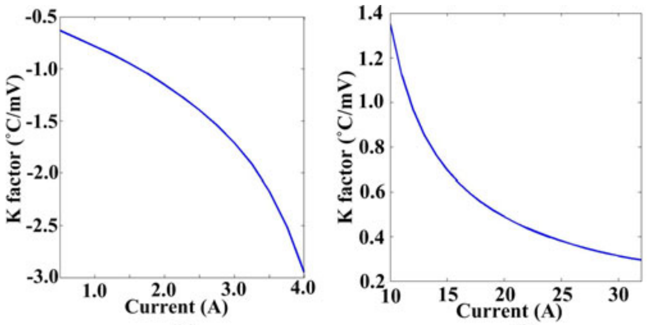


Fig. 5. *I–V* characterization curves of low-side IGBT of phase-V (T_{VL}).



(a) (b)

Fig. 6. Temperature dependent factor of $V_{\mathrm{CE\_ON}}$ at different current levels of T_{VL}.

Fig. 4 shows the measured $-V_{\mathrm{CE\_ON}}$ of low-side IGBT and V_F of low-side diode along with the output current under the converter operation.

IV. Condition Monitoring of IGBT Module for the Different Power Converter Applications

In this section, the several condition monitoring strategies using the proposed measurement circuit for different operating conditions are proposed.

A. Online Measurement Strategies

1) Converter Applications With Fixed Operating Condition or Repetitive Load Profile: If the converter is operated under the fixed operating condition such as constant output power and frequency, the increase of $V_{\mathrm{CE\_ON}}$ due to the wear-out of an IGBT module can simply be monitored by measuring $V_{\mathrm{CE\_ON}}$ at the same current level and angle per one fundamental cycle of the output current. There are two points which have the same current level in a sinusoidal current. However, the junction temperatures at these two points are different each other and thus the measured $V_{\mathrm{CE\_ON}}$ has different values. Therefore, the current angle should also be considered when $V_{\mathrm{CE\_ON}}$ is measured. Further, the temperature variation in a heat-sink or water for cooling due to ambient temperature variation leads to the change of $V_{\mathrm{CE\_ON}}$. However, the effect of the heat-sink or water cooling temperature variation on the change of $V_{\mathrm{CE\_ON}}$ can simply be compensated. From the *I–V* characteristic curves as shown in Fig. 5, the temperature dependence factor of $V_{\mathrm{CE\_ON}}$ at a given current level can be obtained as shown in Fig. 6. For example, if the $V_{\mathrm{CE\_ON}}$ is measured at 20 A, the temperature dependence factor is about 0.43 °C/mV.

A 10 °C temperature increase in the heat-sink or water for cooling may lead to about 10 °C increase in the junction temperature, and thus it can be expected that $V_{\mathrm{CE\_ON}}$ increases by 23 mV. Therefore, the variation in $V_{\mathrm{CE\_ON}}$ due to the temperature increase can be compensated for the condition monitoring. There could be an error in compensation because the 10 °C increase in the heat-sink or water for cooling does not mean exactly 10 °C increase in the junction temperature. However, it is not significant because the compensation error due to a few degree temperature differences is very small compared with the end-of-life criterion of the IGBT module, typically, 5 to 10% increase is more than 100 mV.

By this monitoring strategy, the change of $V_{\mathrm{CE\_ON}}$ due to only the degradation of the IGBT module can be monitored. Further, it can be applied for applications, which are operated under repetitive load profiles by measuring the monitoring parameters at the specific region of the load profiles.

2) Converter Applications With Conditions: In the case of converter applications, operated with various operating conditions, it is more difficult to monitor $V_{\mathrm{CE\_ON}}$, even though it is measured at the same current level and angle. This is because the junction temperature at the instant of the measurement is different depending on operating conditions such as output power, output frequency, etc. Therefore, the measured $V_{\mathrm{CE\_ON}}$ is varied and it is difficult to compensate the $V_{\mathrm{CE\_ON}}$ variation, which comes from the different junction temperature at the instant of the measurement.

There are two types of IGBTs, punch-through IGBTs and non-punch-through (NPT) IGBTs. The NPT-IGBT has become the dominating device in applications, because of its robustness and suitable behavior at parallel connection [7]. The NPT-IGBT has the two regions: negative thermal coefficient (NTC) and positive thermal coefficient (PTC) regions in its *I–V* characterization curves as shown in Fig. 5. There is the NTC region at low current levels where $V_{\mathrm{CE\_ON}}$ decreases as the temperature increases. On the contrary, the PTC region is at high current levels where as the temperature increases, $V_{\mathrm{CE\_ON}}$ also increases. In addition, there is the intersection point between NTC and PTC regions. This point has always the same value regardless of the temperature variation. Therefore, if $V_{\mathrm{CE\_ON}}$ is measured at the intersection point, $V_{\mathrm{CE\_ON}}$ increase due to only the wear-out of the IGBT module can be monitored without regard to the operating conditions of the power converters. For example, the *I–V* characterization curves in Fig. 5, the intersection point is at about 5.7 A and there is no change depending on the temperature.

B. Offline Measurement Strategies

The offline measurement strategy can be applied for the applications which cannot be covered by aforementioned online measurement strategies. $V_{\mathrm{CE\_ON}}$ and V_F are measured whenever the power converter stops its operation.

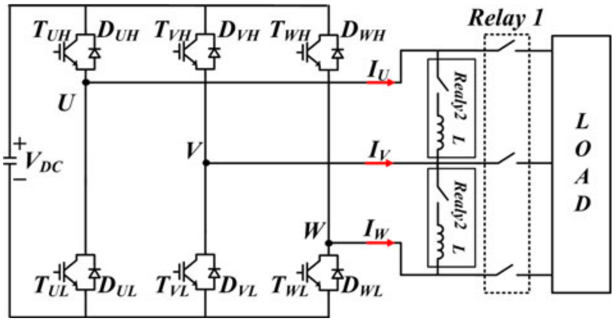


Fig. 7. Topology for the offline measurement of condition monitoring parameter.

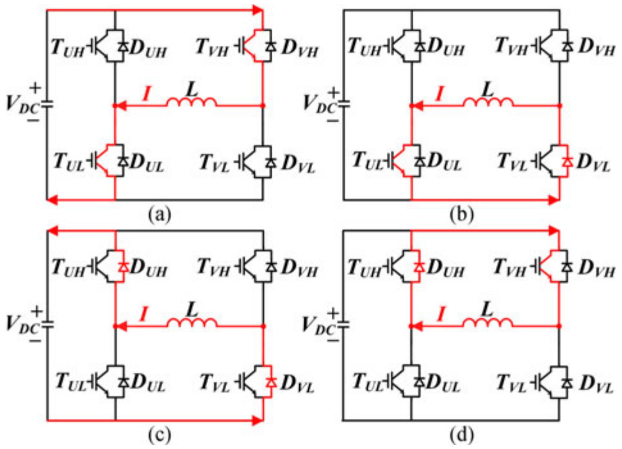


Fig. 8. Switching sequence of the offline measurement for the IGBT module condition monitoring.

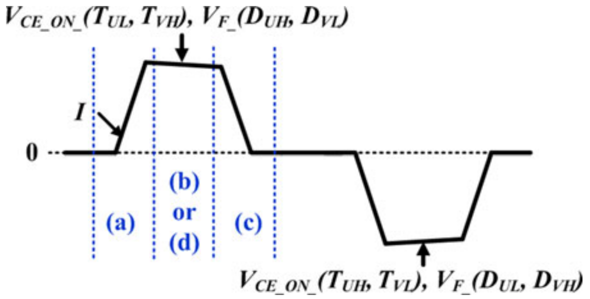


Fig. 9. Current *I* corresponding to the switching sequences shown in Fig. 8.

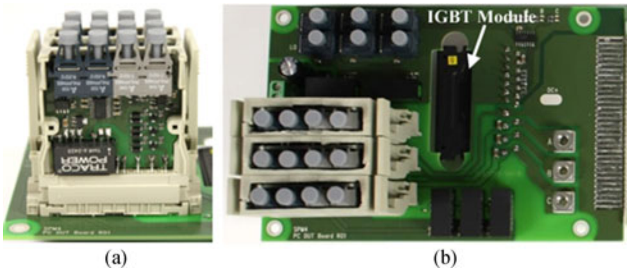


Fig. 10. Experimental setup. (a) $V_{\mathrm{CE\_ON}}$ and V_F measurement circuit and (b) power converter.

TABLE I
OPERATING CONDITION OF CONVERTER FOR EXPERIMENTS

Parameter	Value
DC link	30 A
Peak current	400 V
Switching frequency	10 kHz
Output frequency	1 Hz
Power factor	1
Junction temperature swing	81 °C
Mean junction temperature	102 °C

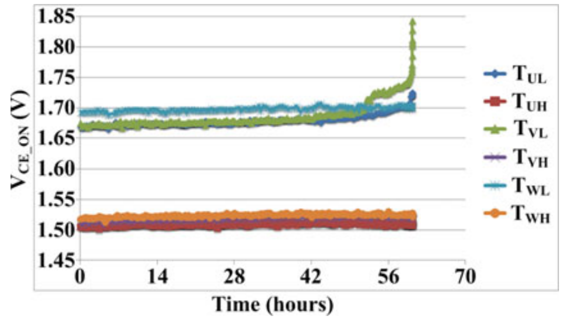


Fig. 11. Experimental result of the condition monitoring of the IGBT module using an online measurement strategy.

TABLE II
OPERATING CONDITION OF CONVERTER FOR THE COMPARISON OF MEASURED $V_{\mathrm{CE\_ON}}$ AT THE INTERSECTION POINT

Condition	Value				
	DC-link voltage	Switching frequency	Peak current	Output frequency	Heat-sink temperature
1	400 V	10 kHz	15 A	1 Hz	26 °C
2	400 V	10 kHz	23 A	20 Hz	36 °C
3	400 V	10 kHz	28 A	50 Hz	42 °C
4	400 V	10 kHz	28 A	10 Hz	44 °C
5	400 V	10 kHz	10 A	20 Hz	27 °C

Fig. 7 shows the proposed topology for the offline measurement strategy. For the offline measurement, some additional components are required. Under normal operation, Relay 1 is turned on and Relay 2 is turned off. If the converter operation is stopped, Relay 1 is turned off in order to disconnect the converter with load and Relay 2 is turned on in order to measure $V_{\mathrm{CE\_ON}}$ and V_F for the condition monitoring of the IGBT module.

Fig. 8 shows the equivalent circuit diagram when Relay 2 between phase-U and phase-V is turned on and also shows the switching sequence for the $V_{\mathrm{CE\_ON}}$ and V_F measurements. If the converter is stopped and Relay 2 is turned on, T_{UL} and T_{VH} are turned on to produce the current *I* as shown in Fig. 8(a). Then, T_{VH} is turned off so that the current flows through T_{UL} and D_{VL} as shown in Fig. 8(b). $V_{\mathrm{CE\_ON}}$ of T_{UL} and V_F of D_{VL} are measured at this point. After that, *I* decreases to zero by turning T_{UL} off as shown in Fig. 8(c). In the case of measurement for D_{UH} and T_{VL}, T_{UL} is turned off after the switching sequence shown in Fig. 8(a). The current flows through D_{UH} and T_{VH}

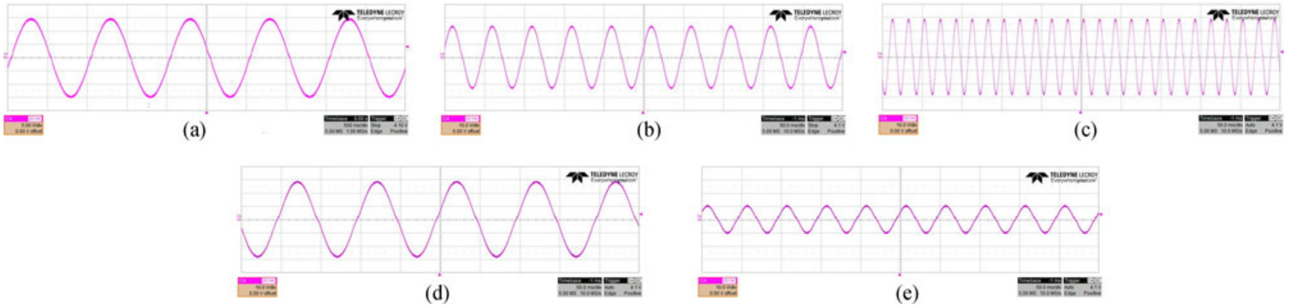

(a) (b) (c) (d) (e)

Fig. 12. Output current under the converter-operating conditions listed in Table II. (a) Condition 1, (b) Condition 2, (c) Condition 3, (d) Condition 4, and (e) Condition 5. *X*-axis: time (500 ms/div), *Y*-axis: current (5 A/div) for (a) and *X*-axis: time (50 ms/div), *Y*-axis: current (10 A/div) for (b)–(e).

as shown in Fig. 8(d) and V_F of D_{UH} and $V_{\mathrm{CE\_ON}}$ of T_{VH} are measured at this point. Then, T_{VH} is turned off to make the current zero.

Each switching sequence is performed in a short period (less than three switching periods of IGBT). Further, only small inductors are required to generate the desired current level in one switching period. These inductors can be replaced with output filter inductors if they exist in the power converter system. The $V_{\mathrm{CE\_ON}}$ and V_F should be measured at the same current level and temperature. Therefore, the dwell times of turn-on states of T_{UL} and T_{VH} for generating current *I* should be the same per $V_{\mathrm{CE\_ON}}$ and V_F measurements and the temperature difference in the heat-sink or water for cooling can be compensated as explained in the online measurement strategy for the converter applications with fixed operating condition. The measurements for the other components can be interpreted in a similar way.

Fig. 9 shows the current *I* corresponding to the switching sequences shown in Fig. 8.

V. EXPERIMENTAL RESULTS

Experiments have been carried out in order to verify the validity of the proposed monitoring method.

Fig. 10 shows the prototype of experimental setup. A 600 V, 30 A, three-phase transfer molded IGBT module is used for the case study. To make the wear-out condition of the IGBT module in a reasonable test time, the converter has been operated under a severe condition. The operating condition and related temperature stress are listed in Table I. In this condition, each IGBT has the big temperature swing due to low frequency output sinusoidal currents.

Fig. 11 shows the online condition monitoring result of the IGBT module. $V_{\mathrm{CE\_ON}}$ of all IGBTs are measured at 20 $\mathrm{A}_{\mathrm{peak}}$ of increasing slope. If $V_{\mathrm{CE\_ON}}$ increases more than 10% from its initial value, the test is stopped in order to protect the tested module against catastrophic failure. The failure occurs in T_{VL} first. After 49 h, there is the sudden increase in $V_{\mathrm{CE\_ON}}$ of T_{VL} and then it is increased by 10% after 60 h.

Further, it can be expected that T_{UL} will fail next, because there is the sudden increase in $V_{\mathrm{CE\_ON}}$ of T_{UL} just before the test is finished.

$V_{\mathrm{CE\_ON}}$ of T_{VL} is measured at the intersection point under the different operating conditions in order to show the independence of $V_{\mathrm{CE\_ON}}$ at the intersection point against operating conditions.

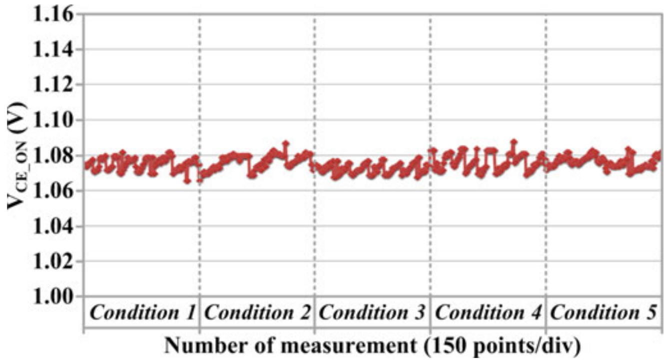


Fig. 13. Measured $V_{\mathrm{CE\_ON}}$ of T_{VL} at intersection point (about 5.7 A) under different converter-operating conditions listed in Table II.

The five different operating conditions which have different current levels from 10 to 28 A and output frequencies from 1 to 50 Hz are chosen as listed in Table II. Fig. 12 shows the output current of the converter corresponding to the operating conditions.

Fig. 13 shows the measured $V_{\mathrm{CE\_ON}}$ of T_{VL} at intersection point (about 5.7 A) under the five different operating conditions. The measured $V_{\mathrm{CE\_ON}}$ at the intersection point have the almost same value regardless of the operating conditions.

It can be seen from the results that the effect of the different junction temperatures at the instant of the measurement, leading to the $V_{\mathrm{CE\_ON}}$ variation, can be eliminated by measuring $V_{\mathrm{CE\_ON}}$ at the intersection point between the NTC and PTC regions. Thus, $V_{\mathrm{CE\_ON}}$ increase due to only the wear-out of the IGBT module can be monitored.

Typically, $V_{\mathrm{CE\_ON}}$ and V_F are monitored at high currents because the resistance increases due to the degradation in electric connection can be monitored more distinctly at high current. However, the current at the intersection point is relatively low and thus the end-of-life criteria should be tightened to determine the degradation condition properly. For the test with online monitoring at the intersection point, the end-of-life criterion is set as 5% increase of $V_{\mathrm{CE\_ON}}$ and V_F.

Fig. 14 shows the online condition monitoring result when $V_{\mathrm{CE\_ON}}$ is measured at the intersection point. In this test, the failure occurs in T_{UL} first. $V_{\mathrm{CE\_ON}}$ starts to increase after operation for about 50 h and it is reached to its end-of-life criterion, 5% increase of $V_{\mathrm{CE\_ON}}$, after about 55 h.

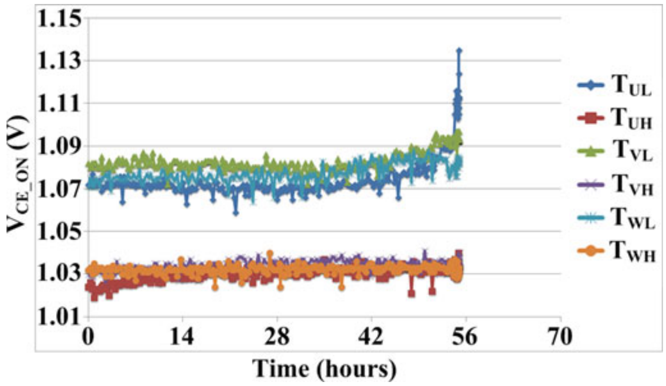


Fig. 14. Condition monitoring result of the IGBT module when $V_{\mathrm{CE\_ON}}$ is measured at the intersection point.

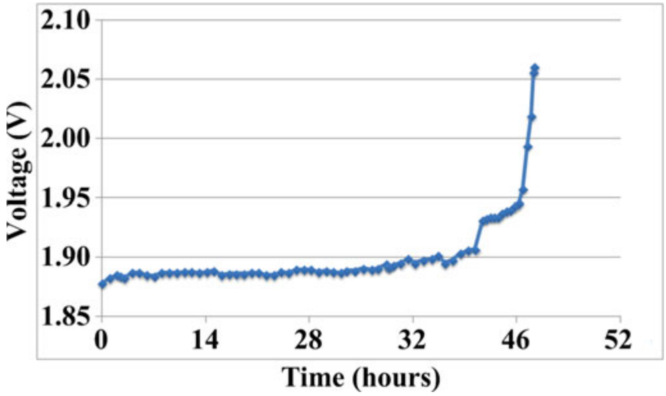


Fig. 15. Experimental result of the condition monitoring with an offline measurement strategy ($V_{\mathrm{CE\_ON}}$ of T_{VL}).

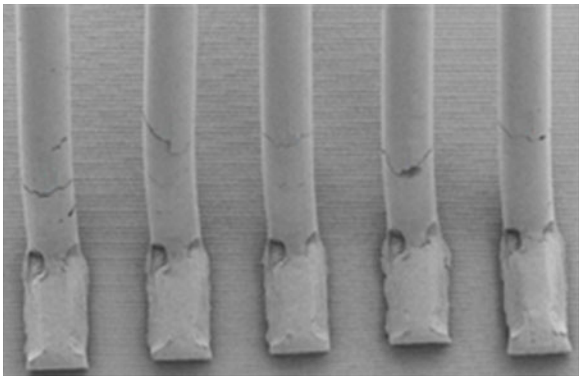


Fig. 16. SEM image of low-side IGBT of phase-V (T_{VL}) in the tested IGBT module.

Condition monitoring by the offline measurement strategy has been also performed. Fig. 15 shows the measured $V_{\mathrm{CE\_ON}}$ of T_{VL}. $V_{\mathrm{CE\_ON}}$ is measured at 28 A per 1 h until there is no distinct increase and then if there appears the visible $V_{\mathrm{CE\_ON}}$ increase, offline measurement has been performed per half an hour. It seems that the first failure occurs in the bond-wire after 50 h of operation, because there is the visible increase of $V_{\mathrm{CE\_ON}}$. After about 57 h of operation, $V_{\mathrm{CE\_ON}}$ increases by 10% from its initial value.

Fig. 16 shows the scanning electron microscopy (SEM) image of one of the tested IGBT modules. The bond-wire cracks are observed in all five bond wires in T_{VL}. This is the root cause of $V_{\mathrm{CE\_ON}}$ increase and agrees well with the condition monitoring result by the proposed method.

VI. CONCLUSION

In this paper, the condition monitoring method of IGBT modules for the reliability improvement of power converter systems has been proposed. The real-time $V_{\mathrm{CE\_ON}}$ and V_F measurement circuit has been proposed first. By the proposed real-time measurement circuit, wear-out condition of the IGBT module in power converter systems can be monitored in real time.

It can also be used for the junction temperature estimation because it is one of TSEPs, even though the junction temperature estimation method is not discussed in this paper.

Further, the condition monitoring strategies using the proposed circuit for the power converter under the different operating conditions have been presented. By means of the proposed strategies, the wear-out condition of the IGBT module under various converter applications can be monitored. In addition, the experiments with a real converter have been performed to validate the effectiveness of the proposed method. Three tests have been performed with the proposed strategies. The test results show that the wear-out condition of the IGBT module is properly monitored by the proposed strategies.

Finally, the validity of the proposed condition monitoring results has been confirmed by investigating the tested IGBT module by SEM. In the tested IGBT module, cracks have occurred in the bond wires and this is the reason that $V_{\mathrm{CE\_ON}}$ increases as monitored by the proposed method.

The proposed method is expected to improve the reliability of power converter systems under various applications by monitoring the wear-out condition of the IGBT modules.

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