# Physics-of-Failure, Condition Monitoring, and Prognostics of Insulated Gate Bipolar Transistor Modules: A Review

Hyunseok Oh, *Member, IEEE*, Bongtae Han, Patrick McCluskey, *Member, IEEE*, Changwoon Han, and Byeng D. Youn

***Abstract*—Recent growth of the insulated gate bipolar transistor (IGBT) module market has been driven largely by the increasing demand for an efficient way to control and distribute power in the field of renewable energy, hybrid/electric vehicles, and industrial equipment. For safety-critical and mission-critical applications, the reliability of IGBT modules is still a concern. Understanding the physics-of-failure of IGBT modules has been critical to the development of effective condition monitoring (CM) techniques as well as reliable prognostic methods. This review paper attempts to summarize past developments and recent advances in the area of CM and prognostics for IGBT modules. The improvement in material, fabrication, and structure is described. The CM techniques and prognostic methods proposed in the literature are presented. This paper concludes with recommendations for future research topics in the CM and prognostics areas.**

***Index Terms*—Condition monitoring (CM), insulated gate bipolar transistor (IGBT), physics-of-failure (PoF), prognostics.**

## I. Introduction

INSULATED gate bipolar transistors (IGBTs) are highly demanded in the market of wind energy generation, high speed rails, and hybrid vehicles, which require power semiconductor devices with a broad range of voltage from 300 V to 6.5 kV and current handling capability larger than power MOSFETs [1]–[3]. Reliability of IGBTs at the early stage of product development is usually assessed by physical testing such as thermal/power cycling, thermal/mechanical shock, and vibration testing [4], although the cycles of test-analyze-fix is expensive and time-consuming [5]. Physics-of-failure (PoF)-based assessment during the design process has been widely accepted as an efficient and cost-effective way for ensuring reliability [6], [7]. It was reported that, due to continuous improvement, the failure rate of the IGBT modules in the traction application dropped from 1000 FIT (failures-in-time: the number of failures in one billion hours) in the year of 1995 to 20 FIT in 2000 and to only a few FITs in recent years [8].

Despite the widespread efforts to improve reliability, failures of power electronics have been observed continuously. According to a recent industry-wide survey [9], 31% of the responders answered that power semiconductor devices are the most fragile components in power electronic converters. Although the exact percentage of IGBT failure was not known, the survey indicated that IGBTs were the most frequently used devices (42%) among power semiconductor devices followed by MOSFETs (27%), thyristors (14%), PiN diodes (10%), etc. Jeong *et al.* [10] and Perpina *et al.* [11] reported the actual field failures of IGBT modules in motor drive and high-speed railway applications, respectively. For safety-critical and mission-critical applications, there is a strong demand for further improvement of the reliability of IGBT modules. Redundancy may not be the best option in those applications.

The scheme of condition monitoring (CM) and prognostics is actively applied to detect incipient faults and to take corrective actions before catastrophic failures occur. CM is different from prognostics. CM is to assess the current health condition of a component/system, while prognostics is to predict the health condition at some point in the future. With only CM techniques, it remains unknown how much time is left before the failure of a component or a system of interest occurs.

CM and prognostic techniques for IGBTs have been developed over the last decade. However, CM and prognostic capabilities directly applicable to systems in the field are still limited. There are three main challenges: 1) how to measure physical quantities related to actual conditions of IGBT modules without interrupting their normal operation; 2) how to correlate health indicators directly or indirectly estimated from physical measurements to the actual conditions of IGBT modules; and 3) how to project health indicators to the future with adequate failure criteria, managing uncertainties related to predictions of remaining useful life (RUL). These challenges have been addressed in numerous studies.

Excellent review papers related to PoF, CM, and diagnostics of power semiconductor devices can be found in the

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literature [8], [12], [13]. More than ten years ago, Ciappa [12] presented potential mechanisms related to power module failures for high-power applications. Lu and Sharma [13] presented existing methods for fault diagnostics and failure protection of IGBTs focusing on, in particular, three-phase power inverters. Later, Yang *et al.* [8] described the CM state-of-the-art of the power electronics. They attempted to identify the benefits and limitations of currently available CM techniques for power electronics, including IGBTs. Yet, the prognostic aspects of IGBTs have not been addressed extensively. In addition, significant new findings on CM as well as advanced prognostic methods using failure precursors have been reported since the review papers appeared in the literature. These are the motivations of this review paper.

The objectives of this review paper are thus: 1) to provide a fundamental understanding of recent advances in CM and prognostics on IGBT modules; and 2) to address challenges and opportunities that are anticipated for implementation of CM and prognostic methods. Section II describes the structure of IGBT modules and the advances in their performance. Sections III and IV describe the CM techniques and prognostic methods, respectively. Section V identifies potential research areas and issues to be addressed for developing reliable CM and prognostics. This paper concludes with recommendations for future research topics in Section VI.

## II. Background: IGBT Modules

The overview of IGBT modules is categorized with two levels: die and package. This classification is based on the role of dies and packages in IGBT modules. Dies provide the essential function of power semiconductor devices, i.e., control of electrical power, whereas packages provide electrical interconnection, heat dissipation path, and environmental and handling protection.

### A. IGBT Modules: Die Level

The basic structure of IGBT dies was first introduced in the early 1980s [14], [15]. While Si-based IGBTs have been continuously improved [16], [17], wide band-gap semiconductor materials such as SiC and GaN also have drawn attention for the future innovation of IGBTs [18]–[20]. New technologies are also being developed based on the concept of superjunctions [21], [22]. The adoption of improved and innovative IGBT technologies potentially introduces new failure modes and mechanisms, which can complicate the tasks of CM and prognostics. This rapid evolution of IGBT technologies will remain as challenges for the CM and prognostics community.

IGBT dies are often packaged with diode dies for some applications such as voltage source converters. Freewheeling diodes can fail under various loading conditions, in particular, during the turn-on transition of IGBTs with a high switching frequency. The failure eventually slows down the switching speed of power converters [23]. Wu *et al.* [24] presented an overview of catastrophic failures of freewheeling diodes in power electronic circuits. Within the current CM technology, however, CM of diode dies may be limited since most of their mechanisms of diode dies are not wearout failures but overstress failures.

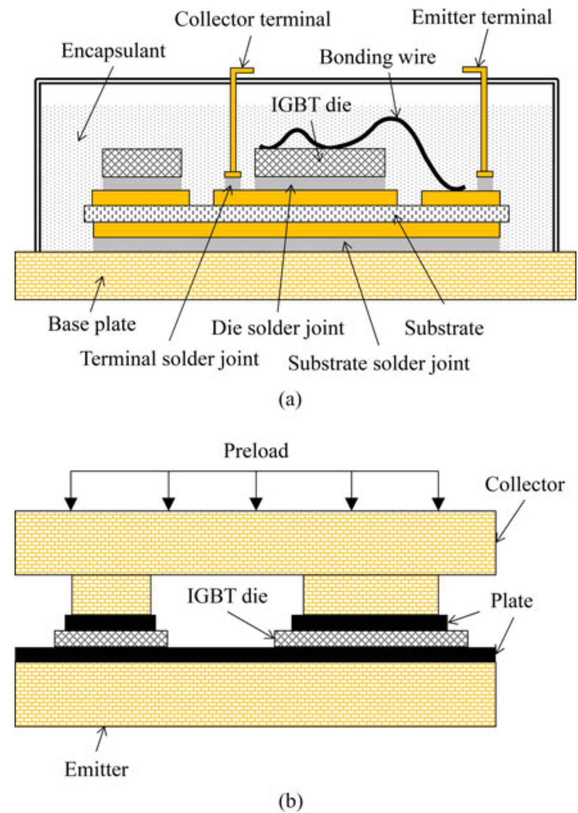


Fig. 1. Cross-sectional view of IGBT modules: (a) wire-bond modules and (b) press-pack modules.

### B. IGBT Modules: Package Level

Two packaging techniques have been used traditionally: wire-bond modules and press-pack modules [25]. Cross-sectional views of the two modules are illustrated in Fig. 1. As the most widely used technology for IGBT packaging, wire-bond modules adopt well-established and low-cost aluminum wire bonding technologies to provide electrical connections between the pads on the top of the die and the output terminals [26]. Press-pack modules for IGBTs were developed to take advantage of the packaging technology used for thyristors [27].

The advantages and disadvantages of wire-bond modules and press-pack modules are compared in Table I. Several studies [28]–[30] claimed that the implementation of IGBT dies in press-pack modules should guarantee higher reliability. In particular, Scheuermann [31] demonstrated that, under both active and passive thermal cycling, IGBT modules that designed with pressure contacts without solder interconnects outperformed those with conventional wire bond technologies. The packaging techniques for IGBTs have been evolving continuously for further improvements [32]–[37]. It should be noted that the adoption of a new technology to mitigate one failure mechanism often leads to the exposure of another [37], [38].

TABLE I
COMPARISON BETWEEN WIRE-BOND AND PRESS-PACK MODULES [28], [30], [90], [91]

| Feature | Wire-bond module | Press-pack module |
|---|---|---|
| Power and thermal cycling reliability | Mismatch in CTE can lead to fatigue failure | The possibility of fatigue failure is reduced since wire bond and solder interconnect are substituted with bondless pressure contact [31]. |
| Single die failure susceptibility | The state (open- or short-circuit) after a single die failure is not defined. It can lead to catastrophic failure of the whole module. | With a redundant design, the module can continuously operate with a single die failure. A failed die can be replaced during planned system services. |
| Explosion safety | An explosion was observed when short-circuit conditions were met [92], [93]. | The plasma formed by a short circuit can be confined inside the module through proper designing. |
| Cooling system | Simple; for example, a heat sink with a cooling fan is used. | Complicated; for example, deionized water is used. |
| Heat dissipation | Large temperature differences between individual dies can occur due to inherent variability in thermal resistance of their solder interconnects and substrates. | Uneven heat dissipation is reduced by sharing common heat sink blocks; for example, the temperature difference between the hottest and the coldest dies were 6 °C during the heating phase of a power cycle [29]. |
| Current distribution | Current flow in individual dies can be uneven due to their temperature differences. | Current flow in individual dies is “quite homogenous” between individual dies [29]. |
| Die mounting | Conventional (inexpensive) | Unique (expensive) |
| Electrical insulation | A ceramic layer itself in the DBC substrate provides the internal insulation. | A die carrier subassembly requires housing for the insulation. |
| Transient voltage at high switching frequency | Transient voltage of individual dies varies unless their electrical circuits are perfectly identical. | Differences in transient voltage of individual dies are reduced since a common inductive path is shared. |

## III. CM

The reliability of IGBT modules has been improved substantially for the past decade and it can be further assured by advanced designs and optimized use of materials. Yet, for safety- or mission-critical applications such as transportation, military, aerospace, and offshore wind power, reliability assessment of IGBT modules during product development may not be sufficient to guarantee the reliability in the field since unpredicted events always happen. According to the industry-wide survey [9], 25% of the responses revealed that the failure/cost ratio (failure cost divided by original system cost) of power conversion systems is very high (i.e., the failure/cost ratio is over 80%). Such failures can result in catastrophic and unrecoverable consequences. The survey showed a strong demand for better ways to handle the reliability of IGBT modules, in particular, for the responders who experienced a high failure/cost ratio.

The CM approach, originally developed in other systems such as rotating machines and electrical equipment, was adopted and implemented to further enhance the reliability of power converters in the field, and thus to be able to prevent failures. The CM approach for IGBT modules aims to detect changes in parameters indicative of die and package degradation during operation.

TABLE II
DEFINITIONS OF PARAMETERS INDICATIVE OF DIE AND PACKAGE DEGRADATION

| Symbol | Definition |
|---|---|
| $V_{\mathrm{CE,on}}$ | Collector–emitter voltage when the IGBT is on-state |
| $V_{\mathrm{GE}}$ | Gate–emitter voltage |
| $V_{\mathrm{GE,th}}$ | Gate–emitter threshold voltage |
| $t_{\mathrm{off}}$ | Duration of the transition from on-state to off-state |
| $t_{\mathrm{on}}$ | Duration of the transition from off-state to on-state |
| $R_{\mathrm{th}}$ | Thermal resistance from junction to case |
| $T_{\mathrm{j}}$ | Junction temperature |

CM techniques are being actively studied in the power electronics technical community. In the following sections, the details of CM techniques for IGBT are described in conjunction with corresponding failure modes and mechanisms.

### A. CM Parameters and Target Failure Mechanisms

The definitions of parameters frequently used in IGBT CM are listed in Table II. The relation between performance parameters such as $V_{\mathrm{CE,on}}$, $V_{\mathrm{GE}}$, and $V_{\mathrm{GE,th}}$ and health conditions of IGBT dies have been studied primarily for the development of CM techniques since a shift in those parameters changes the operation of IGBTs in unintended manners, which can directly degrade the performance of the system. Parameters related to switching IGBTs, such as $t_{\mathrm{on}}$ and $t_{\mathrm{off}}$, were also studied to avoid a catastrophic failure of IGBTs. It is well known that the junction temperature of IGBTs increases as the condition of IGBTs degraded. Estimation of junction temperature $T_j$ or thermal resistance $R_{\mathrm{th}}$ received some attention during the development of CM techniques.

In Table III, the CM parameters are summarized in conjunction with failure modes and mechanisms. Failure modes and mechanisms are dictated by the technology used in IGBT modules [39]. Numerous papers addressed the failure mechanisms of wire-bond modules. Latch-up, dielectric breakdown, bond wire degradation, and solder joint fatigue are the failure mechanisms targeted by the current CM techniques. It is worth noting that a single failure mechanism can induce changes in multiple CM parameters. Not a single CM parameter can be necessary and sufficient to monitor the individual failure mechanisms in IGBTs.

### B. On-State Collector Emitter Voltage-Based Techniques

An IGBT structure has four alternating layers of N-type and P-type regions, which constitute a parasitic thyristor of a PNP transistor and a NPN transistor. The failure occurs when the parasitic thyristor is activated. This failure is irreversible and it is called “latch-up” [40]. Patil *et al.* [41] conducted thermal overstress tests of IGBT components to induce latch-up failures. The junction temperature was raised beyond the maximum rating of 150 °C by reducing the heat transfer capability of the IGBT components (i.e., removing the heat sink). The IGBT components were subjected to power cycling until the latch-up occurred. The voltage bias across IGBT components was removed

TABLE III
FAILURE SITES, MECHANISMS, AND CM PARAMETERS

| | Failure sites | Failure modes | Failure mechanisms | CM Parameters | References |
|---|---|---|---|---|---|
| Die level | Die | Short circuit, burnout, loss of gate control | Latch-up and secondary breakdown | $V_{\mathrm{CE,on}}$ $t_{\mathrm{off}}$ $V_{\mathrm{GE,th}}$ | Patil *et al.* [41] Brown *et al.* [53] |
| | | Short circuit, loss of gate control | Time dependent dielectric breakdown | $V_{\mathrm{GE}}$ $V_{\mathrm{GE,th}}$ | Rodriguez *et al.* [94] Patil *et al.* [41] |
| Package level | Bonding wire: bond | Bond wire liftoff | Fatigue and/or reconstruction | $t_{\mathrm{on}}$ $t_{\mathrm{off}}$ $V_{\mathrm{CE,on}}$ $V_{\mathrm{GE}}$ | Tounsi *et al* [48] Xiong *et al.* [44] Zhou *et al.* [49] Zhou *et al.* [50] Smet *et al.* [42] |
| | Bonding wire: heel | Bond wire heel cracking | Fatigue | | |
| | Bonding wire: body | Open wire | Stress corrosion | | |
| | | Wire burnout | Joule heating | | |
| | Solder joint | Solder joint cracks | Fatigue or grain growth | $R_{\mathrm{th}}$, $V_{\mathrm{CE,on}}$ $t_{\mathrm{off}}$ Low-order harmonics | Patil *et al.* [41] Tounsi *et al.* [48] Xiong *et al.* [44] Xiang *et al.* [65], [70] |

immediately after the latch-up was observed, which prevented a complete failure of the IGBT component. The component was cooled down to ambient and the value of $V_{\mathrm{CE,on}}$ was measured. The results indicated that degradation by thermal overstress decreased the values of $V_{\mathrm{CE,on}}$ regardless of ambient temperatures. The subsequent failure analysis showed that the $V_{\mathrm{CE,on}}$ drop of 8–25% was attributed to die-attach degradation.

Bond wires have been recognized as a major failure site in wire-bond power modules [12], [25]. Due to a large coefficient of thermal expansion (CTE) mismatch, temperature swings during cycling induce: 1) stress at the interface between the silicon die and the aluminum wire; and 2) flexure of the heel of the aluminum wire. Smet *et al.* [42] conducted power cycling tests of wire-bond IGBT modules. Three tests with various minimum and maximum case temperature profiles were performed: 1) 60 and 120 °C; 2) 90 and 150 °C; and 3) 60 and 140 °C. An increase in $V_{\mathrm{CE,on}}$ was observed from all three cases degraded by the power cycling. This was attributed to the aging of wire bonds and bond pad metallization. The CM technique provided warnings as early as approximately 86% of the total life when the increase of $V_{\mathrm{CE,on}}$ by 3% was assumed to be the fault.

Although $V_{\mathrm{CE,on}}$ can be considered as a failure precursor for the wire bonding failure, the application of $V_{\mathrm{CE,on}}$ to the real-time field monitoring is challenging as discussed in [42]. An increase in $V_{\mathrm{CE,on}}$ resulting from the degradation can be overwhelmed by signal noise or disturbance during switching.

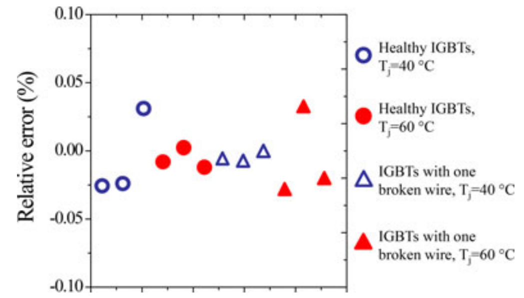


Fig. 2. On-state collector–emitter voltage measurements within an uncertainty of 0.1% [43].

Uncertainty larger than 1% can lead to a significant error in characterizing the health condition of a partially degraded IGBT module, if the failure criterion is assumed to be as small as a 5% increase.

To cope with these problems in electric vehicle applications, Ji *et al.* [43] implemented an analog multiplexer circuit and an advanced CM algorithm. The results of *in situ* measurements of $V_{\mathrm{CE,on}}$ are shown in Fig. 2 [43], where the measurements accuracy of less than 0.1% is evident. Since monitoring of wire bond conditions does not require much time (approximately 0.2 s) as claimed in [43], the method may be applicable when the electrical vehicle stops in red traffic conditions or routine servicing. Practical issues such as the cost and physical dimension of monitoring devices would also have to be considered in actual field applications.

Another issue associated with $V_{\mathrm{CE,on}}$-based CM techniques is that $V_{\mathrm{CE,on}}$ is affected by both junction temperature and health conditions of IGBT modules. To separate the junction temperature effect from the package degradation effect, Xiong *et al.* [44] developed a warning system for electric and hybrid vehicle applications that consisted of the hardware architecture and adaptive-algorithm-based software architecture. The "adaptive" nature of the algorithm enabled an individual vehicle to generate its own lookup table about the junction temperature and the corresponding $V_{\mathrm{CE,on}}$. According to their CM strategy, the CM subroutine in the vehicle control system was activated to compare a measured $V_{\mathrm{CE,on}}$ value to a reference value in lookup tables immediately after the key-on or key-off of each vehicle-use period, which did not change the normal operation of the vehicle and thus hardly increased the hardware cost of the existing vehicle-drive system.

It is worth noting that the trends of $V_{\mathrm{CE,on}}$ presented in the literature are not consistent; the value of $V_{\mathrm{CE,on}}$ decreased in [41] and [44], whereas it increased in [42] and [43]. The reasons [41]–[43] for the opposite trend during the power cycling tests are summarized in Fig. 3. This implies that CM techniques solely relying on $V_{\mathrm{CE,on}}$ may not be dependable when the two failure mechanisms compete with each other and thus the individual effects are nullified. The value of $V_{\mathrm{CE,on}}$ is a sum of voltage potentials of individual circuit components between the collector and emitter terminals of wire-bond modules. Contributions of individual circuit components to changes in $V_{\mathrm{CE,on}}$ and corresponding failure mechanisms should be evaluated if the value of $V_{\mathrm{CE,on}}$ is to be used as a CM parameter.

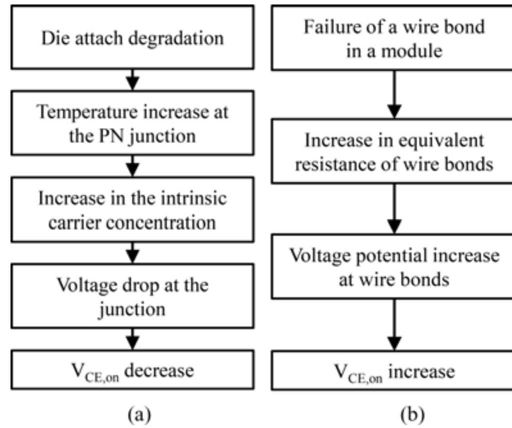


Fig. 3. Two opposite trends in $V_{\mathrm{CE,on}}$ during power cycling tests: the hypotheses that explain (a) decrease and (b) increase.

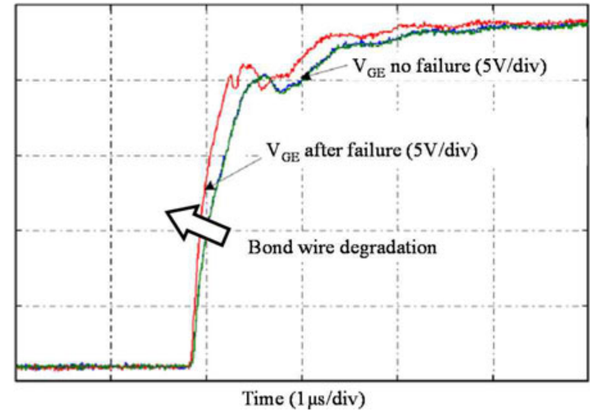


Fig. 4. Gate–emitter voltage waveforms during turn-on [49].

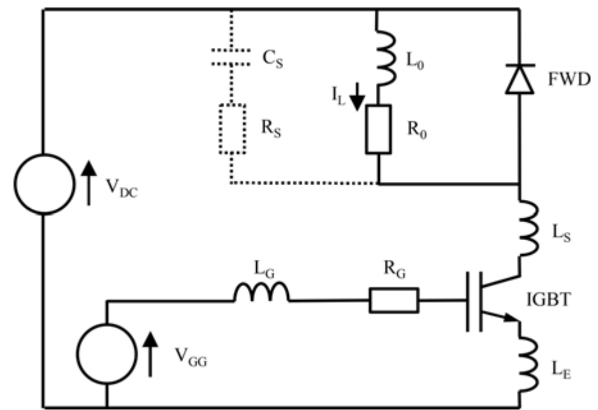


Fig. 5. Equivalent *RLC* circuit model for IGBT inductive turn-on [52].

### *C. Gate Emitter Threshold Voltage-Based Techniques*

An increase of $V_{\mathrm{GE,th}}$ was also observed during thermal overstress tests of IGBT components [41]. The results showed that the value of $V_{\mathrm{GE,th}}$ increased from zero to 11% over a total of eight samples. The capacitance across the gate and emitter terminals was investigated with respect to the gate voltage; the results supported the hypothesis that the presence of trapped electrons in the gate oxide was the cause of the increase of $V_{\mathrm{GE,th}}$ after thermal aging. Bouarroudj *et al.* [45] also reported an increase of $V_{\mathrm{GE,th}}$ by approximately 300 mV when IGBT modules were subjected to the power cycling condition of automotive hybrid traction applications (ambient temperature = 90 °C; and temperature swing = 60 °C). The increase of $V_{\mathrm{GE,th}}$ was attributed to gate oxide degradation. Accumulating a sufficient number of defects and traps in the bulk silicon dioxide as well as at the interfaces, gate oxide breakdown can occur, which causes a catastrophic failure [46]. Gate oxide breakdown has been observed during accelerated power cycling testing of IGBT modules [47].

The studies in [41] and [45] showed that a change in $V_{\mathrm{GE,th}}$ was an indicator for gate oxide degradation of IGBTs subjected to power cycling, albeit under laboratory conditions. Currently, the use of gate emitter voltage-based techniques for field applications is limited. Measurements of $V_{\mathrm{GE,th}}$ interrupt IGBTs' operation and require to inject external signals to the gate. For online monitoring of $V_{\mathrm{GE,th}}$ of IGBT dies in a module, the structure of IGBT modules may have to be modified.

### *D. Switching Time-Based Techniques*

Switching time-based techniques utilize the change of waveforms including $V_{\mathrm{CE}}$, $V_{\mathrm{GE}}$, $I_{\mathrm{CE}}$, and $I_{\mathrm{GE}}$ during turn-on or turn-off [48]. Zhou *et al.* [49], [50] monitored $V_{\mathrm{GE}}$ and $I_{\mathrm{GE}}$ waveforms during turn-on to detect bond wire failure. The representative result is shown in Fig. 4 [49], where the difference between two waveforms was visually observable; the increasing rate of $V_{\mathrm{GE}}$ of a failed component was faster than that of a healthy one.

Later, a switching time-based technique was developed to avoid catastrophic failure caused by the open- and short-gate in IGBT modules [51], where a fault-detection circuit based on $V_{\mathrm{GE}}$ waveform was implemented in the gate drive of induction motor drive systems. It was claimed that the CM technique could prevent the catastrophic failure of an induction motor drive system by detecting imminent failure within a very short time (less than 3 $\mu$s). There is room for further improvement since the immediate shutdown of motor drive systems may not be always desirable.

An in-depth analysis of voltage and current waveforms during switching of IGBTs was conducted through equivalent *RLC* circuit modeling and subsequent validation. Fig. 5 shows an equivalent *RLC* circuit model used in [52]. The bond wires that connected the silicon die to terminal leads were modeled by a resistor and inductor pair. The use of equivalent *RLC* circuit models helped calculate the change of $t_{\mathrm{off}}$ and $t_{\mathrm{on}}$ in current and voltage waveforms.

Brown *et al.* [53] defined $t_{\mathrm{off}}$ as the amount of time for $V_{\mathrm{CE}}$ to increase from 10% to 90% of its final value during turn-off. The study demonstrated the ability to distinguish the difference between aged and healthy IGBT components using online measurements of $t_{\mathrm{off}}$ within an operating temperature range of 305–315 K. In Fig. 6 [53], $t_{\mathrm{off}}$ of a representative healthy IGBT

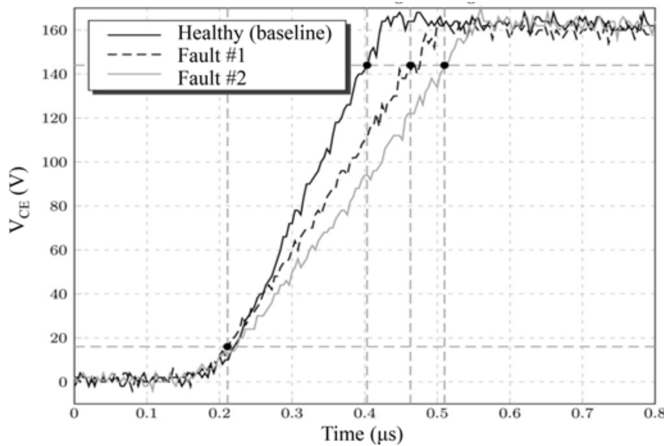


Fig. 6. Collector–emitter voltage waveforms during turn-off [53].

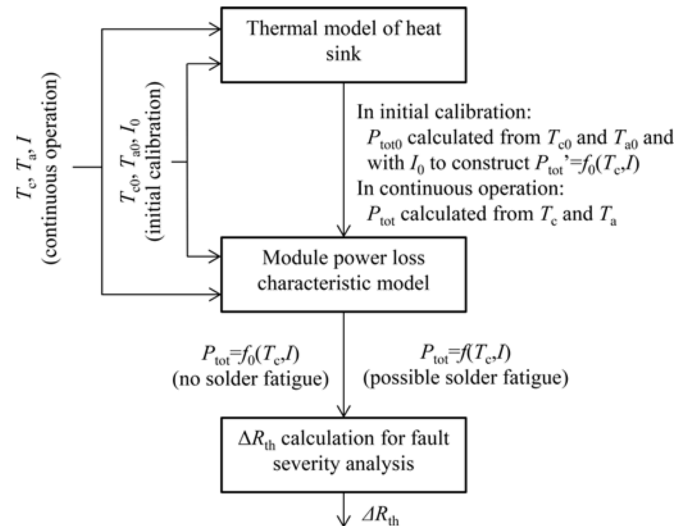


Fig. 7. CM technique based on thermal resistance estimation [65].

component is compared with those of two faulty IGBT components. They claimed that the $t_{\rm off}$ value was an early indicator to latch-up failure caused by damage in the die-attach layer.

As mentioned in [53], more work can be done to improve the technique. A diagnostic circuit has to be developed to detect latch-up at the early stage of degradation by continuously monitoring $t_{\rm off}$ in real time. The effect of an operating temperature on the change in $t_{\rm off}$ should be examined since an operating temperature in the field may not be limited to the range of 305–315 K. A further study is required to quantitatively compare accuracy, resolution, processing time, cost, etc., among the switching time-based techniques.

### *E. Temperature-Based Techniques*

As described in Fig. 1(a), solder layers exist at the interfaces: 1) between the silicon die and the substrate; 2) between the substrate and the base plate; and 3) between the substrate and the terminal leads (or busbar). The repetitive application of thermomechanical loading causes cracking or voiding in the solder layers. These cracks and voids reduce the effective area available for heat dissipation from the silicon die to the heat sink, which increases the thermal resistance in the module, and thus eventually raises the junction temperature. With the increased junction temperature, the die becomes more susceptible to failure mechanisms such as secondary breakdown and catastrophic burnout [54], [55]. Delamination of the metallization layers on a ceramic substrate and brittle fracture of a substrate itself are dominant failure modes of the substrate of wire-bond IGBT modules [56].

Direct assessment of the severity of solder layer damage, i.e., measurements of crack or void sizes, internal thermal resistance, and junction temperature, is not most practical. The estimation of those parameters by monitoring other readily-measurable parameters is more efficient in terms of cost and time. However, challenges still remain as to how quantitatively the readily measurable parameters can be correlated with the actual solder damage in IGBT modules.

The temperature difference between the top and the bottom of a solder layer defines the thermal resistance of the layer for a given heat transfer rate. Therefore, the thermal resistance can be calculated if the temperatures and the amount of heat generation are known. The heat generation considering the power loss was estimated by building and improving the accuracy of electrothermal models [57]–[61].

Several research [62]–[64] focused more on accurate estimation of the junction temperature, which was considered to be most critical to the assessment of solder joint damage. A simple way for measuring the junction temperature is to place a temperature sensor near the junction [62]. This enables online measurements of the junction temperature without interrupting IGBT operation. However, this technique is invasive and the accuracy of the measurements is affected by the sensor location. Another method is to deduce the junction temperature from measurements of a temperature-sensitive parameter such as $V_{\rm CE,on}$, which consists of two steps: one is offline characterization of IGBTs under tests and the other is online estimation of the junction temperature using the characterized data and $V_{\rm CE,on}$ measurements [42], [62]. Although a measurement circuit can be embedded in the gate driver without any invasive modification of IGBTs, real-time measurements of $V_{\rm CE,on}$ is still challenging as the switching frequency of IGBTs gets higher and the magnitude of $V_{\rm CE}$ changes rapidly before and after switching.

Recently, solder layer damages were monitored by measuring the case and the ambient temperatures and subsequently calculating the additional power loss from the measured temperature changes [65]. The process to estimate the damage used in the study is shown in Fig. 7 [65]. The power loss was first estimated from a thermal model that utilized temperature measurements as inputs. A lookup table that provided the information of power loss in healthy IGBT modules was subsequently incorporated, which enabled the estimation of solder layer damage under various operating conditions. In the analysis, the thermal transient within the module was assumed to be much faster than the variation of the operating point. This assumption may limit the use of the method in wind power and traction applications, where the environmental and operating conditions such as wind speed

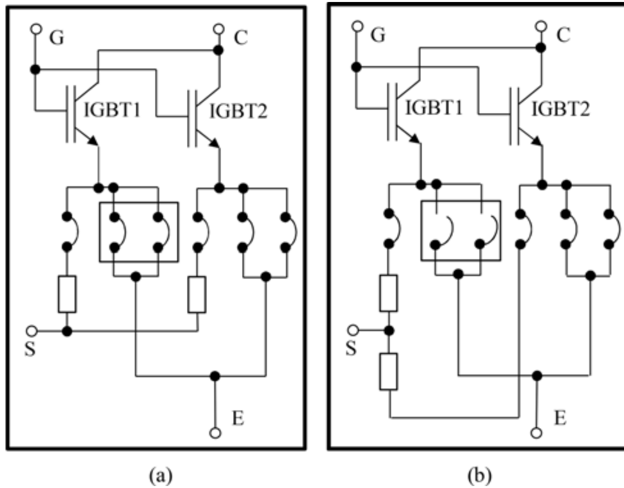


Fig. 8. Equivalent circuit of modified IGBT module: (a) without and (b) with emitter bond wire liftoff [66].

and power control can change faster than the duration required for IGBT dies to reach their steady-state temperature.

### *F. Other Techniques*

In the previous sections, we reviewed CM techniques that addressed how to monitor and assess changes in the performance parameters related to the degradation of IGBT components and modules. In real-life power converter applications, extraction of small deviations from the nominal values of the performance parameters is challenging. Furthermore, the mere act of measuring those parameters may change the operational characteristics of the IGBT modules. Several CM techniques, which do not interfere with the operation of IGBT modules, have also been investigated: they include embedded sensor-based, time-domain reflectometry (TDR)-based, and inverter output-based CM techniques [66]–[70].

An embedded sensor-based CM technique was developed to detect bond wire liftoff [66], [67]. As shown in Fig. 8 [66], redundant bond wires are attached to the emitter of the die. Bond wire failure was detected when the resistance between the emitter terminal and the sensor terminal deviated from a nominal value. Although it provided accurate detection of bond wire failure regardless of the operation, the technique required a modification of the original design of IGBT modules and an implementation of the monitoring circuit in a gate driver.

A TDR-based approach described in [68] created multiple impedance matrices that identified the defect locations in IGBT modules and the corresponding severity of the defects. Those matrices could be used as a reference to determine the degradation of IGBT power module of interest. This ability to identify the defect locations is a unique advantage of the TDR-based CM technique, which can be achieved by correlating reflected TDR signals with response delay. The TDR-based CM technique should be implemented carefully due to practical issues such as impedance control in electrical circuits, resistance variations at probing interfaces, and electromagnetic interferences.

An inverter output-based CM technique detects changes in the voltage and current outputs of power inverters [69], [70]. Ideally, power inverters are supposed to generate a series of inverter phase pulses with perfectly modulating width and perfectly constant amplitude, which produce an ideal harmonic output. In reality, however, the width and amplitude of pulses are distorted as IGBT modules in a power inverter degrade. Ginart *et al*. [69] observed high-order oscillatory responses in the voltage amplitudes and currents during switching. This response was related to the changes of parasitic capacitances present in IGBTs after thermoelectrical aging. Another study by Xiang *et al*. [70] reported changes of low-order harmonics in the output of a voltage-source inverter. This change was attributed to the reduction of the effective area of solder joints, induced by cracks. These harmonics were suppressed by an external control loop, where the control action was used as a CM parameter.

## IV. Beyond CM: Prognostics

"Prognostics" is an engineering discipline to predict the health condition at some point in the future and to estimate the RUL under actual usage conditions. If prognostic capabilities become available, the ability to determine RUL permits more flexibility in decision making, while minimizing the risk of failure [71]–[73]. For example, it would be more cost-effective if the continuous operation of offshore wind turbines is not interrupted until the RUL approaches to zero. Prognostics of IGBTs received attention primarily from mission-critical systems such as avionics, high-speed rail, and offshore wind turbines. In such a system, no failure is acceptable until the next maintenance period. In this section, two prognostic approaches for IGBT modules are presented.

### *A. Model-Based Prognostic Approach*

The model-based prognostic approach relies on PoF models that describe the relationship between lifetime and design parameters, material properties, and loading conditions. Currently, lifetime modeling techniques are utilized to predict fatigue life of wire bonds and solder joints of IGBT modules under cyclic loading conditions. Fatigue life models can be categorized into four groups: stress-based, strain-based, energy-based, and damage-based models. The strain-based model, called the Coffin–Mason equation [74], has been widely used to find the number of cycles to failure of wire bonding under thermomechanical loading [75]–[77]. A damage-based model was also used to predict the cycles to failure of wire bonds in IGBT modules with a temperature swing smaller than 30 °C [78].

Lifetime modeling itself aims primarily to estimate the reliability during product development [79]–[81]. Fatigue models are designed to predict the cycles-to-failure of IGBT modules subjected to repetitive cyclic loading. Failure models are not designed to predict RULs of IGBT modules under "actual" usage conditions. As shown in Fig. 9 [82], the power amplitudes of an offshore wind turbine are not constants but vary in a nonstationary manner. Therefore, additional work is required to predict RULs under "actual" usage conditions.

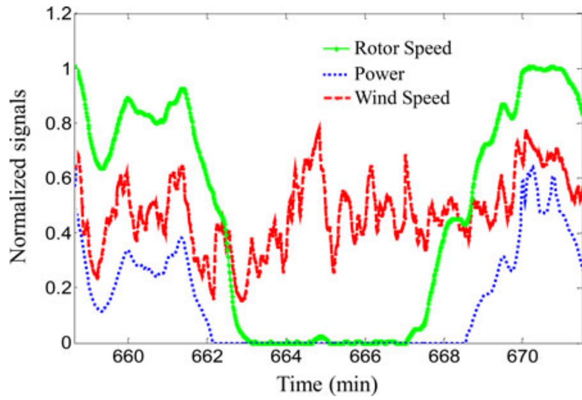


Fig. 9. Operational data recorded from a wind turbine [82].

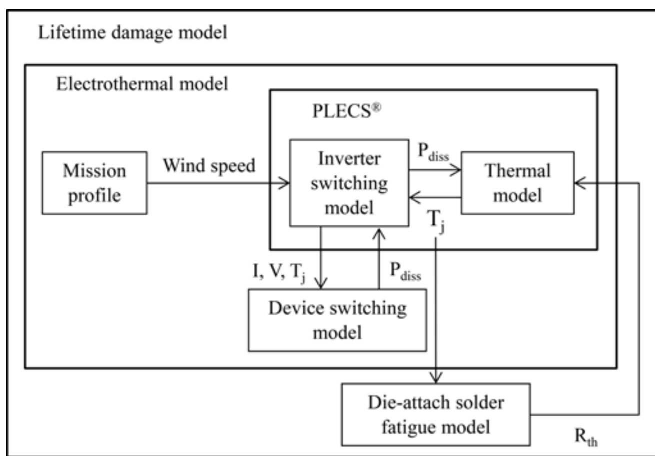


Fig. 10. Lifetime estimation model for voltage-source inverters used in wind turbine applications [86].

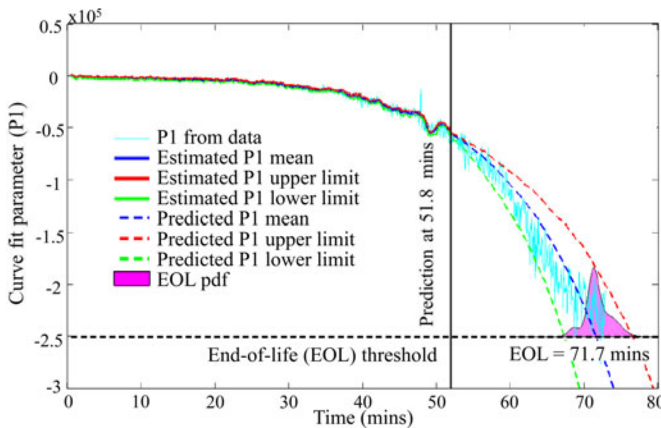


Fig. 11. Predicted probability distribution of time-to-failure of IGBTs [87].

There are three practical issues for a fatigue model-based prognostic approach to be applied to real field applications. The first issue is how to accurately convert the environmental and operational loading conditions into thermomechanical stresses. The second issue is how to define and extract the number, the amplitude, and the duration of thermal cycles experienced by a system, when the system is subjected to a mission (or application) profile. Although several methods were proposed to decompose a mission profile into elementary cycles [83], their accuracy is still unknown. The last issue is how to calculate damages accumulated in wire bonds or solder joints in IGBT modules.

TABLE IV
COMPARISON OF CM TECHNIQUES

| | Pros | Cons |
|---|---|---|
| $V_{\rm CE,on}$ | Useful to detect wire bond degradation or die attach degradation. | Difficult to detect small change from large changes in $V_{\rm CE}$ during fast switching.Can fail when multiple failure mechanisms exist. |
| $V_{\rm GE,th}$ | Useful to detect gate faults. | Interrupts normal operation.Requires external signals to the gate. |
| $t_{\rm on}$ or $t_{\rm off}$ | Can prevent catastrophic failure in wire bonds and the gate.Useful to detect latch-up failure. | Can detect only imminent failure.Can fail when multiple failure mechanisms exist. |
| $R_{\rm th}$ | Effective to detect solder joint degradation. | Requires electrothermal and thermomechanical modeling which can be expensive and time consuming. |
| Sensor-based | Detects bond wire failure without interfering IGBT operation. | Requires modification of original design of IGBT modules. |
| TDR-based | Theoretically possible to determine the location of defects. | Difficult to control impedance in circuits.Can be interfered by electromagnetic waves from external sources. |
| Inverter output-based | Does not need any modification of the system.Useful to detect solder joint degradation | Difficult to understand effect of faults in IGBT modules on outputs of the system. |

Several studies attempted to address these issues encountered in the model-based prognostic approach. Yin *et al.* [84] constructed a linear equation between the power dissipation and the junction temperature, which simplified the true relationship for real-time calculation. A response surface was also constructed to relate the junction temperature to the plastic strain in the SnAg alloy layer of IGBT modules. For a given profile of power dissipated from the IGBT dies, the junction temperature profile can be calculated in real time with the constructed linear equation and the response surface. The RULs are estimated by incorporating the rainflow counting method [85] and the linear damage accumulation law (i.e., Miner's rule). The main contribution of the study was to define a potential way to predict RULs of IGBT modules in the actual application environment; yet, it was difficult to verify the prediction accuracy. Recently, Huang and Mawby [86] presented a more practical prognostic method to calculate the lifetime of voltage source inverters for wind turbine applications in real time, assuming solder joint fatigue as a dominant failure mechanism of the selected IGBT modules. The flowchart used to estimate lifetime is shown in Fig. 10 [86]. Lookup tables constructed from offline electrothermal model simulations were used to speed up the online computation of the junction temperature. Then, the lifetime was calculated using the Coffin–Mason equation, the rainflow counting method, and a modified damage accumulation model. It is worth noting that the prediction accuracy has not been proven yet, which delays applications of prognostic approaches to real systems in the field.

### B. Data-Driven Prognostic Approach

The model-based prognostic approach uses knowledge of material properties, product geometry, life cycle loading, and failure models to estimate the life of a product. This approach is useful when failure models that emulate the actual failure mechanism are available. On the other hand, the data-driven prognostic approach does not require specific knowledge of a product. Instead, information about health conditions is extracted from historical data on the performance of a product without relying on failure models, which can be useful when failure models are not available or too complex to formulate. Then, it predicts the lifetime using machine learning techniques, and statistics and probability theory.

A particle-filtering-based method provides the probability distribution of RULs, which recursively estimates and updates the probability distribution of life model parameters as additional measurements become available. An example of RUL predictions for IGBTs in power cycling testing is described in Fig. 11 [87]. Patil *et al.* [88] proposed a prognostic approach for non-punch-through field-stop IGBTs based on Mahalanobis distance and particle filtering methods. In their study, once an anomalous behavior was detected by the Mahalanobis distance method, an algorithm based on particle-filtering was triggered to predict the RUL of an IGBT.

## V. Discussion on CM and Prognostics

The current stage of CM techniques still warrants significant improvements to enhance the applicability to various real-field environments, and thus to be used in routine industry practice. Advantages and disadvantages of CM techniques discussed in Section III are compared in Table IV. It should be noted that not a single CM technique is perfect.

Table V summarizes potential failure sites, causes, stresses, modes, and mechanisms in IGBT modules. Based on authors' experience (thus subjective), mechanisms that are most widely discussed in the literature as well as most frequently reported from the field failures are fatigue, latch-up, electrostatic discharge, radiation-induced effect, and ceramic substrate fracture. Currently available CM techniques addressed only a part of potential failure mechanisms. Further research is encouraged to prevent other failure mechanisms by relevant CM and prognostic techniques. It should be noted that, within the domain of current technology, CM can only be applied to the wearout failure mechanisms.

In real field applications, IGBT modules are subjected to various operating and environmental conditions. Variations of switching frequency, duty cycle, load, and temperature would contribute to CM parameter changes even when IGBT modules remain in the same health condition. For example, junction temperature variations change carrier mobility and internal electrical resistance, which is ultimately manifested as variations in on-state collector–emitter voltage output [86]. The CM techniques reviewed in this paper were demonstrated under controlled experimental conditions and may not perform as intended in real-operating conditions. Future research, thus, should address this existing but critical challenge more extensively, namely identifying CM parameters only related to the deterioration of IGBT modules and/or developing advanced CM algorithms to separate the CM parameter changes caused only by IGBT degradation from the complex field signals.

During reliability testing of IGBT modules, it is generally observed that multiple failure mechanisms compete with each other, each affecting multiple CM parameters. As discussed in Section III-A, an on-state collector emitter voltage-based technique may fail to detect the degradation of dies or wire bonds as the competing mechanisms cancel the effects each other, which can result in catastrophic consequences. Literature on the development of CM or prognostic techniques for multiple failure mechanisms seems absent. It is suggested that the effect of multiple failure mechanisms on CM parameters should be studied more extensively. If the effects are clearly understood, it is reasonable to expect that CM parameters associated with the corresponding dominant failure mechanisms (i.e., failure precursors) can be determined to help further improve CM and prognostic techniques.

In safe- and mission-critical applications, a component is immediately replaced or overhauled before failure, once an anomalous behavior is detected from the component. As a result, failure data are seldom collected from the field, although run-to-failure data are used in the development of CM and prognostic techniques. To overcome the absence of available data, accelerated tests of IGBT modules are often conducted. However, this is time-consuming and expensive. In reality, there are abundant censored (or suspension) field data, which contain information on how long components survive before repair or replacement. Research on how to incorporate censored field data into the development of CM and prognostic techniques would be valuable.

Practicality considering measurement accuracy, computational costs, and data storage, etc., should be also evaluated during the course of development of CM and prognostic techniques. Tradeoffs have to be optimized for practical implementation. For example, thermomechanical finite-element method models of IGBT dies can provide accurate predictions of temperature distributions in IGBT modules. However, their computational costs are too high for real-time applications. This is ongoing research actively addressed in the CM community. The use of lookup tables or linear equations could reduce computational costs significantly [84], [86]. Bazzi *et al.* [89] presented a simple power loss estimation method that relies on data sheet information and measurement of three parameters of IGBTs and diodes without losing much accuracy (errors less than 8%).

Prognostic methods are inherently based on a certain set of assumptions and simplifications. The most critical assumption would be failure criteria. As shown in Table VI, most failure criteria found in the literature were typically set for reliability testing, and later verified by failure analyses. If a failure criterion does not reflect the actual failure accurately, the physical interpretation of RUL is prone to produce more uncertainties. It is recommended that future research should address this deficiency in failure criteria.

Simplifications for prognostics typically involve an empirical failure model, which often describes complex degradation processes using simple curve fitting. The empirical model is

TABLE V
FAILURE SITES, CAUSES, STRESSES, MODES, AND MECHANISMS IN IGBT MODULES

| Failure sites | | Causes | Stresses | Modes | Mechanisms |
|---|---|---|---|---|---|
| Die level | Die | • Current spike<br>• Overvoltage between collector and emitter with/without high operating temperature | Electrical overstress with/without thermal stress | Short circuit, burnout, loss of gate control | Latch-up and secondary breakdown [10], [37], [55], [95]–[97] |
| | | Overvoltage and overcurrent | Electrical stress | High leakage current | Hot carrier injection [98] |
| | | • Electrostatic discharge to gate oxide<br>• Excessive electric field between gate and emitter | Electrical overstress | Short circuit, loss of gate control | Gate oxide breakdown [46], [47] |
| | | High current flow lowering the breakdown voltage | Electrical stress | Burnout | Dynamic avalanche breakdown [99], [100] |
| | | Unintended ESD during manufacturing and handling | Electrical overstress | Burnout | Electrostatic discharge [10], [101] |
| | | Die exposure to neutrons | Electromagnetic stress | Burnout,gate rupture | Radiation-induced effect [102]– [108] |
| | | • Preexisting defects<br>• Residual stress during manufacturing<br>• Die bending at an elevated temperature | Mechanical or thermomechanical overstress | Die crack | Fracture [109], [110] |
| Package level | Bond pad | High temperature, high current flow | Thermal overstress, electrical stress | Open circuit | Metallization reconstruction [12] |
| | Bonding wire: bond | CTE mismatch between die and wire by temperature excursion | Thermomechanical stress | Bond wire liftoff | Fatigue [33], [111]–[114] |
| | Bonding wire: heel | Expansion and contraction of bond wire due to temperature change | Thermomechanical stress | Bond wire heel cracking | Fatigue [33], [76], [115], [116] |
| | Bonding wire: body | High temperature, high current flow | Thermoelectrical stress | Open wire | Electromigration [117] |
| | | Mechanical loading at high temperature under corrosive environment | Thermal, chemical and mechanical stresses | Open wire | Stress corrosion |
| | | Short circuit due to various causes, e.g., device latch-up | Thermal, mechanical, chemical, and/or electrical overstress | Wire burnout | Joule heating |
| | Solder joint | • CTE mismatch by temperature excursion<br>• Transformation in solder microstructure at high temperature | Thermomechanical stress | Solder joint cracks | Fatigue or grain growth [83], [118]–[120] |
| | Ceramic substrate | • Preexisting defects<br>• Residual stress during manufacturing at metal/insulator interface<br>• Plate bowing | Mechanical stress | Shell-like fracture pattern | Brittle fracture [42], [121] |
| | | Thermal shock | Thermomechanical stress | Delamination | Delamination of metallization [56], [122] |
| | | • Poor etching, particle contamination, and voids trapping during manufacturing and assembly<br>• Excessive voltage and humidity | Electrical overstress | Electrical short | Partial discharge [123]–[126] |

valid only for the given dataset, and thus it can produce significant uncertainties in RUL predictions for different testing and operating conditions. It is thus recommended for future research that more advanced failure models be developed and implemented to make CM and prognostic techniques more reliable, in turn, prediction of RULs more accurate.

## VI. CONCLUSION

Existing CM and prognostic techniques for IGBT modules were reviewed. It is important to recall that failure mechanisms are dictated by the technology used in IGBT modules. Within the current technology domain, failures by wearout mechanisms can be prevented by relevant CM and prognostic techniques. CM parameters related to the performance of IGBT modules such as on-state collector–emitter voltage, gate–emitter threshold voltage, switching time lead/delay, and junction-to-case thermal resistance are claimed to be readily measurable or can be indirectly estimated using external equipment. Most of the existing prognostic methods focus on the prediction of RULs for fatigue mechanisms under thermomechanical loading conditions. However, CM and prognostic capabilities that are directly applicable

TABLE VI
FAILURE CRITERIA OF IGBTS IN LITERATURE

| Parameter | Threshold | Reference |
|---|---|---|
| $R_{\mathrm{th}}$ | 20% increase of the initial value | Fratelli *et al*. [127] Coquery and Lallemand [47] Tounsi *et al*. [48] |
| $V_{\mathrm{CE,on}}$ | 5% increase of the initial value | Coquery and Lallemand [47] Tounsi *et al*. [48] |
| | 10% increase of the initial value | Ciappa and Fichtner [128] |
| | ±15% deviation from the nominal value | Xiong *et al*. [44] |
| | 20% increase of the initial value | Patil *et al*. [88] |
| $I_{\mathrm{GE,leakage}}$ | "Abrupt" increase (not quantified) | Coquery and Lallemand [47] Tounsi *et al*. [48] |

to IGBTs are still very limited. The existing methods may have to be modified or significantly improved to be able to provide reliable estimation of the health conditions and the RUL of IGBT modules in real field applications.

Based on the literature review, potential research areas were suggested: 1) identification of CM parameters only related to the deterioration of IGBT modules themselves; 2) study on the effect of multiple failure mechanisms on CM parameters; 3) incorporation of censored field data; 4) consideration for the practicality of developed methods; 5) development of relevant failure criteria; and 6) development of advanced failure models. Successful completion of the suggested research topics would make significant contributions toward the ultimate goal of CM and prognostics of IGBT modules, i.e., reliable operation of power electronics.

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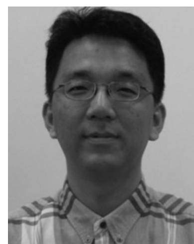

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