



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Catastrophic Failure and Fault-Tolerant Design of IGBT Power Electronic Converters - An Overview

Wu, Rui; Blaabjerg, Frede; Wang, Huai; Liserre, Marco; Iannuzzo, Francesco

Published in:

Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013

DOI (link to publication from Publisher):

[10.1109/IECON.2013.6699187](https://doi.org/10.1109/IECON.2013.6699187)

Publication date:

2013

Document Version

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Wu, R., Blaabjerg, F., Wang, H., Liserre, M., & Iannuzzo, F. (2013). Catastrophic Failure and Fault-Tolerant Design of IGBT Power Electronic Converters - An Overview. In *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013* (pp. 507-513). IEEE Press.
<https://doi.org/10.1109/IECON.2013.6699187>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Catastrophic Failure and Fault-Tolerant Design of IGBT Power Electronic Converters - An Overview

Rui Wu, Frede Blaabjerg, Huai Wang, Marco Liserre
Center of Reliable Power Electronics (CORPE)
Department of Energy Technology, Aalborg University
Pontoppidanstraede 101, 9220 Aalborg, Denmark
rwu@et.aau.dk, fbl@et.aau.dk, hwa@et.aau.dk,
mli@et.aau.dk

Francesco Iannuzzo
Department of Electric and Information Engineering
University of Cassino and southern Lazio
Via G. Di Biasio, 43 03043 Cassino, Italy
iannuzzo@unicas.it

Abstract—Reliability is one of the key issues for the application of Insulated Gate Bipolar Transistors (IGBTs) in power electronic converters. Many efforts have been devoted to the reduction of IGBT wear out failure induced by accumulated degradation and catastrophic failure triggered by single-event overstress. The wear out failure under field operation could be mitigated by scheduled maintenances based on lifetime prediction and condition monitoring. However, the catastrophic failure is difficult to be predicted and thus may lead to serious consequence of power electronic converters. To obtain a better understanding of catastrophic failure of IGBTs, the state-of-the-art research on their failure behaviors and failure mechanisms is presented in this paper. Moreover, various fault-tolerant design methods, to prevent converter level malfunctions in the event of IGBT failure, are also reviewed.

Keywords—*Insulated Gate Bipolar Transistor; catastrophic failure; fault tolerant circuit; power electronics*

I. INTRODUCTION

Nowadays, power electronics play an important role in motor drives, utility interfaces with renewable energy sources, power transmission (e.g. high-voltage direct current systems, and flexible alternating current transmission systems), electric or hybrid electric vehicles and many other applications. Therefore, the reliability of power electronics becomes more and more vital, and should draw more attention [1]. According to a survey, semiconductor failure and soldering joints failure in power devices take up 34% of power electronic system failures [2]. Another survey shows that around 38% of the faults in variable-speed ac drives are due to failure of power devices [3]. A recent questionnaire on industrial power electronic systems also showed that all the responders regard power electronic reliability as an important issue, and 31% of the responders selected the “semiconductor power device” as the most fragile component [4]. It can be seen that studying the reliability of power devices is important.

Insulated Gate Bipolar Transistors (IGBTs) are hybrid bipolar-metal-oxide semiconductor, which have the advantages of low on-state resistance, voltage control of the gate and wide safe operating area. IGBTs are also one of the most critical components as well as the widely used power devices in power electronic systems in the range above 1 kV and 1 kW. According to the survey, the most used power devices for

industrial applications are IGBTs [4]. Therefore it is worth investigating IGBT's failure and exploring the solutions to improve the reliability of IGBT power electronic converters.

The failure of IGBTs can be generally classified as catastrophic failure and wear out failure. IGBT wear out failure is mainly induced by accumulated degradation with time, while catastrophic failure is triggered by single-event overstress, such as overvoltage, overcurrent, overheat and so on. Prognostics and Health Management (PHM) method can monitor the degradation of IGBTs and estimate wear out failure [5]. However, PHM is not applicable for catastrophic failure, which is more difficult to be predicted.

Several overview papers have covered the topics on IGBT failure and fault diagnosis, and protection methods [6-12].

In [6], C. Busca *et al* discuss the major wear out failure mechanisms of IGBTs in wind power application. It covers the bond wire lift-off, solder joint fatigue and bond wire heel cracking due to coefficients of thermal expansion (CTEs) mismatch, aluminum reconstruction, and cosmic ray induced failure for IGBT modules. The fretting damage, spring fatigue, spring stress relaxation and cosmic ray induced failure of press-pack IGBTs are summarized. The aforementioned failure mainly occurs due to long time operation or power/thermal cycling, which can be classified as wear out failure, while no catastrophic failure is investigated.

In [7], M. Ciappa gives a comprehensive overview on IGBT module wear out failure mechanisms, such as bond wire fatigue, aluminum reconstruction, substrate cracking, interconnections corrosion, and solder fatigue and voids, while IGBT catastrophic failure is not discussed in detail except for the mechanism of latch-up. In particular, the bond wire lift-off mechanism is also discussed and modeled in [8].

In [9], S. Yang *et al* review the condition monitoring for semiconductor devices in power electronic converters. Some general failure mechanisms of power devices are also described. Bond wire lift-off and solder fatigue are investigated in detail, while only latch-up, gate oxide breakdown are mentioned for IGBT catastrophic failure. Diagnosis and prognosis methods for power devices degradation are also investigated.

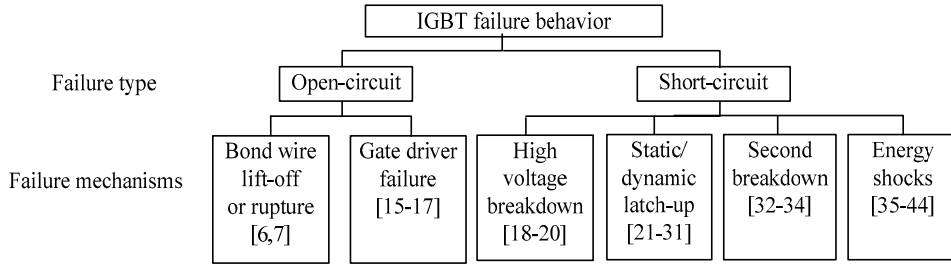


Fig. 1. Overview of IGBT catastrophic failure.

In [10], J. Flicker *et al* discuss IGBT failure in detail, including all wear out failure mechanisms mentioned above, as well as some catastrophic short-circuit failure mechanisms. However, the failure mechanisms such as second breakdown, high voltage breakdown and the open-circuit catastrophic failure have not been covered.

IGBT failure is also generally mentioned in references [11] and [12], which are more focused on IGBT fault diagnosis, detection and protection methods.

As discussed above, previous review papers on IGBT failure are mainly focused on wear out failure. A detailed and comprehensive review on IGBT catastrophic failure is still lacking, though. Moreover, it is also worth having an overview on the fault-tolerant designs to deal with or isolate IGBT catastrophic failure in power electronic converters.

Therefore, the aim of this paper is to provide an unbiased review of the major types of IGBT catastrophic failure due to overstresses and the corresponding fault-tolerant designs to deal with the failure at converter level. The paper is organized as follows: Section II classifies the IGBT catastrophic failure types. Section III summarizes the catastrophic failure of IGBTs in terms of failure mode and failure mechanism. Section IV discusses modern redundancy techniques for catastrophic failure tolerance. The detailed mechanisms of the fault tolerant circuits are also illustrated. The concluding remarks are summarized in Section V.

II. CLASSIFICATION OF IGBT CATASTROPHIC FAILURE

IGBT catastrophic failure behaviors can be classified as open-circuit failure and short-circuit failure. Normally, open-circuit failure is considered as not fatal to converters, since the converter can operate with lower quality of output. On the contrary, short-circuit failure is almost fatal to converters, as the uncontrolled short-circuit current may destroy the failed IGBT and/or other components in the circuit. IGBT catastrophic failure can be classified as shown in Fig. 1.

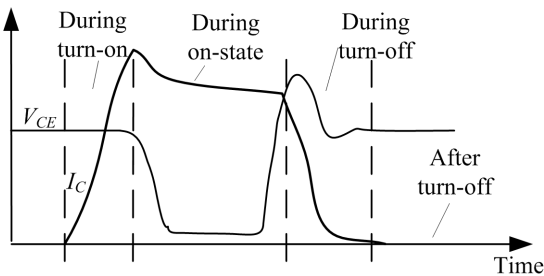


Fig.2. Time-sequence classification of IGBT short-circuit failure.

A. Open-circuit Failure

IGBT open-circuit failure can happen after external disconnection due to vibration, as well as bond wires lift-off or rupture due to high short-circuit current. It may lead to pulsating current, output current/voltage distortion, and result in secondary failure of other components after some time. Open-circuit can also be due to absence of gate drive signal. The common reasons could be the damage of components in drivers and the disconnection between driver board and IGBTs.

B. Short-circuit Failure

IGBT short-circuit failure modes can be classified with respect to time-sequence as shown in Fig. 2 [13]. IGBT short circuit during turn-on can be caused by high gate voltage and external failure. Failure during on-state may be caused by static latch-up or the rapid increase of intrinsic temperature caused by second breakdown, as well as by energy shocks. Failure during turn-off can be caused by dynamic latch-up and high voltage breakdown. Failure during off-state may be due to thermal runaway phenomenon. The detailed failure mechanisms will be illustrated in the next section.

III. IGBT CATASTROPHIC FAILURE MECHANISMS

Generally, catastrophic failure mechanisms are more related to semiconductor physics and overstress working conditions. As mentioned in Fig. 1, there are two failure mechanisms of open-circuit and four of short-circuit failure.

A. Open-circuit Failure Mechanisms

IGBT open-circuit failure is not fatal to the converter immediately, but may result in secondary failure in other devices and the converter. The mechanisms are as follows:

1) Bond wire lift-off or rupture.

Bond wire lift-off failure can happen after short-circuit failure. It is generally due to mechanical reasons. The main mechanisms are related to mismatch of coefficients of thermal expansion (CTEs) between Silicon and Aluminum, together with high temperature gradients. Crack initiates at the periphery of the bonding interface, and the bond wire finally lifts-off when crack propagates to the weaker central bond area [14]. Central emitter bond wires normally fail first, and then the survivor bond wires follow. Another failure mechanism is bond wire rupture, which is slower than lift-off and usually observed after long power cycling tests [7].

2) Gate driver failure.

There are various causes of gate driver failure, such as power stage devices (e.g. BJTs or MOSFETs) damaged; wires between drive board and IGBT disconnected [15]. The driver failure may result in IGBT intermittent misfiring, degraded output voltage, and overstress of other IGBTs and capacitors.

Abnormal work conditions in power terminals of IGBT can also lead to driver failure. Continued narrow overvoltage spikes between collector and emitter may open the gate-emitter resistance, while over-current of IGBT's collector may lead to gate-emitter resistance degradation [16]. Gate open-circuit failure can result in thermal runaway or high power dissipation [17]; however detailed research on the physical failure mechanism is still lacking. Moreover, modern IGBTs can work at 175°C junction temperature, which means the case temperature could reach 100°C or more, while most components in the driver cannot work normally at such high temperature. Thus this is a challenge for gate driver working at high temperature.

B. Short-circuit Failure Mechanisms

IGBT short-circuit failure can lead to potential destruction to the failed IGBT, remaining IGBTs, and other components, as it induces uncontrolled high current through the circuit. As shown in Fig.1, short-circuit failure can be classified as the following four different types.

1) High voltage breakdown.

High voltage spikes induced by high falling rate of collector current (I_C) and stray inductance can destroy IGBT during turn-off, especially under repetitive spikes [18,19]. Due to the high turn-off voltage spike, electric field can reach the critical field and break down one or a few IGBT cells first, and lead to high leakage current as well as high local temperature. Subsequently, the heat-flux radially diffuses from the overheated region to the neighboring cells. Collector-emitter voltage (V_{CE}) collapses after the voltage spike, and then I_C rises again. Also, the gate terminal may also fail, which results in gate voltage (V_{GE}) rising up.

High value of V_{CE} and V_{GE} can also lead to short-circuit during turn-on. An abrupt destruction and peak current happen after several microseconds during turn-on. The hole current caused by avalanche generation concentrates on a certain point (usually high-doped p+ region). The destruction point is always located at the edge of the active area close to device's peripheral region [20]. Therefore, it is critical to clamp V_{GE} and V_{CE} during switching transients.

2) Static/dynamic latch-up.

Latch-up is a condition where the collector current can no longer be controlled by the gate voltage. With respect to Fig. 3, latch-up happens when the parasitic NPN transistor is turned on, and works together with the main PNP transistor as thyristor, and then the gate loses control of I_C . IGBT latch-up can be divided into two types, static and dynamic latch-up [21].

Static latch-up happens at high collector currents, which turn on the parasitic NPN transistor by increasing the voltage drop across the parasitic resistance R_s .

Dynamic latch-up happens during switching transients, usually during turn-off, when the parasitic NPN transistor

biased by the displacement current through junction capacitance C_{cb} between the deep P+ region and the N-base region. There are two distinct conditions that may lead to dynamic latch-up [22-27]. One is when the gate voltage drops very fast and induces excessive displacement current through the gate oxide that flows through the parasitic resistance. The other one is when the off-state collector-emitter voltage is quite high and induces excessive charging currents within the IGBT during the switching transient, which will flow through the parasitic resistance. Both conditions may trigger the parasitic NPN transistor and eventually lead to latch-up. It should be noticed that the collector current leading to dynamic latch-up is lower than that of static latch-up.

When latch-up happens, IGBT will be almost inevitably damaged due to the loss of gate control, as confirmed by the 2D finite element simulations [28,30]. Therefore, several methods are proposed to predict latch-up, especially based on the collector-emitter on-voltage $V_{CE(on)}$ and turn off time [28,29].

It is worth mentioning, though, that latest-generation IGBTs with trench-gate structure and heavily doped P-base region under N-emitter, have been proved to have good latch-up immunity [31], and latch-up is not a common failure in the latest devices anymore.

3) Second breakdown.

Second breakdown is a kind of local thermal breakdown for transistors [32] due to high current stresses, which can also happen to IGBTs during on-state and turn-off.

The failure mechanism of second breakdown is as follows: with the increase of current, the collector-base junction space-charge density increases, and the breakdown voltage decreases, resulting in a further increase in the current density. This process continues until the area of the high current density region reduces down to the minimum area of a stable current filament. Then, the filament temperature increases rapidly due to self-heating and a rapid collapse in voltage across IGBT occurs. This has been comprehensively simulated and measured in [33]. How to improve IGBT ruggedness at high current density and prevent second breakdown is still an interesting research topic [34].

4) Energy shocks.

During short circuit at the on-state, failure may happen due to high power dissipation. The high power dissipation within a short time is defined as energy shock. The high short-circuit

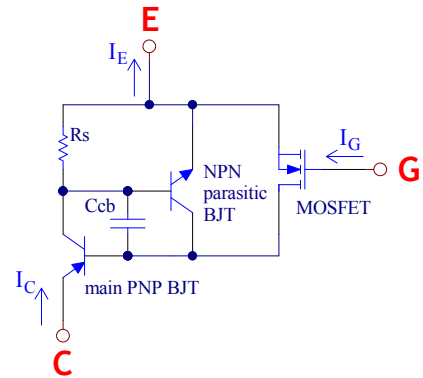


Fig. 3. The equivalent circuit of IGBT [21].

TABLE I. SUMMARY OF IGBT SHORT-CIRCUIT FAILURE MECHANISMS

Failure Mechanisms	Failure Behavior	Failure Location	Thermal Behavior
High voltage breakdown	During turn-off: V_{CE} collapses and I_C rises after voltage spike	At the edge of active area	Overheating on few peripheral cells at first, and then spreads to the whole chip
	During turn-on: peak I_C results in destruction		
Latch-up	Static latch-up during on-state: high I_C leading to loss of gate control	Active area	Overheating on a stable subset of cells of the device
	Dynamic latch-up during transients: high dv/dt leading to loss of gate control		
Second breakdown	Local thermal breakdown due to high currents	Emitter regions	Very high local temperature spots
Energy shocks	$E > E_C$: thermal runaway after successfully turned-off	Emitter regions	Very high local temperature spots
	$E < E_C$: degradation of die metallization	Al metallization layer, bond wires lift-off	Local overheating of Al metallization layer after 10^4 cycles

current will result in energy shock and high temperature [35,36]. However, IGBT will not immediately fail even the junction temperature exceed the rated temperature. Until reaching the intrinsic temperature (about 250°C for the doped silicon), further rise in junction temperature would lead to exponential increase in the carrier concentration and thermal runaway. With further increase of temperature, the silicon die may become fatally damaged and the contact metal may also migrate into the junctions.

Even the short-circuit current is successfully turned-off, short-circuit failure could still happen after several microseconds, which is called delayed failure in [31]. It is verified by experiments and numerical simulation that large leakage current leads to the thermal runaway [37]. A “critical energy (E_C)” is proposed to explain the mechanisms of catastrophic failure and wear out failure under repetitive short-circuit operations [38]. When short-circuit energy is below E_C , IGBT may survive for more than 10^4 times repetitive short-circuit operations before failed. However, when short-circuit energy is far beyond E_C , IGBT may fail after first short-circuit due to thermal runaway. A further experimental investigation show that IGBT can turn-off successfully after short-circuit but fails after several microseconds when the short-circuit energy

is lightly higher than E_C . It is still challenging to determine the exact value of E_C , even though many experiments and numerical simulations have been done in the prior-art research [38,39].

A recent research also demonstrates this failure mechanism in trench gate field-stop structure IGBT by comprehensive experiments [40]. Since trench-gate field-stop IGBT has a smaller heat capacity [31,37], a state-of-the-art process has been proposed which can increase E_C by 80% according to simulations [41]. The basic principle is to use a thicker front side metallization, made of copper instead of aluminum, and a newly developed diffusion soldering process to attach the direct bonded copper (DBC) substrates.

Furthermore, it is worth mentioning that IGBTs can fall into short-circuits due to external causes, like the dynamic avalanche of freewheeling diodes; therefore it is also crucial to design high performance freewheeling diodes [42-44].

A summary of IGBT short-circuit failure mechanisms is presented in Table I. As discussed before, short-circuit currents inevitably introduce high energy and temperature to IGBT chips, therefore it is important to design an efficient thermal management to improve the ability of withstanding short-circuits in order to have time to detect failure and protect IGBTs.

IV. FAULT-TOLERANT CIRCUITS

Broadly speaking, it is worth to note first as a general principle that whatever fault-tolerant circuit or topology adds complexity and cost to the converter, and may fail by itself. For this reason, the final reliability-level is a trade-off between enhancing fault tolerance and increasing weaknesses. With the above in mind, different fault-tolerant designs at circuit level have been proposed, which are classified as shown in Fig. 4.

A. Device Redundancy

Contrary to modules, press-pack IGBTs intrinsically short after a catastrophic failure, due to the absence of bond wires and direct connection between die and metal contacts [45]. This feature can be profitably used for series redundancy, where several devices work as a single-switch. Nowadays it is widely used in traction, high power drives and power transmission systems [46,47]. However, for the sake of completeness, it should be pointed out that failed press-pack IGBTs could be open-circuit after some time, due to the interaction of molten aluminum (Al), molybdenum (Mo) and Si leading to various intermetallics, following with poor conductivity as open-circuit [48].

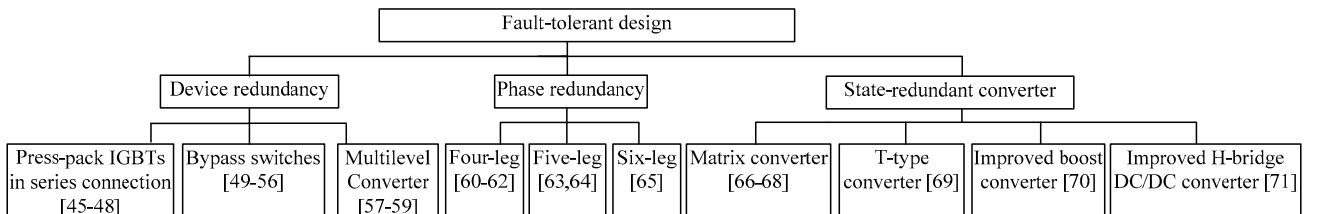


Fig. 4. Classification of typical fault-tolerant circuits.

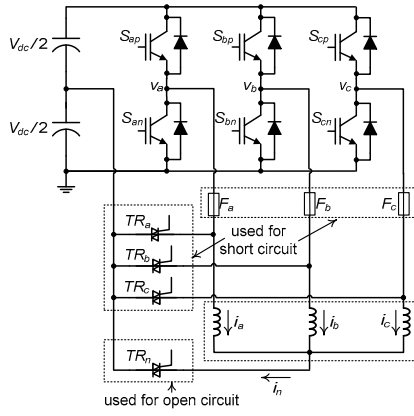


Fig. 5. Typical bypass switches redundant circuit [51].

Another way is using bypass switches, as shown in Fig. 5 [49]. The bypass switches are located between the neutral point and phase output. Failure occurred in switching devices (e.g. S_{ap}) can be cleared by blowing fuses (e.g. F_a) through turning on the bypassing switch (e.g. TR_a). The circuit operates as a four-switch three-phase inverter, with lower quality of the output. This topology can also handle open-phase failure in motor drive application, which needs to turn on TR_n and change the phase currents to maintain motor's torque constant. This method has been applied in neutral point clamped (NPC) converters [50]. Similar solutions are also presented in [51-56].

The other method with both series redundancy and bypass switches is cascaded H-bridge multilevel (CHBM) converter [57,58] or modular multilevel converter (MMC) [59]. When a fault occurs to a switch, the faulty H-bridge (or half H-bridge) cell is bypassed. The output voltage magnitude can be maintained with an increase of harmonic distortion.

B. Phase Redundancy

This concept consists of introducing an additional phase leg to replace a faulty phase leg, as shown in Fig. 6 [60]. The fault-tolerant control scheme is as follows: firstly, the gate driving signals of the two switches in the faulty leg (e.g. S_1 and S_2) are set to be zero level; secondly, the suited bidirectional switch is triggered (e.g. t_1); finally, the two switches in redundant phase (e.g. S_7 and S_8) are controlled by gate driving signals to resume the role of the two switches in faulty leg. This method has been applied in three-level converters [61,62]. Five-leg [63,64] and six-leg converter [65] also have similar fault redundancy.

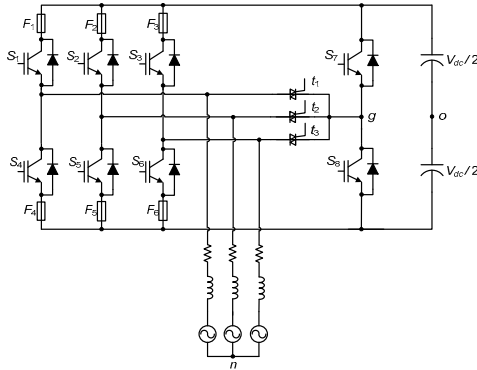


Fig. 6. Typical phase redundant circuit [61].

TABLE II. SUMMARY OF FAULT-TOLERANT CIRCUITS' PERFORMANCE WITH POWER SWITCHES FAILURE

Fault-tolerant Design	Failure Types of Power Switch	
	Short-circuit	Open-circuit
Press-pack IGBTs in Series Connection	✓ ^a	✗ ^b
Bypass Switches	✓ ^c	✓
CHBM/MMC	✓	✓
Four-leg Converter	✓	✓
Five-leg Converter	✓	✓
Six-leg Converter	✓	✓
Matrix Converter	✗	✓
T-type Converter	✗	✓
Improved Boost Converter	✗	✓
HBALSC	✓	✓

^a. Maintain Operation with Normal Output; No fault-tolerant ability; Maintain Operation with Degraded Output

C. State-redundant Converter

Some circuits have inherent redundant ability, such as the sparse matrix converter [66-68], and T-type three-level converter [69], which can handle open-circuit failure of switches. Moreover, researchers also proposed modifications to traditional converters to obtain fault-tolerant ability, such as an improved three-level boost converter for photovoltaic applications [70], an H-bridge DC-DC converter with auxiliary leg and selector cells (HBALSC) [71].

A summary of fault-tolerant circuits' performance with respect to power switches failure is presented in Table II. It is worth mentioning that short-circuit failure is more difficult to handle than open circuit, and it usually needs very short detection times.

V. CONCLUSIONS

Catastrophic failure of IGBT is fairly important issues both in design phase and in operation phase of power electronic converters. The failure mechanisms of two open-circuit modes and four short-circuit modes are reviewed in this paper. Even though the initial triggering factors for those failure modes are different, the final destruction is almost due to over-temperature, which reveals the importance of thermal design and fine thermal management of IGBTs in reliability-critical applications. At present, plenty of circuit-level fault-tolerant solutions are available to isolate faulty IGBTs and enhance converter reliability, which have been discussed in this work. Exploration of fault-tolerant solutions with reduced complexity and reduced cost is a hot theme and progresses in this field are highly expected in the near future.

REFERENCES

- [1] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics - challenges, design tools and opportunities," *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 17-26, Jun. 2013.
- [2] E. Wolfgang, "Examples for failures in power electronics systems," presented at *ECPE Tutorial on Reliability Power Electronic System*, Nuremberg, Germany, Apr. 2007.
- [3] F. W. Fuchs, "Some diagnosis methods for voltage source inverters in variable speed drives with induction machines—A survey," *Proceedings of IEEE Industrial Electronics Society Annual Conference*, pp. 1378-1385, Nov. 2003.
- [4] S. Yang, A. T. Bryant, P. A. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441-1451, May/Jun. 2011.
- [5] N. M. Vichare and M. G. Pecht, "Prognostics and health management of electronics," *IEEE Transactions on Components and Packaging Technologies*, vol. 29, no. 1, pp. 222-229, Mar. 2006.
- [6] C. Busca, R. Teodorescu, F. Blaabjerg, S. Munk-Nielsen, L. Helle, T. Abeyasekera, and P. Rodriguez, "An overview of the reliability prediction related aspects of high power IGBTs in wind power applications," *Microelectronics Reliability*, vol. 51, no. 9-11, pp. 1903-1907, Sep./Nov. 2011.
- [7] M. Ciappa, "Selected failure mechanisms of modern power modules," *Microelectronics Reliability*, vol. 42, no. 4-5, pp. 653-667, Apr./May. 2002.
- [8] M. Ciappa and F. Wolfgang, "Lifetime prediction of IGBT modules for traction applications," *Proceedings of 38th Annual IEEE International Reliability Physics Symposium*, pp. 210-216, 2000.
- [9] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner, "Condition monitoring for device reliability in power electronic converters: a review," *IEEE Transactions on Power Electronics*, vol. 25, no. 11, pp. 2734-2752, Nov. 2010.
- [10] J. Flicker, R. Kaplar, B. Yang, M. Marinella, and J. Granata, "Insulated gate bipolar transistor reliability testing protocol for PV inverter applications," *Progress in Photovoltaics: Research and Applications*, doi: 10.1002/pip.2351
- [11] K. Rothenhagen and F.W. Fuchs, "Performance of diagnosis methods for IGBT open circuit faults in three phase voltage source inverters for AC variable speed drives," *Proceedings of 2005 European Conference on Power Electronics and Applications*, pp.1-7, 2005.
- [12] B. Lu and S. Sharma, "A literature review of IGBT fault diagnostic and protection methods for power inverters," *IEEE Transactions on Industry Applications*, vol.45, no.5, pp.1770-1777, Sept./Oct. 2009.
- [13] J. Yamashita, A. Uenishi, Y. Tomomatsu, H. Haruguchi, H. Takahashi, I. Takata, and H. Hagino, "A study on the short circuit destruction of IGBTs," *Proceedings of the 5th International Symposium on Power Semiconductor Devices and ICs. ISPSD '93*, pp. 35-40, May 1993.
- [14] W.S. Loh, M. Corfield, H. Lu, S. Hogg, T. Tilford, and C.M. Johnson, "Wire bond reliability for power electronic modules - effect of bonding temperature," *Proceedings of International Conference on Thermal, Mechanical and Multi-Physics Simulation Experiments in Microelectronics and Micro-Systems*, pp.1-6, Apr. 2007.
- [15] K. S. Smith, L. Ran, and J. Penman, "Real-time detection of intermittent misfiring in a voltage-fed PWM inverter induction-motor drive," *IEEE Transactions on Industrial Electronics*, vol. 44, no. 4, pp. 468-476, Aug. 1997.
- [16] L. Chen, F. Z. Peng, and D. Cao, "A smart gate drive with self-diagnosis for power MOSFETs and IGBTs," *Proceedings of 23rd Annual IEEE Applied Power Electronics Conference and Exposition (APEC2008)*, pp.1602- 1607,2008.
- [17] C. Delepout, S. Siconolfi, O. Mourra, and F. Tonicell, "MOSFET gate open failure analysis in power electronics," *Proceedings of 28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC2013)*, pp.189-196, Mar. 2013.
- [18] B. Wang, A. Hu, Y. Tang, and M. Chen, "Analysis of voltage breakdown characteristic of IGBT," *Transactions of China Electrotechnical Society*, vol.26, no. 8, pp.145-150, Aug. 2011.
- [19] X. Perpiñà, J. F. Serviere, X. Jorda, S. Hidalgo, J. Urresti-Ibanez, J. Rebollo, and M. Mermet-Guyennet, "Over-current turn-off failure in high voltage IGBT modules under clamped inductive load," *Proceedings of 13th European Conference on Power Electronics and Applications (EPE '09)*, pp.1-10, 2009.
- [20] I. Masayasu, H. Koji, K. Sachiko, S. Takahide, S. Tonioyuki, F. Takeshi, and H. Kimimori, "Investigation of IGBT turn-on failure under high applied voltage operation," *Microelectronics Reliability*, vol. 44, no. 9-11, pp. 1431-1436, Sep./Nov. 2004.
- [21] B. J. Baliga, "Fundamental of power semiconductor devices," Springer: 2008, ISBN:9780387473130, pp.938-948.
- [22] J. G. Fossum and Y. S. Kim, "Static and dynamic latchup in the IGBT," *IEEE Transactions on Electron Devices*, vol. 35, no. 11, pp. 1977- 1985, Nov. 1988.
- [23] K. Heumann, "Second breakdown and latch-up behavior of IGBTs," *Proceedings of Fifth European Conference on Power Electronics and Applications*. vol.2, pp. 301- 305, 1993.
- [24] P. Rose, D. Silber, A. Porst, and F. Pfirsch, "Investigations on the stability of dynamic avalanche in IGBTs," *Proceedings of the 14th International Symposium on Power Semiconductor Devices and ICs*, pp.165-168, 2002.
- [25] I. Takata, "Non-thermal destruction mechanisms of IGBTs in short circuit operation," *Proceedings of the 14th International Symposium on Power Semiconductor Devices and ICs*, pp.173-176,2002.
- [26] K. Oh, Y. Kim, K. Lee, and C. Yun, "Investigation of shortcircuit failure limited by dynamic-avalanche capability in 600-V punchthrough IGBTs," *IEEE Transactions on Device and Materials Reliability*, vol. 6, no. 1, pp. 2-8, Mar. 2006.
- [27] F. Iannuzzo, G. Busatto, "Physical CAD model for high-voltage IGBTs based on lumped-charge approach," *IEEE Transactions on Power Electronics*, vol. 19, no. 4, pp. 885-893, Jul. 2004.
- [28] D. W. Brown, M. Abbas, A. Ginart, I. N. Ali, P. W. Kalgren, and G. J. Vachtsevanos, "Turn-off time as an early indicator of insulated gate bipolar transistor latch-up," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 479-489, Feb. 2012
- [29] N. Patil, J. Celaya, D. Das, K. Goebel, and M. Pecht, "Precursor parameter identification for insulated gate bipolar transistor (IGBT) prognostics," *IEEE Transactions on Reliability*, vol. 58, no. 2, pp. 271-276, Jun. 2009.
- [30] A. Benmansour, S. Azzopardi, J. Martin, and E. Woigard. "A step by step methodology to analyze the IGBT failure mechanisms under short circuit and turn-off inductive conditions using 2D physically based device simulation," *Microelectronics Reliability*, vol. 47, no. 9-11, pp. 1800-1805, Aug./Nov. 2007.
- [31] T. Laska, G. Miller, M. Pfaffenlehner, P. Turkes, D. Berger, B. Gutschmann, P. Kanschat, and M. Munzer, "Short circuit properties of Trench-/Field-Stop-IGBTs-design aspects for a superior robustness," *Proceedings of IEEE 15th International Symposium on Power Semiconductor Devices and ICs (ISPSD '03)*, pp. 152-155, 2003.
- [32] P. L. Hower and K. Reddi, "Avalanche injection and second breakdown in transistors," *IEEE Transactions on Electron Devices*, vol. 17, no. 4, pp. 320, Apr. 1970.
- [33] C. C. Shen, A. R. Hefner, D. W. Berning, and J. B. Bernstein, "Failure dynamics of the IGBT during turn-off for unclamped inductive loading conditions," *Proceedings of IEEE Industry Applications Conference*, vol.2, pp. 831- 839, 1998.
- [34] G. Breglio, A. Irace, E. Napoli, M. Riccio, and P. Spirito, "Experimental detection and numerical validation of different failure mechanisms in IGBTs during unclamped inductive switching," *IEEE Transactions on Electron Devices*, vol. 60, no. 2, pp. 563-570, Feb. 2013
- [35] A. Benmansour, S. Azzopardi, J. C.Martin, and E.Woigard, "Failure mechanisms of trench IGBT under various short-circuit conditions," *Proceeding of IEEE Power Electronics Specialists Conference 2007 (PESC 2007)*, pp. 1923- 1929, 2007.
- [36] R. S. Chokhawala, J. Catt, and L. Kiraly, "A discussion on IGBT short-circuit behavior and fault protection schemes," *IEEE Transactions on Industry Applications*, vol. 31, no. 2, pp. 256- 263, Mar./Apr. 1995.

- [37] M. Otsuki, Y. Onozawa, and T. Matsumoto, "A study on the short-circuit capability of field-stop IGBTs," *IEEE Transactions on Electron Devices*, vol. 50, no. 6, pp. 1525-1531, Jun. 2003.
- [38] S. Lefebvre, Z. Khatir, and F. Saint-Eve, "Experimental behavior of single-chip IGBT and COOLMOS devices under repetitive short-circuit conditions," *IEEE Transactions on Electron Devices*, vol. 52, no. 2, pp. 276-283, Feb. 2005.
- [39] Z. Khatir, S. Lefebvre, and F. Saint-Eve, "Experimental and numerical investigations on delayed short-circuit failure mode of single chip IGBT devices," *Microelectronics Reliability*, vol. 47, no. 2-3, pp. 422-428, Feb./Mar. 2007.
- [40] Z. Xu and F. Wang, "Experimental investigation of Si IGBT short circuit capability at 200°C," *Proceedings of 27th Annual IEEE Applied Power Electronics Conference and Exposition*, pp.162-168, 2012.
- [41] F. Hille, F. Umbach, T. Raker, and R. Roth, "Failure mechanism and improvement potential of IGBT's short circuit operation," *Proceedings of 22nd International Symposium on Power Semiconductor Devices and IC's (ISPSD2010)*, pp. 33-36, 2010.
- [42] M.T. Rahimo, N.Y.A. Shammas, "Freewheeling diode reverse-recovery failure modes in IGBT applications," *IEEE Transactions on Industry Applications*, vol. 37, no. 2, pp. 661-670, Mar./Apr. 2001.
- [43] R. Wu, F. Blaabjerg, H. Wang, and M. Liserre, "Overview of catastrophic failures of freewheeling diodes in power electronic circuits", accepted by 24th European Symposium on Reliability of Electron Devices, Failure Physics and Analysis (ESREF 2013).
- [44] J. Lutz, U. Scheuermann, H. Schlagenotto, and R. de Doncker, "Semiconductor power devices," Springer: 2011, ISBN: 3642111246.
- [45] S. Eicher, M. Rahimo, E. Tsyplakov, D. Schneider, A. Kopta, U. Schlappbach, and E. Carroll, "4.5kV press pack IGBT designed for ruggedness and reliability," *Proceedings of 39th IAS Annual Meeting Industry Applications Conference*, vol. 3, pp. 1534-1539, 2004.
- [46] Y. Uchida, Y. Seki, Y. Takahashi, and M. Ichijoh, "Development of high power press-pack IGBT and its applications," *Proceedings of 22nd International Conference on Microelectronics*, vol.1, pp. 125-129, 2001.
- [47] O. S. Senturk, S. Munk-Nielsen, R. Teodorescu, L. Helle, and P. Rodriguez, "Electro-thermal modeling for junction temperature cycling-based lifetime prediction of a press-pack IGBT 3L-NPC-VSC applied to large wind turbines," *Proceedings of IEEE Energy Conversion Congress and Exposition (ECCE2011)*, pp. 568-575, Sept. 2011.
- [48] S. Gunturi, D. Schneider, and C. Res, "On the operation of a press pack IGBT module under short circuit conditions," *IEEE Transactions on Advanced Packaging*, vol. 29, no. 3, pp. 433-440, Aug. 2006.
- [49] T. A. Lipo, T. M. Jahns, and S. E. Schulz, "Fault tolerant three-phase AC motor drive topologies: a comparison of features, cost, and limitations," *IEEE Transactions on Power Electronics*, vol. 19, no. 4, pp. 1108-1116, Jul. 2004.
- [50] S. Li and L. Xu, "Strategies of fault tolerant operation for three-level PWM inverters," *IEEE Transactions on Power Electronics*, vol. 21, no. 4, pp. 933-940, Jul. 2006.
- [51] F. Richardeau, Z. Dou, J. M. Blaquiere, E. Sarraute, D. Flumian, and F. Mosser, "Complete short-circuit failure mode properties and comparison based on IGBT standard packaging. application to new fault-tolerant inverter and interleaved chopper with reduced parts count," *Proceedings of the 14th European Conference on Power Electronics and Applications (EPE 2011)*, pp.1-9, 2011.
- [52] J. J. Park, T. J. Kim, and D. S. Hyun, "Study of neutral point potential variation for three-level NPC inverter under fault condition," *Proceedings of 34th IEEE Annual Conference of the IEEE Industrial Electronics Society (IECON2008)*, pp. 983-988, Nov. 2008.
- [53] J. C. Lee, T. J. Kim, D. W. Kang, and D. S. Hyun, "A control method for improvement of reliability in fault tolerant NPC inverter system," *Proceedings of 37th IEEE Annual Power Electronics Specialist Conference (PESC2006)*, pp. 1-5, Jun. 2006.
- [54] J. Li, S. Bhattacharya, and A. Q. Huang, "Three-level active neutral point clamped (ANPC) converter with fault tolerant ability," *Proceedings of 24th Annual IEEE Applied Power Electronics Conference and Exposition (APEC2009)*, pp. 840-845, Feb. 2009.
- [55] T. Bruckner, S. Bernet, and H. Guldner, "The active NPC converter and its loss-balancing control," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 855-868, Jun. 2005.
- [56] S. Ceballos, J. Pou, E. Robles, J. Zaragoza, and J. L. Martin, "Performance evaluation of fault tolerant neutral-point-clamped converters," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 8, pp. 2709-2718, Aug. 2010.
- [57] L. Maharjan, T. Yamagishi, H. Akagi, and J. Asakura, "Fault-tolerant operation of a battery-energy-storage system based on a multilevel cascade PWM converter with star configuration," *IEEE Transactions on Power Electronics*, vol. 25, no. 9, pp. 2386-2396, Sep. 2010.
- [58] M. A. Parker, N. Chong, and R. Li, "Fault-tolerant control for a modular generator-converter scheme for direct-drive wind turbines," *IEEE Transactions on Industry Electronics*, vol. 58, no. 1, pp. 305-315, Jan. 2011.
- [59] S. Shao, P.W. Wheeler, J.C. Clare, and A.J. Watson, "Fault detection for modular multilevel converters based on sliding mode observer," *IEEE Transactions on Power Electronics*, vol. 28, no. 11, pp. 4867-4872, Nov. 2013.
- [60] S. Karimi, P. Poure, and S. Saadate, "Fast power switch failure detection for fault tolerant voltage source inverters using FPGA," *IET Power Electronics*, vol. 2, no. 4, pp. 346-354, Jul. 2009.
- [61] S. Ceballos, J. Pou, E. Robles, I. Gabiola, J. Zaragoza, J. L. Villate, and D. Boroyevich, "Three-level converter topologies with switch breakdown fault-tolerance capability," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 982-995, Mar. 2008.
- [62] S. Ceballos, J. Pou, J. Zaragoza, E. Robles, J. L. Villate, and J. L. Martin, "Soft-switching topology for a fault-tolerant neutral-point-clamped converter," *Proceedings of IEEE International Symposium on Industrial Electronics (ISIE2007)*, pp. 3186-3191, Jun. 2007.
- [63] M. Shahbazi, P. Poure, S. Saadate, and M. R. Zolghadri, "Fault-tolerant five-leg converter topology with FPGA-based reconfigurable control," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 6, pp. 2284-2294, Jun. 2013.
- [64] M. Salehifar, R. S. Arashloo, M.-E. Manuel, V. Sala, and L. Romeral, "Fault tolerant operation of a five phase converter for PMSM drives," *IEEE 28th Annual Applied Power Electronics Conference and Exposition (APEC2013)*, pp.1177-1184, Mar. 2013.
- [65] M. Shahbazi, P. Poure, S. Saadate, and M.R. Zolghadri, "FPGA-based reconfigurable control for fault-tolerant back-to-back converter without redundancy," *IEEE Transactions on Industrial Electronics*, vol.60, no.8, pp.3360-3371, Aug. 2013.
- [66] S. Kwak, "Fault-tolerant structure and modulation strategies with fault detection method for matrix converters," *IEEE Transactions on Power Electronics*, vol. 25, no. 5, pp. 1201-1210, May 2010.
- [67] S. Khwan-On, L. De Lillo, L. Empringham, and P. Wheeler, "Fault-Tolerant Matrix Converter Motor Drives With Fault Detection of Open Switch Faults," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 1, pp. 257-268, Jan. 2012.
- [68] L. Eunsil, and K. B. Lee, "Fault diagnosis for a sparse matrix converter using current patterns," *Proceedings of 27th Annual IEEE Applied Power Electronics Conference and Exposition*, pp.1549-1554, Feb. 2012.
- [69] U. M. Choi, K. B. Lee, and F. Blaabjerg, "Diagnosis and tolerant strategy of an open-switch fault for T-type three-level inverter systems," *IEEE Transactions on Industry Applications*, to be published in 2014, early access: <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&number=6542725&queryText%3DDiagnosis+and+tolerant+strategy+of+an+open-switch+fault+for+T-type+three-level+inverter+systems>.
- [70] E. Ribeiro, A. J. M. Cardoso, and C. Boccaletti, "Fault-tolerant strategy for a photovoltaic DC-DC converter," *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 3008-3018, Jun. 2013.
- [71] K. Ambusaidi, V. Pickert, B. Zahawi, "New circuit topology for fault tolerant H-bridge DC-DC converter," *IEEE Transactions on Power Electronics*, vol. 25, no. 6, pp. 1509-1516, Jun. 2010.