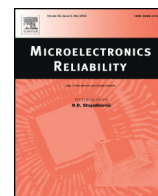




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Modern IGBT gate driving methods for enhancing reliability of high-power converters — An overview

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ABSTRACT

This paper presents a survey of existing gate driving approaches for improving reliability of Insulated Gate Bipolar Transistors (IGBTs). An extensive and various lists of techniques are introduced and discussed, including fast detection, identification and protection against IGBT failures, also considering cost-effective solutions. Gate-driver circuit solutions to improve short-circuit robustness, overload, voltage and current overshoots withstanding capability are first introduced to cope with abnormal conditions severely affecting lifetime expectation. Later, some advanced, state-of-the-art control techniques are discussed to minimize the real-mission-profile stresses in terms of voltage and current stresses to the device, together with, not least, temperature variations. Future challenges and perspectives are finally discussed at the end of the paper.

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1. Introduction

After three decades of development, Insulated Gate Bipolar Transistors (IGBTs) are widely used in many high power industrial applications [1,2]. The reliability issues have been studied by employing solutions in active and passive components, mechanical structures, packaging designs and control strategies. While the complex and harsh working conditions demanding for higher reliability are also considered [3]. According to the industrial survey indication, the semiconductor and solder failures in devices account for 34% of failures in the power conversion systems, and that is the highest proportion in all failure cases [4]. Therefore, it is necessary to investigate the failure mechanisms and propose alternative methods for improving the reliability of the IGBTs.

As an important interface between IGBT modules and micro controllers, the gate drivers do not only carry out control signals but also obtain the operation statuses of IGBT modules. The voltage-source gate drivers are usually adopted for IGBT modules. The gate drivers have the capability of varying the switching speeds of the IGBT by adjusting the gate resistors. With the increase of switching frequency, switching losses can be significantly influenced by the power circuit and voltage-source gate driver. To solve this problem, the current-source gate drivers are proposed to reduce the gate driver's losses and enhance the switching frequency [5]. The current-source gate driver behaves nearly like a constant current source, so

that the rise and fall times of the gate-emitter voltage v_{ge} are faster in contrast with the voltage-source gate drivers. Accordingly, the turn-on and turn-off times significantly decrease so that the switching losses may decrease as well. Due to the advantages of switching losses reduction and accelerating switching speeds, the idea of controllable gate current in current-source gate driver is also introduced in modern gate drivers [5,6].

Benefiting from the understanding of semiconductor and digital control unit, the IGBT abnormal operations and its wear out can be monitored and detected thanks to modern IGBT gate driver. As a result, the random failures rates and long-term wear out can easily be detected by the gate drivers. In reliability engineering, the classic bathtub curve which represents three stages of failures is plotted in Fig. 1 [7]. The failures can be divided into three main stages: early failure, middle random failure and the wear-out failure period.

Stage I: early failure period. Most of the design and manufacturing defects can be detected before the component is shipped to the end-user. In case that any defective component is delivered to the end-user, it will lead to an early failure in the Stage II. The reliability improvements predominantly come from advanced semiconductor and packaging techniques.

Stage II: middle random failure period. The root-cause failures are mainly coming from unexpected excessive electrical stress and thermal runaway (e.g. short-circuit current and avalanche breakdown) [8]. If properly designed, the gate drivers can be used to monitor different aging parameters and foresee the end-of-life of the IGBT.

Stage III: long-term wear-out failure period. In this period, the power conversion system needs to withstand comprehensive stresses even if the power device has some degradation. Owing to the features of

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Nomenclature

V_{ge}	gate-emitter voltage
V_{th}	threshold voltage
V_{gp}	Miller plateau voltage
V_{gon}	steady state turn-on gate voltage
V_{goff}	steady state turn-off gate voltage
V_{ce}	collector voltage
i_c	collector current
V_{peak}	peak voltage at turn-off transient
I_{peak}	peak current at turn-on transient
V_{dc}	DC-link voltage
I_{load}	load current
t_{off}	turn-on time
t_{on}	turn-off time
t_{doff}	turn-off delay time
t_{don}	turn-on delay time
C_{ge}	capacitor between gate and collector
C_{gc}	capacitor between gate and collector

slowing propagation and aging regularity, wear-out failure is the most likely to be monitored and predicted by gate drivers during long-term service [9].

To improve the reliability of IGBTs and prolong the useful life of conversion systems, efforts have been put into reliability issues from the bottom die level to top system level. Prior research works have covered the above five aspects of optimization objectives as shown in Fig. 1, in terms of die level failure mechanisms [10], packaging of device [11,12], fault diagnosis, redundant design of converter and long-time monitoring of power conversion system [13–18].

However, the intervention time scales would strongly differ depending upon the hardware sources, application requirement and working environment. From the user's perspective, the fault detection and protection by gate driver are today the only way to carry out the fastest fault diagnosis on packaged IGBT modules within microseconds (μs) at a low cost. Furthermore, the electrical and thermal information collected and calculated by the gate driver is the fundamental of further condition monitoring and lifetime prediction in Stage III. With a better understanding of physics semiconductor and the mature IC technology,

the advanced gate driver does not only implement the diagnosed faults and protection during the short-term and long-term periods, but also takes the initiative to improve reliability of the power conversion system.

This paper is organized as follows. In Section 2, the switching performances of IGBT under conventional voltage-source gate drivers are briefly introduced. Besides, the principles of detection and protection method classification are also discussed. In Section 3, the detection and protection methods for short-circuit and overload are summarized. In Section 4, the optimization and suppression methods for voltage and current overshoots are introduced. A summary of switching trajectory control methods is finally given in Section 5. Section 6 draws some conclusion and gives some perspectives in the field.

2. Detection and protection method classification

For the switching characteristic test, the half-bridge circuit with double pulse test method is widely adopted for the investigation of power devices [19]. The typical switching waveforms of the IGBT (e.g. collector-emitter voltage and collector current) together with the gate voltage are plotted in Fig. 2. Both the turn-on and turn-off transitions can be divided into four stages, respectively.

The details of transition stages and potential failure mechanisms are summarized in Table 1. Different types of failure cases occurring in specific stages of turn on/off transitions are also shown in Table 1. The abnormal operation of the IGBT can be detected by the gate driver if they differ from the normal turn on/off transitions.

In earlier hard switching applications, the overshoots of voltage and current are minimized by applying passive methods, such as gate resistor adjustment and clamping circuits. Nowadays, more and more optimization methods can be addressed by advanced gate drivers. This means that the reliability issues can be solved without additional efficiency costs. According to the sampling signal sources from IGBT module, the advanced protection and optimization solutions can be divided into: (i) collector voltage v_{ce} based approach, (ii) gate based approach, (iii) collector current i_c based approach, and (iv) collector current rate di_c/dt based approach [20]. The typical four types of IGBT fault detection methods are depicted in Fig. 3.

A brief analysis and comparison of the four basic types of schematics are shown in Table 2. Importantly, by combining the four basic approaches, more optimized and sophisticated protection methods

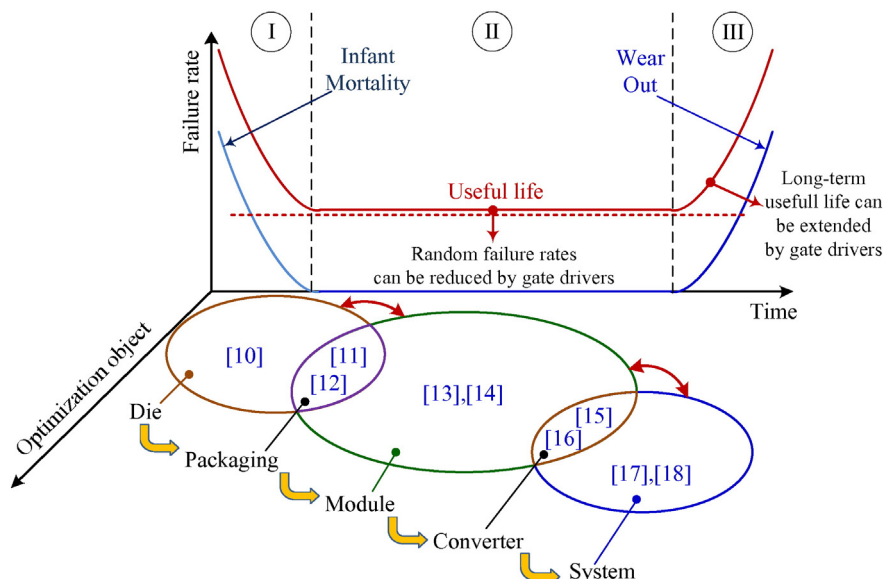


Fig. 1. Classic bathtub curve of failures and corresponding optimization objects.

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