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Power cycling test and failure analysis of molded Intelligent Power IGBT Module under different temperature swing durations

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ABSTRACT

Molded IGBT modules are widely used in low power motor drive applications due to their advantage like compactness, low cost, and high reliability. Thermo-mechanical stress is generally the main cause of degradation of IGBT modules and thus much research has been performed to investigate the effect of temperature stresses on IGBT modules such as temperature swing and steady-state temperature. The temperature swing duration is also an important factor from a real application point of view, but there is a still lack of quantitative study. In this paper, the impact of temperature swing duration on the lifetime of 600 V, 30 A, 3-phase molded Intelligent Power Modules (IPM) and their failure mechanisms are investigated. The study is based on the accelerated power cycling test results of 36 samples under 6 different conditions and tests are performed under realistic electrical conditions by an advanced power cycling test setup. The results show that the temperature swing duration has a significant effect on the lifetime of IGBT modules. Longer temperature swing duration leads to the smaller number of cycles to failure. Further, it also shows that the bond-wire crack is the main failure mechanism of the tested IGBT modules.

1. Introduction

Thermo-mechanical stress is generally the main cause of degradation of IGBT modules [1–3]. Therefore, much research has been performed to investigate the effect of temperature stresses on IGBT modules such as temperature swing ($\triangle T$) and mean temperature (T_m) by performing accelerated power cycling tests [4–6]. While the impacts of $\triangle T$ and T_m on degradation of IGBT modules are well investigated, there is still a lack of quantitative study on the effect of temperature swing duration ($t_{\triangle T}$).

In recent research [7], the impact of load pulse duration on power cycling lifetime has been investigated for solder-free power modules based on the DC power cycling test and a related lifetime model has been made. In [7], it has been concluded that the load pulse duration has a significant impact on the power cycling lifetime of IGBT modules. However, this kind of prior art research has some limitations that the detailed testing data and corresponding post failure analysis are usually not provided. Further, there is also a lack of statistical experimental results. In addition, most of power cycling test has been performed by DC power cycling test [2,6–8]. In these tests, the tested module is not operated under realistic electrical conditions. There are no switching, no high DC-link voltage, no dynamic losses, etc. Further, an overload current may be required for high temperature swing in a short period. In [7] there is a large error in the verification of the model, which presents the impact of the load pulse duration with the real power converter. Therefore, more research considering above limitations is still required. Of course, there is still a lack of study on effect of operating conditions of tested IGBT modules during power cycling test on results, and thus this effect is still an open question [9,10]. However, the power cycling test under more realistic electrical operating conditions can minimize the uncertainty, which may be able to come from other parameters or test conditions and may affect the test results.

In this paper, the impact of junction temperature swing duration on lifetime of 600 V, 30 A, 3-phase molded Intelligent Power IGBT Module (IPM) is investigated. More detailed information about target IPM can be obtained in [12]. The study is based on the test results by an advanced power cycling test setup with 36 samples under six different test conditions. A post-failure analysis of the tested IGBT modules is also performed by Scanning Electron Microscopy (SEM) and Scanning Acoustic Microscopy (SAM).

2. Advanced accelerated power cycling test

2.1. Power cycling test setup

Fig. 1 shows a configuration of an advanced accelerated power cycling test setup for molded modules. Two three-phase converters are

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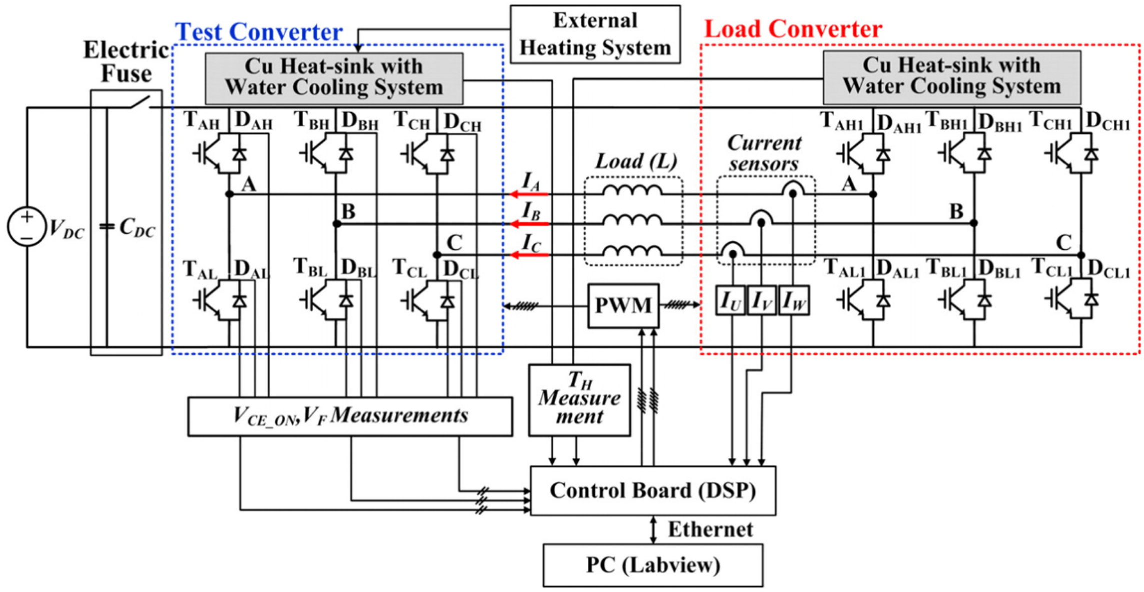

Fig. 1. Configuration of the advanced power cycling test setup.

connected through load inductors. The left one in Fig. 1 is a test converter and right one is a load converter. The IGBT module under test is used for the test converter and operated under the desired test conditions. The load converter is controlled to produce such an output voltage to generate the desired output current for the power cycling test. These two converters are connected with a DC source (V_{DC}) via an electric fuse in order to protect the overall system from an abnormal high current during the test. The on-state collector-emitter voltages (V_{CE_ON}) of IGBTs and forward voltages (V_F) of the diodes are measured in real time by an on-line measurement circuit to monitor the wear-out condition of the IGBT module under the test. The two converters are controlled by a control board with a Digital Signal Processor (DSP) and Labview interface communicates with a DSP to manage and monitor the overall system. Water cooling and external heating systems are used to keep the heat-sink temperature of the test module constant during the test and to change the heat-sink temperature according to the desired test conditions.

The main advantages of this approach are the following. First, the accelerated power cycling tests can be performed under more realistic electrical conditions close to real 3-phase converter applications compared with conventional DC power cycling test. Second, it is possible to apply various thermal stress conditions in a short cycle period and it is easy to set temperature swing amplitude and periodic condition. Further, the wear-out condition of the tested power module can be monitored in real time which gives a convenience to perform the test. Finally, the power consumption during power cycling tests can be kept low because the generated power is circulated between two converters. It means that there are only losses by two IGBT modules and load inductors. Thus, it is cost-effective solution compared with power cycling test with real loads [16]. More detailed description of the test setup can be obtained in [11,12].

Fig. 2 shows the prototype of the test setup.

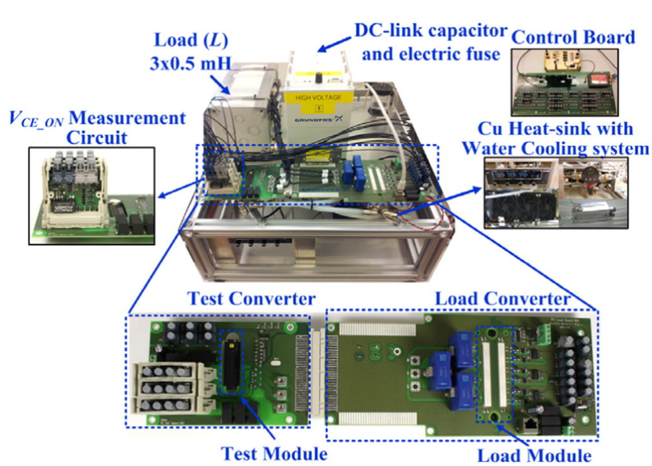

Fig. 2. Prototype of the test setup [10].

2.2. Test conditions

Power cycling tests are performed under the six operating conditions listed in Table 1, which have almost the same $\triangle T$ and T_m as about 81 °C and 102 °C, respectively but they have different swing durations from 0.59 s to 10 s. The different temperature swing durations can be achieved by changing the output frequency. The above test conditions have been validated by measuring the temperature of an open module covered by black paint using a high

Table 1
Operating conditions of test converter for the power cycling tests.

Condition	$t_{\triangle T}$	f_{OUT} (Hz)	f_{SW} (kHz)	I_{peak} (A)	V_{ref} (V)	T_H (°C)	$\triangle T$ (°C)	T_m (°C)
1	10	0.1	10	21	113	59	80.8	102.3
2	5	0.2	10	22	116	57	80.6	102.5
3	2	0.5	10	25	145	53	82.0	101.3
4	1	1	10	30	140	48	81.6	101.5
5	0.8	1.25	12	30	140	50	81.8	102.4
6	0.59	1.7	15	30	143	48	80.8	102.0

$t_{\triangle T}$: temperature swing duration, f_{OUT}: output frequency, f_{SW}: switching frequency, I_{peak}: peak current, V_{ref}: output reference voltage, T_H: heat-sink temperature, $\triangle T$: temperature swing, T_m: mean temperature.

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