ARTICLE IN PRESS
MR-12125; No of Pages 6
Microelectronics Reliability xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Microelectronics Reliability
journal homepage: www.elsevier.com/locate/mr

Mission-profile-based stress analysis of bond-wires in SiC power modules

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ARTICLE INFO

Article history:
Received 10 July 2016
Accepted 11 July 2016
Available online xxxx

Keywords:
Bond-wire fatigue
Electro-thermal model
Thermo-mechanical model
SiC Power Module
Mission profile
Reliability

ABSTRACT

This paper proposes a novel mission-profile-based reliability analysis approach for stress on bond wires in Silicon Carbide (SiC) MOSFET power modules using statistics and thermo-mechanical FEM analysis. In the proposed approach, both the operational and environmental thermal stresses are taken into account. The approach uses a two-dimension statistical analysis of the operating conditions in a real one-year mission profile sampled at time frames 5 min long. For every statistical bin corresponding to a given operating condition, the junction temperature evolution is estimated by a thermal network and the mechanical stress on bond wires is consequently extracted by finite-element simulations. In the final step, the considered mission profile is translated in a stress sequence to be used for Rainflow counting calculation and lifetime estimation.

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1. Introduction

Silicon carbide (SiC) MOSFET power modules are attractive devices for high power electronics enabling high temperature and high frequency operations especially in renewable energy systems, automotive and aerospace applications [1]. The SiC material properties (electrical, thermal and mechanical) enable them to overcome the shortcomings of the silicon (Si)-based power modules, and to develop power electronic systems with more integration, higher efficiency, and higher power density [2]. Nevertheless, despite their inherent material properties compared to the silicon devices, fulfilling the product design specifications is still a challenge with increasing demands for more lifetime requirements and cost constraints. Owing to its higher current density capability together with higher thermal conductivity, much higher temperature variations are observed in SiC devices in comparison to Si devices rated at the same current. So, the reliability prediction of SiC devices becomes a critical issue in the design of emerging power electronic converters.

Many efforts have been devoted to the reliability prediction of power converters from the system level to the component level analysis e.g. by the military handbooks such as [3]. The reliability calculation methods in such handbooks are easy to be used, but may not be appropriate for design of power electronic components in real field operation, as they are based on constant failure rates and degradation of the components are neglected. Moreover, in FIDES guide [4], reliability methodologies for electronic components have been given that they include wear-out failures and different stressors e.g. temperature and humidity [4]. The given data in FIDES are general and limited to a few number of components e.g. IGBTs and capacitors without making a difference between different technologies and manufacturers. Moreover, the failure mechanisms of power electronics are complex and are affected by different stressors [5]. It has been admitted that the thermal cycling is one of the most critical stressors occurring in power electronic components [6,7]. This is due to the Coefficient of Thermal Expansion (CTE) mismatch between different materials that leads to crack and thus failure of the device after certain number of cycles. Many manufacturers of power electronic components have developed reliability models for their products that are based on accelerated or aging tests, and can give lifetime information of the components by a certain thermal cycling [8–11]. However, failures in the power electronic components may occur at different rates for different component design and applications where the thermal cycling or extreme temperatures can result from the variation of environmental or loading conditions, i.e. mission profiles. Therefore, in order to achieve improvement in the reliability and reduction in costs of the power electronic system, it is important to estimate the lifetime of the components based on the mission profiles.

In wind power applications, wind speed and ambient temperature variations cause temperature excursions in the power modules. The thermal stress originates firstly from power cycling that is caused by load variations due to mission profiles and secondly originates from temperature cycling that is caused by ambient temperature variations. So, power modules are thermally stressed by variation of temperature fluctuations and frequencies. So far, three aging phenomena have been identified in the bond wires: fatigue phenomenon due to the deformation related to the temperature fluctuation that leads to heel fracture, mechanical stress on aluminium-silicon joints due to the CTE mismatch between aluminium and silicon that leads to bond wire lift-

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http://dx.doi.org/10.1016/j.microrel.2016.07.102
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Please cite this article as: A.S. Bahman, et al., Mission-profile-based stress analysis of bond-wires in SiC power modules, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2016.07.102

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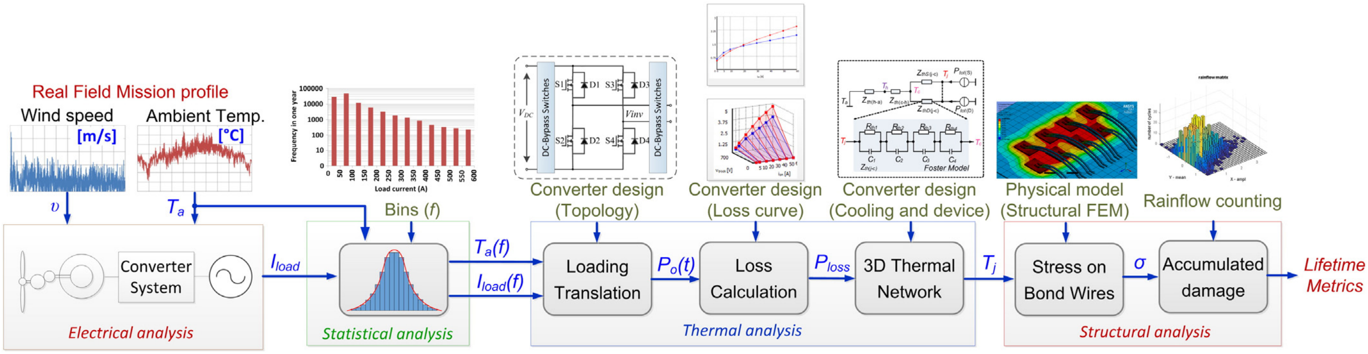

Fig. 1. Proposed mission profile based reliability analysis method for SiC power modules.

off, and thermo-mechanical stress on aluminium wires originated from the CTE mismatch between aluminium and silicon that leads to metallurgical damage [12]. Bond wire degradation depends on the low frequency temperature cycling regime (milliseconds to tens of seconds). Moreover, bond wires are one of the most critical parts in power modules, where failure occurs [12]. Unfortunately, cyclic thermo-mechanical stresses imposed to the interconnections strongly depend on the actual mission profile and no reasonable prediction can be confidently carried out a priori [13]. On the other hand, the large number of data from typical mission profiles make unfeasible to use a Finite Element Method (FEM) approach to confidently estimate such a stress. This paper presents a systematic and simplified approach to calculate the junction temperature and the thermo-mechanical stress of the bond wires based on the real power profile and environmental temperature. This approach can be used to study the impact of mission profiles on device degradation and lifetime estimation using the Rainflow counting method.

2. Proposed mission profile based analysis method

This paper proposes a mission-profile based reliability assessment approach for a SiC-based power module used in a wind power converter. As it is shown in Fig. 1, the case study consists of 1) a real-field mission profile (wind speed and ambient temperature) of a grid-connected wind power converter; 2) a statistical analysis model; 3) an electro-thermal model based on a 3D thermal network; 4) a thermo-mechanical stress model; and 5) a Rainflow analysis model. The proposed method includes several analysis models to transform the real field mission profiles to lifetime metrics. Each block employs distinct analysis tool to process the input data and to provide the required data for the next block: circuit simulator, FEM-based simulator, and numerical computing environment. The parameters used in Fig. 1 are as follows: υ – wind speed, T_a – ambient temperature, I_{load} – converter output current, $T_a(f)$ – distributed ambient temperature, $I_{load}(f)$ – distributed converter output current, $P_o(t)$ – distributed converter power, P_{loss} – power losses

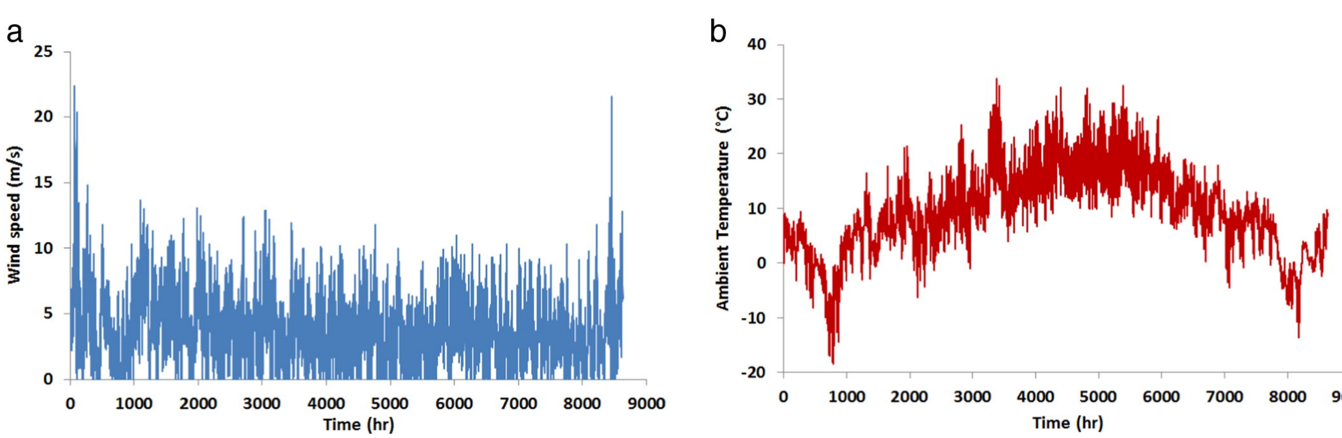

Fig. 2. Mission profile A from a wind farm (5 min averaged): (a) wind speed; (b) ambient temperature.

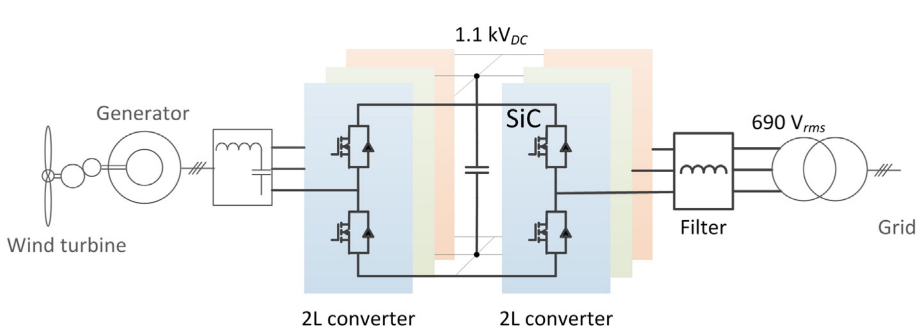

Fig. 3. Wind power converter used for reliability analysis.

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