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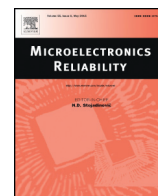
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Mission-profile-based stress analysis of bond-wires in SiC power modules

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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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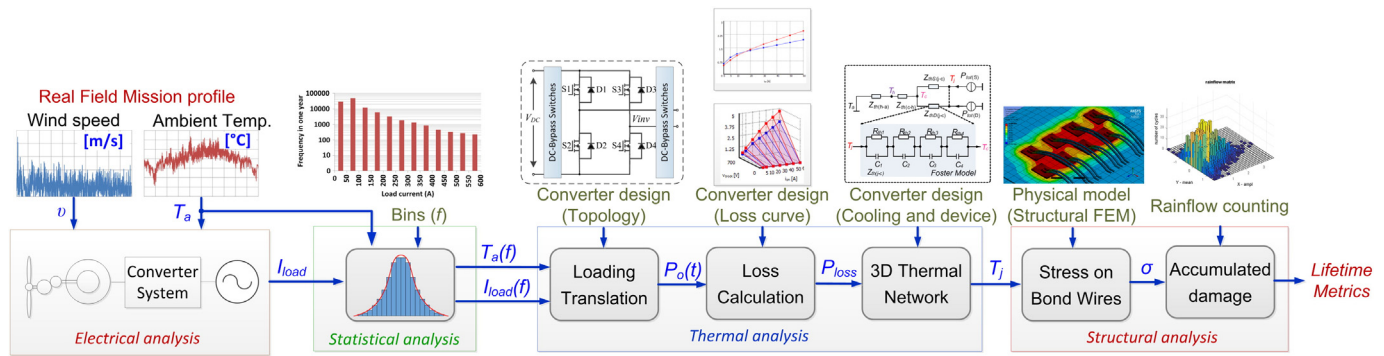


Fig. 1. Proposed mission profile based reliability analysis method for SiC power modules.

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: v – 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

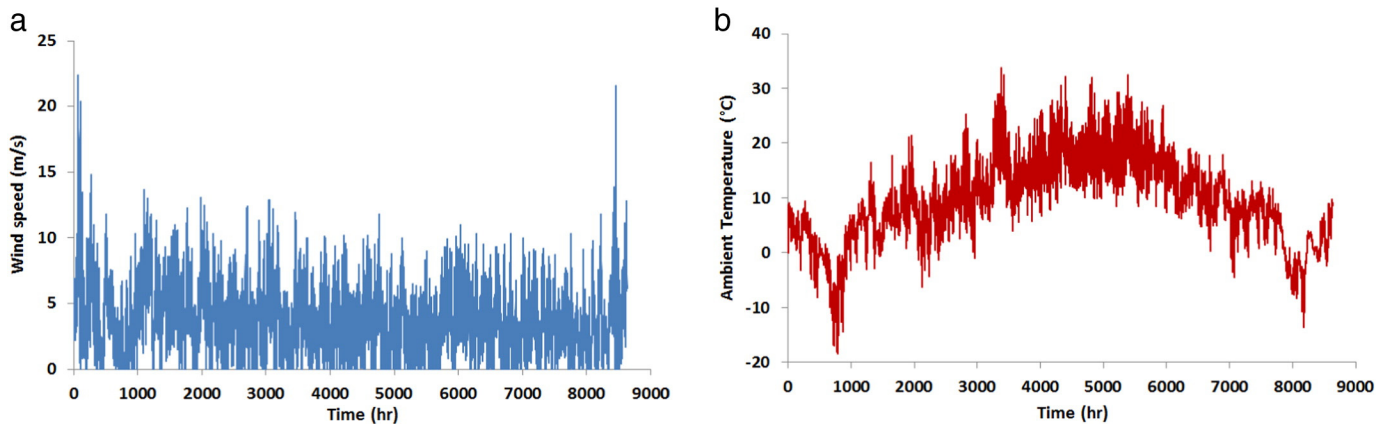


Fig. 2. Mission profile A from a wind farm (5 min averaged): (a) wind speed; (b) ambient temperature.

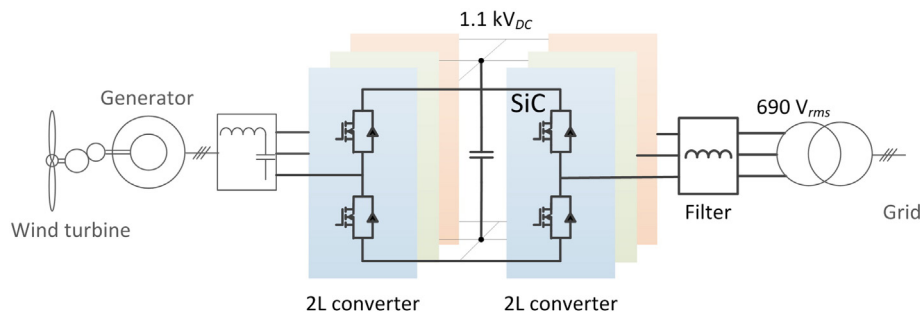


Fig. 3. Wind power converter used for reliability analysis.

Table 1
Parameters of converter shown in Fig. 3.

Rated output active power P_o	500 kW
Output power factor PF	1.0
DC bus voltage V_{dc}	1100 VDC
*Rated primary side voltage V_p	690 V rms
Rated load current I_{load}	209 A rms
Fundamental frequency f_o	50 Hz
Switching frequency f_c	2 kHz
Filter inductance L_f	1.9 mH (0.2 p.u.)

* Line-to-line voltage in the primary windings of transformer.

of the device, T_j – device junction temperature, σ – stress on bond wires. A description of each block is presented in the following sections.

3. Mission profile analysis model

The proposed reliability analysis model develops the mission profiles of the real field wind power converter operation based on one year measurement of wind speed (v) and ambient temperature (T_a) averaged at 80 m hub height which was collected from a wind farm close to Thyborøn, Denmark. The sampling time of the measured data is 5 min. So, a realistic loading condition of the converter can be achieved considering long operation and short data measurement time. As shown in Fig. 2, a one year wind speed and ambient temperature profile – mission profile A – is used with measurement frequency of 5 min.

In respect to the type of wind power converter, the most popular topology is the two-level back-to-back voltage source converter, as shown in Fig. 3. Only the grid side converter is adopted in the case study for lifetime studies. The parameters used in the converter are listed in Table 1, which typical is used in a state-of-the-art two-level wind power converter. In the electrical analysis model, the wind turbine, generator and converter are included. The output power of the wind turbine can be obtained from the power curve provided by the manufacturer and can be used as the direct power delivered from the wind power converter [14]. As the rated primary side voltage V_p is 690 Vrms, the long rated current profile of the converter is extracted to be used for the next analysis model. The load current profile is shown in Fig. 4.

4. Statistical analysis model

The converter load current profile from the electrical model and ambient temperature profile are complex data and need to be simplified in size for reliability analysis. So, a two-dimensional frequency distribution is performed based on ambient temperatures and load currents to generate a compact spectrum of operating conditions. The frequency distribution reveals the frequency of various predefined values in a sample [15]. The output of the statistical model contains the frequency of the occurrence of the values, which are divided into few numbers of bins

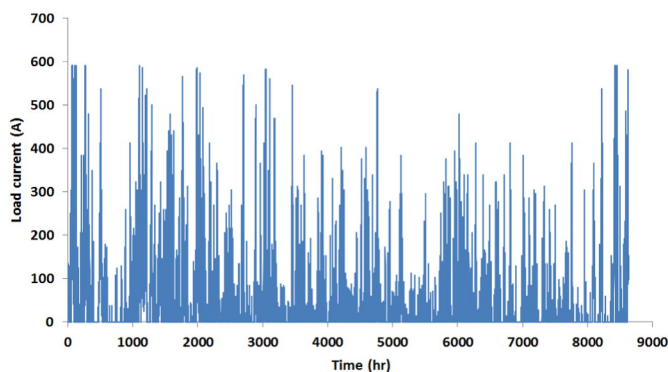


Fig. 4. One-year load current profile for the converter shown in Fig. 3 and the mission profile in Fig. 2.

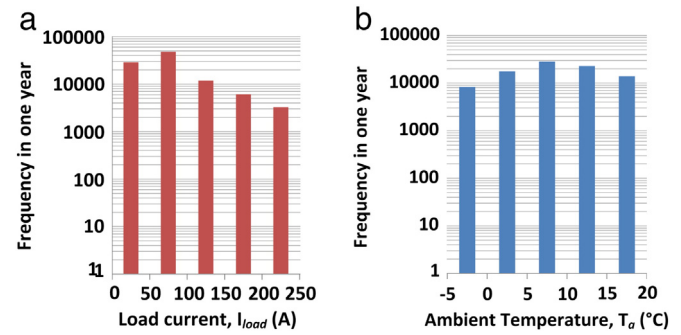


Fig. 5. Frequency in the one-year wind turbine profile: (a) load current bins; (b) ambient temperature bins.

where each bin encompasses a range of values. For the converter load current, the bins are selected in 50 A and for the ambient temperatures, steps of 5 °C are selected in this case (totally 5×5 bins that are the most repeated bins), but the quantization can be made arbitrarily smaller and smaller at the expense of increased calculation complexity. The frequency of the load current bins and the ambient temperature bins in the given one-year profile are presented in Fig. 5.

5. Electro-thermal analysis model

The proposed approach is aimed to estimate the lifetime of the SiC power module by calculation of the junction temperature and the bond wire temperature. So, in order to calculate the junction temperature, the SiC power module is simulated in a two-level voltage source converter under study and the power semiconductor losses are directly acquired from a lookup table to accelerate the analysing speed. The power modules are from ROHM BSM180D12P2C101 (180 A/1200 V/150 °C), consisting of 8 SiC MOSFET dies in a half-bridge topology (Fig. 6) are chosen as the power semiconductor devices. The input data in the electro-thermal model are: the samples of the load current and ambient temperature ($I_{load}(f)$ and $T_a(f)$), DC bus voltage (V_{DC}), and the switching frequency (f_{SW}). In order to enable the temperature dependency, the power semiconductor losses are decided by the input converter power and the junction temperature. The power losses are simulated in circuit simulators in which complete switching behaviours of the SiC module, conduction losses, switching losses, and reverse recovery losses are taken into account. To calibrate the circuit simulation results, power losses can be measured by power device analyzer and double pulse tester. However, the electro-thermal analysis follows the same approach in all methods of power device losses characterization.

The thermal model – i.e. the network of thermal resistances and thermal capacitances – which transfers the power losses to the corresponding temperatures of the power module is critical for the identification of the loading profile. The thermal model given by the device datasheet is typically characterized in specific testing conditions, so it is inaccurate when the mission profile is changing. So, in order to increase the accuracy, a thermal model based on the physical behaviour of the device in different environmental and operating conditions has been developed. A detailed geometry of the device is first simulated by using FEM. Pulsed power losses are fed to the SiC semiconductor dies in a physical-based 3D thermal model together with the ambient

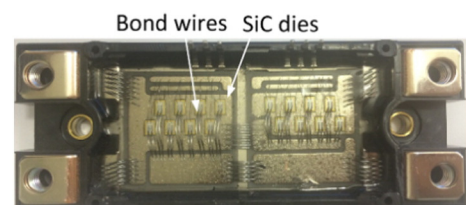


Fig. 6. SiC MOSFET power module under study.

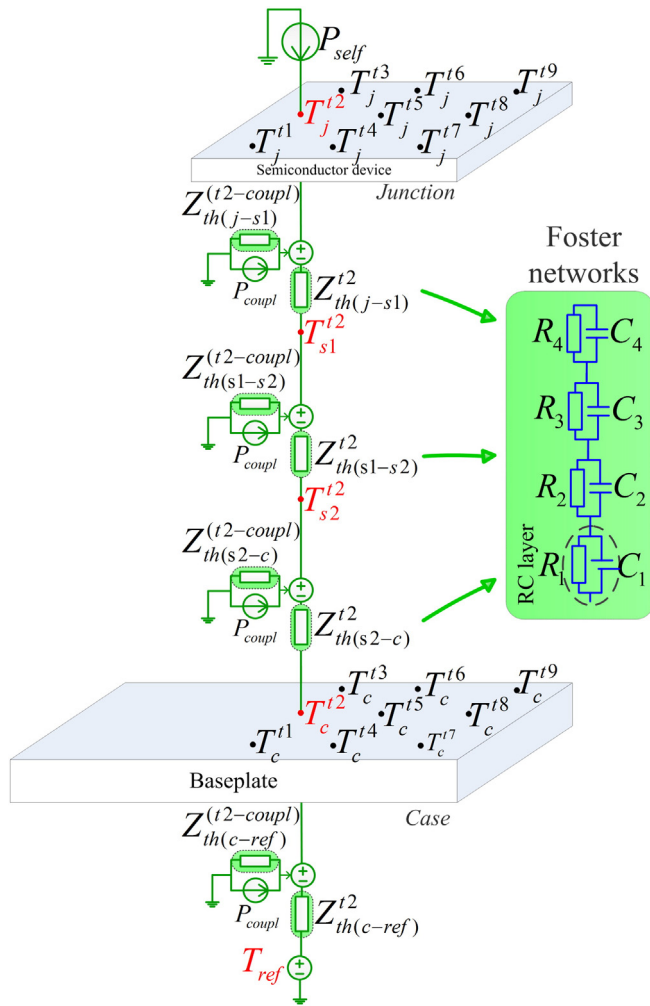


Fig. 7. 3D thermal network structure from chip (junction) to reference (cooling system) used for analysis.

temperature, which is used to estimate the heatsink temperature, to calculate the junction temperature of the dies corresponding to the bond wires feet positions [16]. The temperature responses in the junction area of the dies – T_j – corresponding to the bond wire feet positions as well as critical lower layers – e.g. chip solder “ T_{s1} ” and baseplate solder “ T_{s2} ” are monitored. Then, the junction to case partial Foster thermal networks for the mentioned points are extracted based on the method given in [16]. Moreover, to include cross-coupling thermal impacts from neighbour dies, coupling thermal impedance networks are added

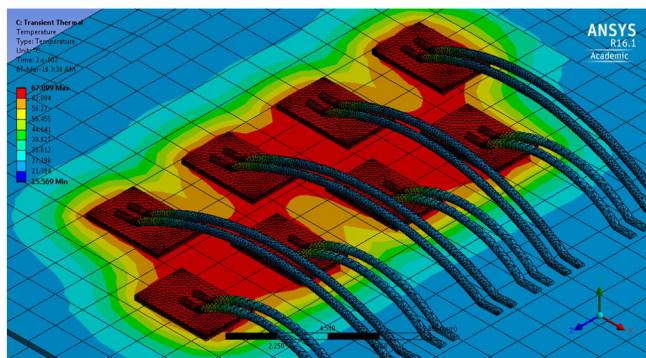


Fig. 8. Simulated thermo-mechanical stress profile by FEM in the SiC power module under study with bins: load current [200 A–250 A] and ambient temperature [5 °C–10 °C].

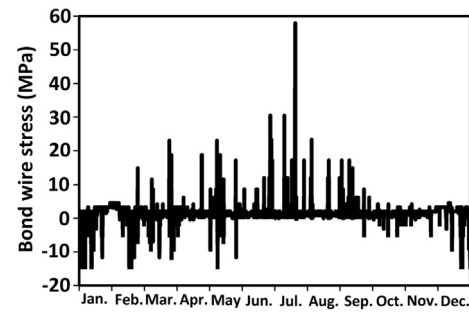


Fig. 9. Bond wire stress mean value profile for the mission profile given in Fig. 2.

as controlled voltage source between layers. It should be mentioned that the thermal resistances and thermal capacitances in the thermal network are variable with the change of ambient temperature and load current in order to taking into account the material nonlinear behaviours in real operating conditions [17,18]. Thus, a 3D thermal network is developed that can be used to estimate the temperatures in the bond wire feet positions for any mission profiles. A schematic of the thermal network is shown in Fig. 7. The thermal impedance element values may increase gradually due to degradation of the SiC module – e.g. solder delamination – which can be taken into account in the thermal analysis. In the proposed thermal network, Z_{th} is the partial Foster network, Z_{th}^{coup1} is the partial coupling Foster network, P_{self} is the power losses fed to the die, P_{coup1} is the power losses fed to the neighbour dies, T_j is the temperature in the junction layer, T_{s1} is the temperature in the chip solder, T_{s2} is the temperature in the baseplate solder, T_c is the temperature in the case layer, T_{ref} is the cooling temperature, and $t1...t9$ are several temperature points considered in the bond wire feet positions.

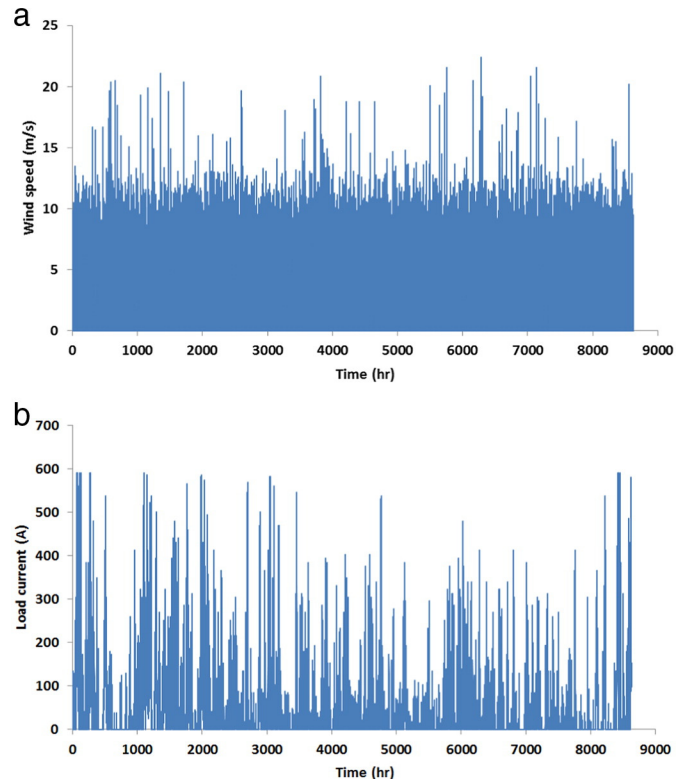


Fig. 10. Mission profile B: (a) one-year wind speed (5 min averaged); (b) load current.

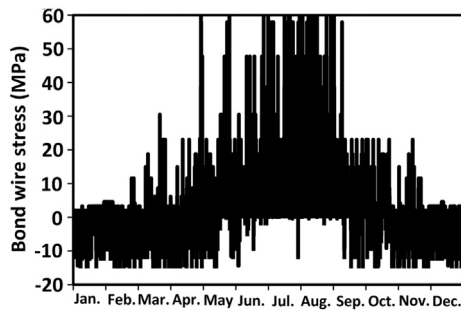


Fig. 11. Bond wire stress mean value profile for the mission profile given in Fig. 10.

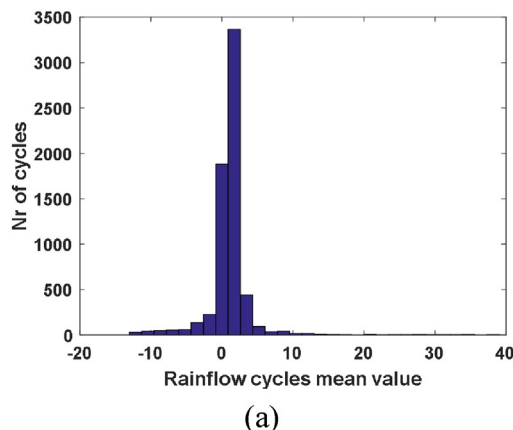
6. Thermo-mechanical model

The output of the electro-thermal model is a two-dimensional series of temperature profiles for load current and ambient temperature bins. The temperature profile is pure data that should be translated into mechanical stresses for reliability analysis. So, a single cycle of each temperature profile is given to the thermo-mechanical model of the device in the FEM mechanical environment, for each of every bin. In order to save the simulation time, the initial temperature given to the bond wire feet position is the steady state junction temperature in each bin. All the material mechanical properties in the FEM mechanical environment are temperature dependent. The mechanical stress profile of the SiC module with the following bins is shown in Fig. 8: at a load current interval [200 A–250 A] and at an ambient temperature interval [5 °C–10 °C]. As it is observed, the most stressed position is in the interconnection between the aluminium bond wire and the SiC dies, so the mechanical stress for the highest thermally stressed bond wire is extracted for all mission profile bins.

For each bin, the mechanical stress in the bond wire feet position is extracted and is used as look-up table for every time step of the whole mission profiles, ending up in a calculated stress mission profile. Fig. 9 represents the bond wire stress calculated for the mission profile given in Fig. 2.

In order to make the thermo-mechanical stress comparison in different loading conditions, another mission profile – mission profile B – is presented in Fig. 10 with the same ambient temperature profile as mission profile A. The corresponding bond wire stress calculated by FEM simulation is shown in Fig. 11.

As it is seen, in the mission profile “B”, bond wires are highly stressed with large stress fluctuations compared to the mission profile “A” that will affect the lifetime of the SiC power module in long-term operation. It worth to mention that in order to calibrate the FEM simulations, a displacement controlled mechanical shear testing method given in [19] can be used to characterize the mechanical fatigue on bond wires.



7. Mission profile-based lifetime model

Despite intensive work has been done in power cycling testing of SiC power modules, well-developed degradation and lifetime models are still missing and designers are using IGBT reliability models for lifetime estimation. Moreover, most of the reliability models provided by manufacturers are based on accelerated power cycling and temperature cycling tests, which can only cover very limited ranges of temperature swings and frequencies because the accelerated tests are very time consuming. Moreover, some testing conditions are relatively hard to implement such as very fast or very slow thermal cycling [8–10]. So, in the proposed approach, a method to estimate the lifetime of the SiC power module is presented to map the mission profiles into accurate lifetime estimation. In a given mission profile, temperature cycles do not follow a repetitive regime in terms of amplitude and frequency, hence Rainflow counting method is utilized for the cyclic accumulated damage in bond wires [20]. Rainflow counting is a fatigue analysis method in order to reduce the spectrum of varying stress into a series of simple stress values [21]. In this method, Miner's rule, which is a linear cumulative damage rule, has been employed to assess the fatigue life of the component subjected to given mission profiles [22]. The Rainflow counting of bond wire stress mean values for two mission profiles are shown in Fig. 12.

The whole lifetime of the SiC module can be divided into fractions of damage for each bin of the simplified mission profile data. For various bins (load currents and ambient temperatures), the Miner's rule can give an estimation of the SiC module life consumption (LC) as follows [22]:

$$LC = \sum_{i=1}^k \frac{n_i}{N_{fi}} \quad (1)$$

$$LC = \left[\frac{n_1}{N_1} \right]_1 + \left[\frac{n_2}{N_2} \right]_2 + \left[\frac{n_3}{N_3} \right]_3 + \dots + \left[\frac{n_k}{N_k} \right]_k$$

where i refers to different applied bins, n_i and N_{fi} are the number of cycles accumulated at stress S_i and number of cycles to failure at the stress S_i respectively, for each different bins from 1 to k . In general, when the damage fraction (LC) reaches 1, failure occurs. Based on Miner's rule for cumulative damage the lifetime of the bond wires in the mission profiles A and B are estimated as 18.2 and 12.5 years respectively. Therefore, it is concluded that the mission profile of the field where the wind power converter is operating has a major impact on the lifetime of the device and it should be considered in the design stage of the converter.

The simulation time for the whole process is about 2 h. However, once the calculation of the bond wire stresses is done by FEM, it takes less than a minute to calculate lifetime for the given mission profile. It is worth to mention that the estimated lifetime of the SiC module only

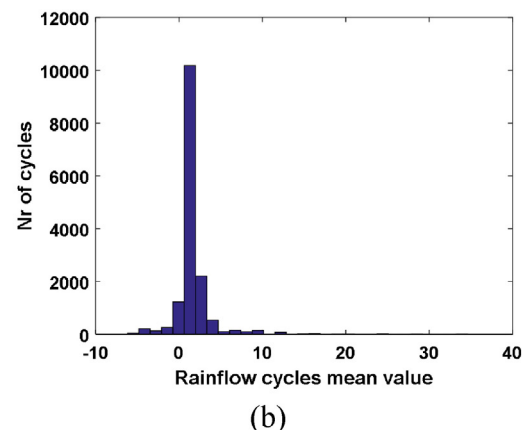


Fig. 12. Rainflow counting cycles for bond wire stress mean values: (a) mission profile A; (b) mission profile B.

considers the end-of-the-life of the bond wires. Indeed there are other failure mechanisms of SiC modules, e.g. chip solder fatigue, baseplate solder fatigue, and catastrophic failures such as short-circuit events. The lifetime of the SiC module depends by the combination of all failure mechanisms, of which bond wires are only a part of it.

8. Conclusions

A mission-profile-based method for analysis of bond wire stress in SiC power modules has been developed pushed by the real demand for realistic estimation of stress calculation on such devices. By means of statistical distribution, a one year mission profile has been reduced to a few bins and the thermo-mechanical stresses in each scenario have been extracted by FEM with a large reduction in simulation time. The fatigue-related bond wire damage has been calculated by using Rainflow counting and the lifetime of the bond wires has been estimated. The proposed method is very general and can be successfully applied for fast reliability evaluation in real and complex mission profiles.

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