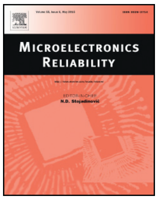
ARTICLE IN PRESS
MR-12164; No of Pages 10

Microelectronics Reliability xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr



Lifetime estimation for IGBT modules in wind turbine power converter system considering ambient temperature

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ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 15 July 2016
Accepted 15 July 2016
Available online xxxx

Keywords:
IGBT
Lifetime estimation
Wind power converter
Junction temperature
Thermal cycling

ABSTRACT

Power semiconductors in the wind turbine power converter system suffer from two-scale thermal loadings, the fundamental frequency thermal cycling caused by the output frequency of converter and the low frequency thermal cycling due to the variation of long-term wind speed. These two-scale thermal loadings introduce different consumed lifetimes. Accurate lifetime estimation in the wind power application is desired for reliability prediction and health management. This paper adopts the Bayerer lifetime model to evaluate the consumed lifetime of power semiconductors in wind power converter systems based on a numerical junction temperature calculation method. Lifetime estimation can be improved by taking into account the ambient temperature. Studies show that fluctuations of the ambient temperature increase the consumed lifetime due to the low frequency thermal cycling, but have little effect on the consumed lifetime due to the fundamental frequency thermal cycling. Our results also show that the consumed lifetime due to fundamental frequency thermal cycling mainly falls on the high wind speed area, whereas the consumed lifetime due to low frequency thermal cycling is clustered in the area due to large low frequency junction temperature fluctuations. The resulting distribution characteristics can be used in the thermal management for reliability improvement.

1. Introduction

With the rapid development of wind power generation, the capacity of wind turbine has been increased constantly while it has a growing influence on the power grid. A reliable wind turbine power converter system (WTPCS) is desirable [1,2]. The converter availability depends on the components reliability. Power semiconductor device is one of the most prone to fail components in the wind power converter, and power converter failure is largely attributed to semiconductor device failure [3]. Consequently, it is urgent that a reliable lifetime estimation of power devices in the WTPCS be well studied. Accurate estimation enables cost reduction of the wind power technology.

It is known [4,5] that the thermal cycling is one of the common failure causes of IGBT modules. Two commonly encountered thermal loadings are the low frequency thermal cycling and the fundamental frequency thermal cycling. The low frequency thermal cycling is mainly produced by the variation of wind speed and the fundamental frequency thermal cycling is mainly governed by the output frequency of the power converter [6]. This two-scale thermal loadings lead to different consumed lifetimes of power converters. Hence accurate lifetime estimation needs to be investigated according to the fundamental frequency thermal cycling and the low frequency thermal cycling. On the other hand, the temperature fluctuation on different materials with mismatched coefficients of thermal expansion (CTE) leads to different levels of heat stress. Since the thermal fatigue failure of power device is the result of long-term accumulation of heat stress, it is desired that long-term (e.g., more than one year) mission profiles be incorporated into the lifetime evaluation of power devices for accurate lifetime estimation.

Most lifetime estimation and junction temperature calculation methods for power devices reported so far consider the wind speed mission profile, but not ambient temperature [6]–[14]. These results may lead to some deviations from reality since the ambient temperature also influences the thermal cycling of power device [15,16]. However, considering the complete mission profile of ambient temperature increases the junction temperature computational load dramatically [13]. Several studies have used a finite number of ambient temperatures for junction temperature calculation to reduce the computational work [15]–[16]. Results showed that the accuracy was lost [16] and the lifetime estimation of power device was not accurate enough [13]. Further, the performed analysis could not demonstrate the impact of ambient temperature on consumed lifetime.

The ultimate goal of controlling the junction temperature is to extend the lifetime of power devices. Several studies have been reported to control the junction temperature of power devices from the

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http://dx.doi.org/10.1016/j.microrel.2016.07.141
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Please cite this article as: X. Du, et al., Lifetime estimation for IGBT modules in wind turbine power converter system considering ambient temperature, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2016.07.141

viewpoint of thermal management [17]–[19]. For example, by injecting reactive power into the wind power system junction temperatures can be regulated to reduce the thermal cycling and alleviate junction temperature fluctuation [18], or by regulating the switching frequency to control the junction temperature variation of IGBT modules [19]. These methods mainly focus on designing control strategies to regulate the junction temperature.

However, few reports have addressed the issue of the effect of long-term lifetime distribution of IGBT module to thermal management. The healthy thermal management should be able to provide the power converter a reference control setting such that the junction temperature can be regulated accordingly. If the reference control setting for long-term junction temperature is available, then the thermal management can be more specific to the design of control strategy. Analysis of the consumed lifetime distribution of power devices can offer long term reference control setting for healthy thermal management and reliability improvement.

All above problems can be attributed to the expensive computation required for long-term junction temperature calculation. Existing lifetime estimation methods usually employ the electro-thermal simulation to generate the long term temperature profile. And they usually do not take into account the variation of ambient temperatures which increases the amount of calculations dramatically. The numerical junction temperature calculation method proposed in [20] is a fast junction temperature calculation method for long-term mission profile. This method enables the calculation of junction temperature by replacing the circuit elements of thermal networks with MATLAB M-functions. In this manner, simulation of the WTPCS considering the electro-thermal characteristic of power devices allows larger time steps than the conventional simulation tools, which results in greatly improved time performance [20]. In addition, this method includes the ambient temperature in the calculation of junction temperature.

In this paper, a lifetime estimation method for IGBT modules in WTPCS considering the effects of long-term ambient temperatures and wind speeds is proposed. It adopts the junction temperature calculation method in [20] to evaluate the consumed lifetime of IGBT module. The lifetime distributions of IGBT modules are also analysed such that the results may be used for efficient thermal management and reliability improvement. The organization of this paper is as follows. Section 2 describes the lifetime estimation procedure, including the mission profile, wind power model, power loss model, thermal network, junction temperature method, and lifetime calculation. Results of consumed lifetime estimation of IGBT modules considering the long-term wind speed and ambient temperature are presented in Section 3. The distribution characteristics of consumed lifetimes of IGBT modules for different thermal loadings are investigated in Section 4, followed by the conclusions.

2. Lifetime estimation procedure

The consumed lifetime calculation of power devices in WTPCS considering long term wind speed and ambient temperature mission profiles is described in this section. The flow chart detailing the procedure for lifetime calculation is presented in Fig. 1. Two consumed lifetimes of power device are calculated: the consumed lifetime due to fundamental frequency thermal cycling CL_F and that due to low frequency thermal cycling CL_L. As can be seen from Fig. 1, the fundamental frequency junction temperatures of power module for one year are generated by the numerical junction temperature calculation method using the wind speed and ambient temperature data. Then this temperature profile is employed to calculate the consumed lifetime of IGBT, CL_{F_IGBT}, and Diode, CL_{F_Diode}.

It is also shown in Fig. 1 that the consumed lifetime of power device due to the low frequency thermal cycling is calculated according to the low frequency junction temperature mission profiles. The calculated IGBT/Diode fundamental frequency junction temperatures are employed to find the mission profiles of low frequency junction temperature. The rainflow counting method is employed to transform the low frequency thermal profile into the low frequency thermal cycles. So the consumed lifetime of IGBT/Diode in the low frequency thermal cycle (CL_{L_IGBT} and CL_{L_Diode}) can be calculated. The details will be given in the following sections.

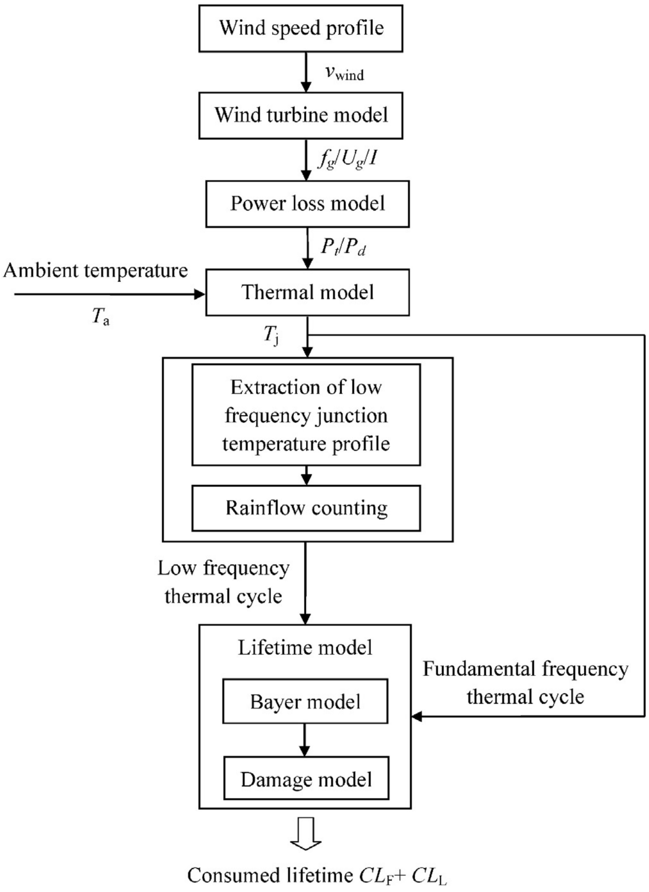

Fig. 1. Flow-chart for lifetime calculation of IGBT module in WTPCS.

2.1. Mission profile of WTPCS

A 1.2 MW wind power generation system is chosen for the case study with detail parameters given in Table 1. This system is depicted in Fig. 2. It consists of a permanent-magnet synchronous generator (PMSG), a three-phase power converter in the generator side (CGe), and a three-phase power converter in the grid side (CGr). The power converters adopt two-level back-to-back topology.

About one-year mission profiles of wind speeds and ambient temperatures are depicted in Figs. 3 and 4. These data are obtained every minute from Dublin, Ireland in 2011.The annual average wind speed is 5.2 m/s and the average ambient temperature is 11.5 °C [21].

Table 1
Parameters of 1.2 MW wind turbine power converter system.

Parameters	Values
Rated output active power	1.2 MW
Cut-in wind speed	2.5 m/s
Rated-wind speed	10.5 m/s
Cut-out wind speed	20 m/s
Rated frequency of wind turbine	16 Hz
Rated voltage for the grid connection point	690 V
Switching frequency	3 kHz
DC bus voltage	1100 V
Rated voltage of turbine generator at maximum speed	690 V

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