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Comparison of the electro-thermal constraints on SiC MOSFET and Si IGBT power modules in photovoltaic DC/AC inverters

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ABSTRACT

This article presents a comparative study between SiC MOSFETs and Si IGBTs regarding changes in their junction temperature in a PV inverter application. The estimation of these variations is made by introducing the current mission profiles extracted from a photovoltaic plant over one year into a calculation tool. The latter is based on a losses model and a thermal model including a coupling between them. The calculation of the losses in SiC MOSFETs in the 3rd quadrant is detailed. The results are the mission profiles of the junction temperature of semiconductors, which allow for determining and comparing the thermal constraints in SiC MOSFET and Si IGBT power modules.

1. Introduction

Silicon carbide (SiC) semiconductor components are being used increasingly in power electronic applications, mainly because of their high switching speeds which improve the overall efficiency and/or the compactness of the inverters [1] [2] [3].

In the case of photovoltaic installations, the inverter has the highest failure rate and the anticipation of its breakdowns is an important issue. Moreover, few studies have been conducted on the reliability of this type of converter using SiC MOSFETs [4].

In this context, the junction temperature T_J of the semiconductors and its variations over time ΔT_J contribute to accelerating the ageing of the DC/AC inverter [5] [6] [7]. Many studies have proposed methods to estimate this temperature especially for IGBT power modules using thermal models [8] [9].

The aim of our study is to compare the junction temperature swings in a SiC MOSFET and in a Si IGBT power module used in a 2 level photovoltaic inverter, having the same current and voltage ratings. A numeric tool is used to estimate the junction temperature from current mission profiles.

Knowing the temperature and its variations over time, coupled with the study of degradation modes and mechanisms as well as the mission profiles, will allow to estimate the lifetime of these semiconductors in photovoltaic applications.

In this paper, the method used to estimate the junction temperature of the devices is described. This model is composed of several submodels, the main ones being the losses estimation model and the thermal model. These two models can be coupled in order to take into account the variation of the losses depending on the temperature of the components. Temperature, estimated as a function of time, is then injected into a cycle counting algorithm named “Rainflow” that allows to obtain, for a given temperature profile, the number of occurrences for each value of ΔT_J [10]. This approach is shown in Fig. 1, where I is the current profile, P the losses profile for a given semiconductor component, T_J the junction temperature profile, ΔT_J the variation of this temperature, T_{J_M} the mean temperature and T_A the ambient one. All the calculations are made with analytical models and are implemented in Matlab software.

2. Methodology

2.1. Selection of the components

The direct comparison of SiC and Si technologies is not obvious. In fact, the electro-thermal stresses on the packaging depend a lot on the chosen configuration. For example, using the same technology, these stresses are different when changing the current rating of the devices: the maximum temperature and the thermal management system will change. Furthermore these stresses depend a lot on the application (current level, switching frequency…). The cost would also be an important point. Thus, following the goal of providing an objective

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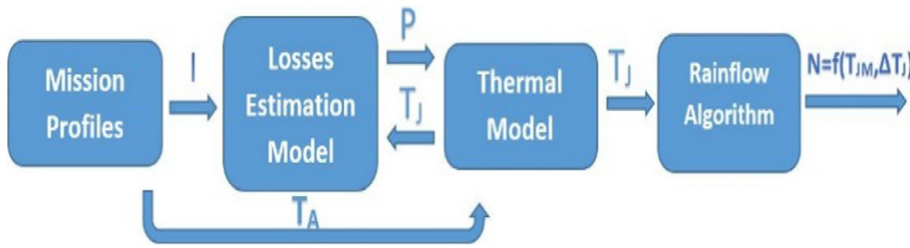

Fig. 1. Block diagram of the proposed approach.

comparison, it was decided to compare both technologies with power modules having the same current and voltage ratings and to apply the methodology for the PV inverter application.

To conduct this study, the SiC MOSFET power module CAS300M17BM2 and the Si IGBT power module FF225R17ME4, having a voltage rating of 1700 V and a current rating of 225 A were selected. Note that the diodes in the IGBT power modules are PiN diodes and the ones in the SiC MOSFET modules are Schottky ones.

This study was conducted with a two levels three phase voltage inverter, presented in the case of SiC modules in Fig. 2, where V_{DC} is the DC bus voltage, C_{bus} the value of busbar capacitor, C_1 to C_6 the gate driver signals applied on MOS_1 to MOS_6, and LCL the output filter. A DC bus voltage V_{DC} of 1200 V and a phase to phase output voltage of 690 V, with the grid frequency $f_{bf} = 50$ Hz, using a modulation factor $m = 0.95$ and a switching frequency $f_c = 4$ kHz, with a power factor $\cos\varphi = 1$ are considered.

Given that the electrical and thermal performances of the two types of modules are very distinct from one another, it would lead to very different maximum junction temperatures (and therefore no comparable results in terms of temperature swings) if the heat sink was the same for each case. Thus, as it will be shown in Section 5, two separate air cooling systems are chosen in order to have the same maximum junction temperatures in steady state and under the maximum measured RMS current.

2.2. The mission profiles

The measurements of the current produced and of the ambient temperature, coming from a photovoltaic plant in the south of France, recorded in 2015, are injected into a losses estimation model. They are represented over a year in Figs. 3 and 4. In Fig. 5, a typical evolution of these parameters over one day can be observed. These typical profiles are presented to highlight the shape of the current produced by a photovoltaic system and the corresponding ambient temperature.

Measurements are acquired with a sample time of 5 s. To estimate the average junction temperature and the losses in the power modules within the fundamental period T_{bf} (i.e. every 20 ms), a linear interpolation on the mission profiles between each measurement point is applied. Note that verifications were made to be sure that the scale of 5 s was enough to observe all the current dynamics of the studied photovoltaic plant.

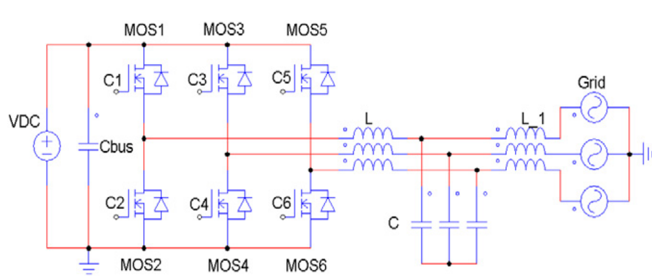

Fig. 2. The 3 phase DC/AC 2 levels inverter using SiC MOSFETs.

3. Operation and losses estimation model

3.1. Considerations for the calculation

The evolution of the losses in the semiconductor components as function of time is estimated using the mission profile presented above. Due to the large number of samples (one sample every 20 ms as explained in Section 2.2) throughout the year, the calculations are simplified using only the value of the average losses on the fundamental period T_{bf}. Therefore, the temperature variations within each fundamental period in our calculations [11] are not taken into account.

In the following paragraphs the losses estimation method will be developed [12] [13]. I will be the current through each switch (transistor + antiparallel diode). It will be defined as $I = I_T - I_D$ with I_T the current in the transistor and I_D the current in the diode.

Operation in the first quadrant ($I > 0$)

When the transistor is turned on and the current I is positive, the current in the transistor I_T equals I because the antiparallel diode is in off-state.

In the case of MOSFET, the relationship between this current and the voltage V_{DS} across its power terminals is:

$$V_{DS} = R_{DS_{on}} \cdot I_T \tag{1}$$

with R_{DSon} the on state resistance of the MOSFET. I_T is the current in the MOSFET channel. In this configuration I_T equals I.

In the case of IGBT, the relationship between I_T and the voltage V_{CE} across power terminals can be expressed by:

$$V_{CE} = E_T + R_T \cdot I_T \tag{2}$$

where E_T is the threshold forward voltage of the IGBT and R_T its dynamic resistance.

Parameters R_{DSon}, E_T and R_T are deducted from manufacturer datasheets and are all temperature dependent.

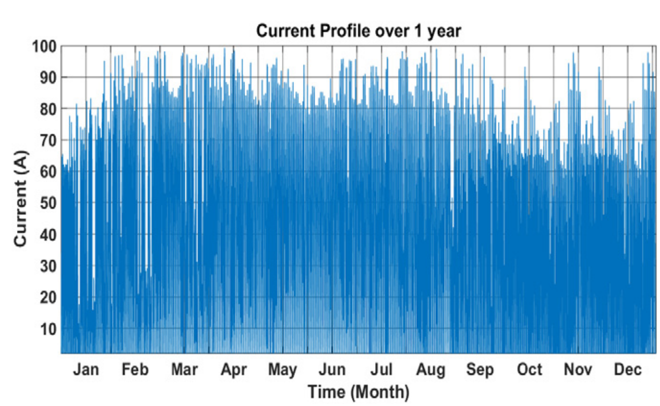

Fig. 3. The current profile over year 2015.