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Real-time system for monitoring the electro-thermal behaviour of power electronic devices used in boost converters

C. Batunlu, A. Albarbar *

Power, Renewable and Sustainability Research Group, School of Engineering, Manchester Metropolitan University, Manchester, United Kingdom

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ABSTRACT

Reliability of power electronic devices (PEDs) is a key issue to secure power supplies in modern word, especially, those generated from renewable energy sources. Thermal stress due to switching frequency and environmental conditions are commonest cause of currently unsatisfactory PEDs reliability scores.

In this paper, the electro thermal performance of PEDs and related parameters are critically investigated using three types of differently manufactured insulated gate bipolar transistors (IGBTs). Namely, punch through (PT), non-punch through (NPT) and field stop (FS) silicon trench gate technologies.

First, currents and voltages of the examined IGBTs were measured under different operating temperatures, switching frequencies and electrical loading conditions.

Second, power losses of the examined devices were calculated, in real time, based on their measured currents and voltages using realistic mathematical model embedded in a dSPACE system. Subsequently, the power losses for each device were used as an input to a finite element model to graphically predict heat distributions for each of the monitored devices.

Compared to expensive measurements taken by high-resolution thermal imaging cameras, the accuracy of the developed system achieved 97%. The obtained results demonstrate the developed model would serve as an inexpensive and powerful tool for monitoring PEDs thermal conditions.

1. Introduction

Increased demand for power electronic converters (PECs) especially in renewable energy applications has necessitated deeper investigation into the reliability of such systems. Insulated gate bipolar transistors (IGBTs) are widely used as switching devices for PECs. IGBTs serve as switching elements where temperature cycling causes thermal stress and eventual failures. Hence, accurate electro thermal modelling, temperature monitoring and control are essential to estimate and extend the life cycle of PECs. Latest manufacturing technologies of IGBTs have led to thinner silicon- and trench-gated devices [1]. To overcome the downsides of the planar gate devices such as punch-through (PT) and Non-Punch-Through (NPT), vertical, trench gate technology has been developed. Charge injection enhancement, reduced tail current at turn off and decreased power loss profiles were achieved by this technology. Further improvements such as faster switching capability and higher current density, attained with Field Stop (FS) emerging technology which is constructed by field-stop region added to thin-wafer NPT device. Fig. 1 shows the physical differences among these three trench gate structured IGBTs.

In literature, Chibante et al. studied physics based models for NPT [2] and PT IGBTs [3] for hole/electron distribution based on ambipolar diffusion equation. Takaishi et al. [4] studied analytical formulation turn-off waveform for advanced trench gate IGBTs for calculating trade-off curve between turn-off loss and saturation voltage. Ronsisvalle et al. [5] proposed an experimental characterization for the input capacitance of FS Trench IGBTs.

In contrast, accurate electro thermal modelling and temperature monitoring of IGBT's depends on collector tail current and collector to emitter saturation voltage. Thus, power sensing elements have to be coupled within electro thermal models accurately. Electro thermal models consist of power loss and thermal models, which can continuously monitor temperature variation for power electronic devices. Power losses occur due to the rapid changes in current and voltage ratings leading to thermal flux through those devices. Since the energy losses are accepted as the main cause of the heat generation through power semiconductor devices [6], modelling power losses of those power system elements is essential for determining their electro thermal behaviour. Tang et al. [7] proposed FS switching transient model for simulating the turn-off tail current switching transient of IGBT at different temperatures. It was analysed that base excess carrier lifetime

* Corresponding author at: Engineering and Materials Research Centre School of Engineering, Manchester Met. University, Manchester M1 5GD, United Kingdom.
E-mail addresses: canras.batunlu@stu.mmu.ac.uk (C. Batunlu), a.albarbar@mmu.ac.uk (A. Albarbar).

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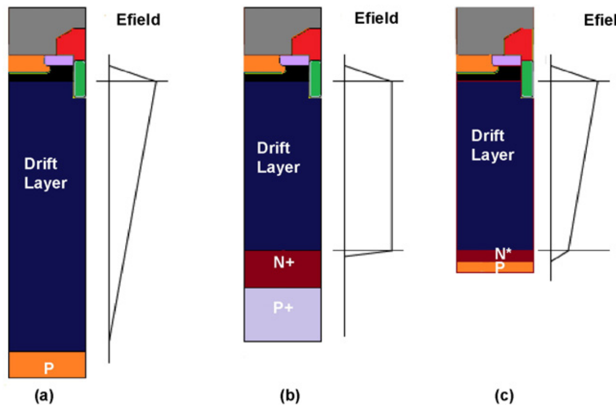

Fig. 1. (a) Trench NPT, (b) Trench PT and (c) Trench FS IGBTs.

has a great influence on the temperature characteristics of switching transient and thermal behaviour greatly changes during on and off times. Dynamic avalanche on PT IGBTs to locate active areas of chip region and thermal analysis using FE simulations studied by Lefranc et al. [8]. Yet, parasitic elements of IGBTs such as carrier mobility, excitation concentration and transconductance vary with temperature [7]. Hence the performance of IGBTs in terms of on-state voltage, tail current, switching speed and lifetime are affected [9]. Many studies present FE models of power modules for thermal impedance characterization and derive thermal models based on the generic current signals. In fact, limited amount of data is supplied by the manufacturer datasheets for the switching characteristic although the listed properties above are temperature depended. This can cause vital changes in the electro thermal performance of IGBTS based on the application type they are used [10]. For instance, DC-DC boost converters are widely used in a number of applications [11]. A reliability study presented by Khosroshahi et al. [12] showed that IGBT technology used operating modes of the converter matter on overall life time. For accurate electro thermal modelling, Blinov et al. [13] investigated ways on improving the calculation of conventional power loss based on manufacturers' datasheet information. Energy losses were calculated with respect to the sample current–voltage input characteristics. Similar model was proposed by Rui et al. [14] with the extension of temperature and on time resistance dependent electro thermal models. The simulation was executed with PSCAD software and 1.4% loss rating is estimated compared to analytical calculations. Similar approach, presented by Ivakhno et al. [15], was carried out using logic blocks in Simulink. Power loss calculation was achieved based on the output current and voltage signals of IGBT/Diode block element and coupled within thermal models. Zhou et al. [16] studied another time-domain electro thermal model which was extended by other authors [17,18]. Look up table based power loss calculations were integrated with thermal models for electro thermal monitoring of multilevel converter power electronic devices. Pittini et al. [19] developed electro thermal model for two level converter using PSCAD block sets to determine thermal and energy losses using parameters extracted from device's datasheet. Kim et al. [20] stated that power losses are highly dependent on the operating temperature and current signal characteristics at different operating conditions. Hence, analytical electro thermal calculations with generic signals can show significant inaccuracies.

In this study, voltage and current data are collected from three boost converter sets (designed with different IGBTs) and stored into dSPACE system where a carefully derived mathematical electro thermal model was embedded to predict temperatures and power losses in the tested devices. The developed system used actual boost converters operated under different conditions and processed the measured voltage and current in dSPACE. The predicted power losses are subsequently used by the FE model (derived in COMSOL) to estimate and graphically display heat distributions for the tested devices.

The paper is structured as follows: in Section 2, methodology and experimental setup are outlined. The mathematical and electro thermal models (in Simulink and COMSOL) for the tested IGBTs are described in Section 3. Results and comments on theoretical and experimental investigations are presented in Section 4. Conclusions are depicted in the final section.

2. Methodology and experimental setup

2.1. Methodology

The developed methodology flowchart and the experimental setup in this study are shown in Figs. 2 and 3, respectively.

All of the tested IGBTs were initially supplied by a constant gate signal and 5 V collector-emitter voltages under constant loads until steady state temperatures. Current and voltage measurements were taken, in addition to temperatures every 5 s, taken by high-resolution thermal camera (FLIR T440) [21]. The thermal impedance was intentionally represented by three exponential terms in order to increase the computational speed and they were extracted by curve fitting using the least square method.

Devices thermal resistances R_{th} and capacitances C_{th} were determined using Eq. (1)

$$T_m(s) = \sum_{k=1}^{N} \frac{1/C_{thn}}{s + 1/(C_{thn} \cdot R_{thn})} P_n(s) \tag{1}$$

where T represents temperature and P is the power loss. The model, built in Simulink, was based on thermal Foster network shown in Fig. 4.

The calculated thermal resistances and capacitances are shown in Table 1. Measured currents and voltages in addition to calculated thermal resistances and capacitances are interfaced to the real-time electro-thermal monitoring scheme (in dSPACE) depicted in Fig. 5.

The dSPACE blocks are shown in Fig. 5, two (DS2004ADC) blocks are used for current and voltage readings and three (DS5101PWMDAC) for providing gate signals to each IGBT used in boost converters. DS 2004 A/D platform of dSPACE uses 5 V gain for protection purpose. Hence the first constant is to acquire the gain caused by the A/D platform itself. The collector current signals were monitored by hall-effect based

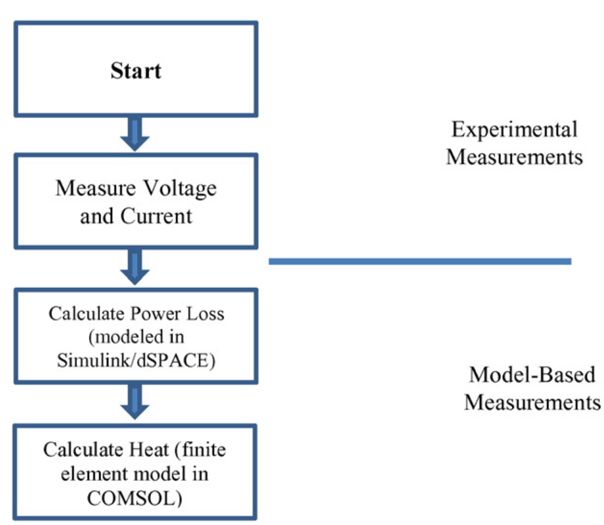

Fig. 2. Flowchart of the proposed system.