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Observer based dynamic adaptive cooling system for power modules

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ABSTRACT

This paper presents an advanced dynamic cooling strategy for multi-layer structured power electronic modules. An observer based feedback controller is proposed to reduce a power device or module's thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The full-state observer design is based on a developed Cauer type thermal model. The observer enables estimation and control of the temperature at reliability critical locations only measuring one accessible location. This makes the method particularly powerful and suitable for application in power systems. The designed strategy is confirmed experimentally. Although the experiment is developed for a specific application scenario, the proposed strategy is of general validity.

1. Introduction

In power electronics, the failure mechanisms generally can be grouped by random and wear-out failures [1–3]. Wear-out mechanism failures make up the majority of failures in power electronic modules [4]. In wear-out mechanism, thermo-mechanical stress plays a very important role in affecting power electronic devices/modules reliability [1,5], such as fracture propagation and degradations in solder layers [6], wire-bond lift-off [7] and emitter metallization [8]. The failure mechanisms are influenced by both environmental and load conditions [9, 10]. To address this issue, research has addressed different aspects, for example, new semiconductor and material technologies [11,12], package architecture [13], interconnection [14], control of power electronic modules [15] and advanced cooling technologies [5,16].

Fig. 1 describes a summary of the results of extensive reliability tests on IGBT power modules [17]. These results clearly indicated that, over the considered temperature range, a power module operational lifetime depends mainly on two parameters: 1) the amplitude of the thermal cycles, ΔT, that the module experiences; and 2) the average operational temperature, Tm. Fig. 1 clearly shows that if ΔT is reduced by even the same amount that Tm is increased, a much higher number of cycles to failure can be achieved. For instance, moving from point 1 to point 2, as ΔT is fixed at 50 K, increasing Tm by 20 K from 80 (353.15 K) to 100 (373.15 K), the cycles to failure will be reduced by 3×10^5 cycles from point 1 (5×10^5 cycles) to point 2 (2×10^5 cycles). However, moving from point 2 to point 3, keeping the same Tm, a reduction of 20 K in ΔT increases the number of cycles to failure to 2×10^6, that is, even better than the starting point 1. In other words, quantitatively, ΔT has a much more significant effect on the reliability of power modules than Tm.

Presently, typical power device thermal management only aims at ensuring that the maximum operating temperature is kept below a safety critical value at full-load or worst-case conditions and the cooling device is based on fixed designed parameters. In view of the close considerations, from a reliability point of view, this is clearly not optimum. Some temperature regulated thermal management strategies have been proposed with consideration of maintaining device operation temperature variation as small as possible [18–20]. A temperature control system is presented in [18], where the device under test (DUT) is sandwiched with a heat sink and heater. By electrically controlling the heater power, heat flow to/from the electronic device is quickly adjusted; and that in turn regulates the device temperature. This strategy is actually a heating strategy instead of a cooling strategy and it costs extra power for heating the device to a certain temperature value. The patent in [19] demonstrates a temperature controlled cooling method. In this method, the DUT is cooled by mechanically swinging the cooling fluid direction (e.g. the cooling fan facing direction) towards the heat dissipation element to regulate the temperature to a target value. However, this method requires several parallel mounted cooling fans and each fan needs a motor for swing functions, which increases the complexity of the cooling system and limits its thermal response time. In [20], a method to control the fan speed used in cooling integrated circuits is presented. In this method, a thermal diode is used to monitor device temperature, and the fan speed is adjusted by looking up a predefined temperature-speed table. There are two main shortages for

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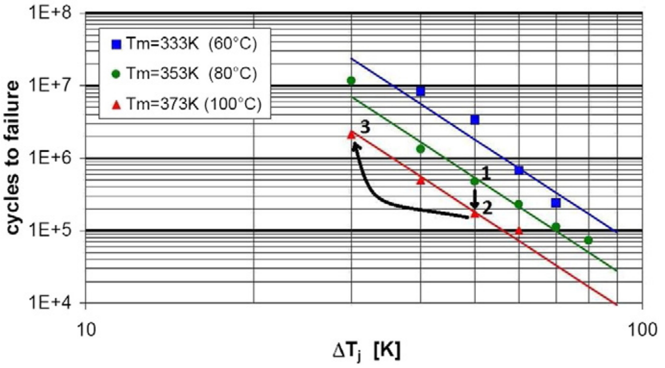

Fig. 1. Reliability of power modules as a function of thermal cycle amplitude for different values of average temperature [17].

this method: 1) a temperature sensor must be mounted inside the device; and 2) controlling cooling fan by look-up table is an open loop control, thus it is sensitive to system variations and easy to have temperature errors. Therefore, considering the reliability and temperature control issues, an observer-based adaptive cooling strategy with multi-variable feedback control technique is proposed here.

As shown in Fig. 2, the temperature with constant cooling power will vary as load changes. In order to decrease ΔT, the cooling power can be adjusted according to the load variations and this can be achieved simply by reducing the cooling power.

This paper presents an advanced dynamic cooling strategy for multi-layer structured power electronic modules. An observer based feedback controller is proposed to reduce a power device or module's thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The proposed methodology is schematically illustrated in Fig. 3.

The temperature at a reliability critical location of the power assembly is controlled against variations in the actual load and power losses P_{diss} (i.e., power dissipation) and boundary condition T_{amb} (i.e., ambient temperature). The feedback control loop monitors the temperature of the desired location T_{out} and intervenes on the cooling parameter $V_{cooling}$ to eliminate temperature errors T_{err} to control the temperature output and decrease temperature variations. The control parameter $V_{cooling}$ is the controller output signal used to control the cooling devices. It can be the bias voltage applied on the fan for a forced air convection cooling, or the voltage on the pump in a liquid cooling system. By controlling the cooling device, the thermal impedance of the system, Z_{th}, is adjusted to meet the temperature regulation. An observer based feedback controller is proposed to reduce a power device or module thermal cycle amplitude during operation, with the aim of improving reliability and lifetime. The full-state observer design is based on a developed *Cauer* type thermal model. To ensure the accuracy of the developed model, FEA (Finite Element Analysis) method is applied to derive a Cauer type thermal network where the observer is modelled on. The observer enables estimation and control of the temperature at reliability critical locations only measuring one accessible location. This makes the method particularly powerful and suitable for application in power systems. The designed strategy is confirmed experimentally. Although the case-study experiment is developed for a specific application scenario, the proposed strategy is of general validity.

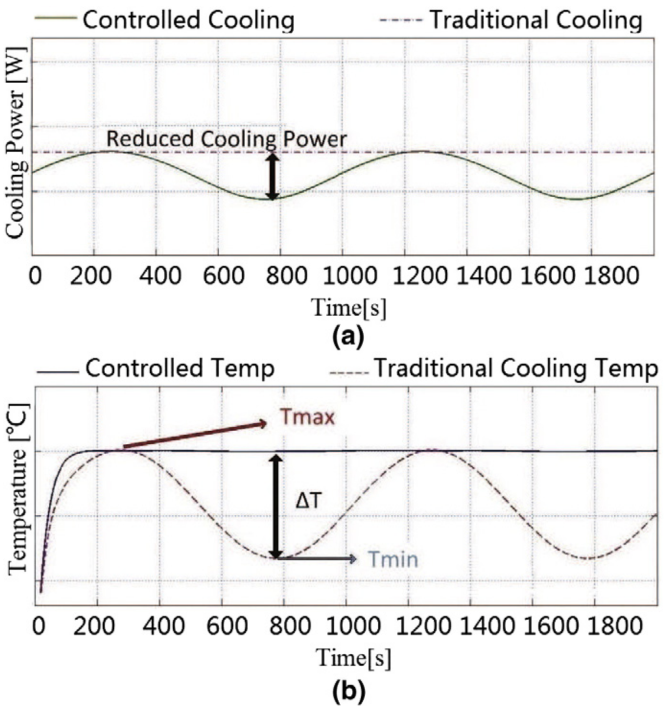

Fig. 2. Change in thermal cycling with traditional cooling approach and with the proposed cooling strategy: (a) cooling power, (b) temperature.

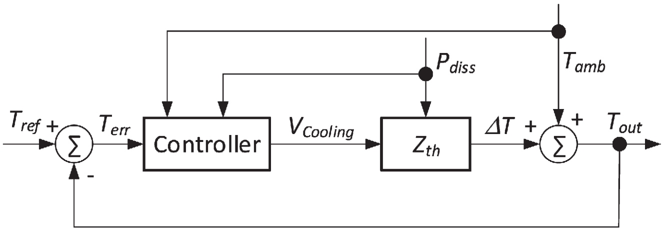

Fig. 3. Block diagram for the control design.

2. Temperature estimation

A common way to estimate junction temperature is building a real-time thermal model and match the model to experiment data to get a reference look-up table for temperature estimation [21]. This requires high accuracy physical parameters, proper initial conditions to ensure the precision of modelling, high initial efforts to build up the look-up table and basically only for junction temperature estimation. Here, the proposed temperature full-order observer is a system that provides an estimation of the internal states (temperatures) of a given real system (power module). The state-space thermal model is based on module's physical structure and material properties, thus knowing the system's inputs P_{diss} (i.e., power dissipation), T_{amb} (i.e., ambient temperature) and output (i.e., the temperature at any certain layer location inside the module), the observer will be able to calculate the junction temperature and temperatures at other layers inside the module. This allows to apply the proposed methodology both to modules with inbuilt temperature sensors [22], as well as modules without any sensing. The system states are necessary to solve many control theory problems so that the state observer can be used in investigating the critical temperature location (e.g., junction temperature or solder layer temperature) in active temperature control applications. Because the temperatures are treated as internal states in the observer, the temperature information at all physical layers can be achieved at same time.

For validation purposes a simple test assembly was produced as shown in Fig. 4, and the validation process and results are discussed in detail in early works [23]. This consists of an IGBT to be used as the heating element and a diode to be used as temperature sensor; the top surface of the IGBT (source terminal) was contacted with hollow copper bumps, into which a thermocouple (here, a K-type thermocouple was used) was inserted to provide a second temperature measurement point, much closer to the actual heat source (i.e., the IGBT chip).