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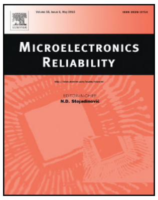

Study of reliability-efficiency tradeoff of active thermal control for power electronic systems

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ABSTRACT

Active thermal control for power modules can potentially extend the lifetime of the converter. This paper investigates the trade-off between the lifetime extension or de-rating and its cost due to the efficiency reduction. A short review on the existing approaches using control to reduce thermal stress of power modules is presented. Based on a given junction temperature profile, a method to evaluate the active thermal control's trade-off is presented. The concept is validated on a laboratory setup, where active thermal control is implemented by adapting the switching frequency. A discussion of the possible lifetime extension at the efficiency's expense is finally given.

1. Introduction

Power electronics is today a key component in new application fields like transportation or the electrical grid [1,2]. Beside the advantages of a potentially better controllability and flexibility of the system, the reliability has to be guaranteed. Failures need to be minimized to reduce the associated costs. For power electronics the thermal cycling and spatial temperature gradients are affecting aging and the related failure mechanisms are well known in literature [3,4]. The manufacturers of power electronic modules and capacitors aim at increasing the reliability of the system by improving the single components [5–7]. Usually, from the user's point of view, reliability is part of the design process, which is iterated until the reliability targets are fulfilled [8,9]. To fulfill the requirements, the system can be designed for a reduced maximum junction temperature or for higher current ratings.

It is also possible to use active thermal control to increase the reliability. The controller reduces the thermal swing of the power semiconductors and thus the thermal stress in operation. This increases the expected lifetime and consequently improves the reliability of the system. Possible implementations of active thermal control are: variable forced cooling [10–12], thermoelectric cooling [13] and electric parameters' variation [14–16]. This study focuses on active thermal control by means of the latter one.

The control of the temperature by means of active thermal control leads to the problem of increased losses and reduced efficiency of the system. Since efficiency directly influences the operation cost, an estimation of the reduced system efficiency is mandatory before the system is designed and a thermal controller is tuned. This estimation has to be based on the system design and on the real operation of the module, referred to as mission profile. Several works calculate the temperature profile of the system based on the mission profile and the system parameters [17–21]. The procedure is well known and several simulations have been presented, which analyze different applications. In these studies critical ambient and operating conditions have been detected, which limit the lifetime of the power semiconductors [22].

This work assumes the temperature profile due to the operating condition as a starting point to investigate the potential for active thermal control. Based on this junction temperature profile, a qualitative method is introduced to analyze the tradeoff between reduced thermal stress and increased system loss. For the quantification of the conflicting goals, a system without thermal control and with thermal control is considered. The implemented thermal controller applies an adaptation of the switching frequency in a full bridge converter to show the resulting lifetime enhancement or possible de-rating and the related increase in energy loss.

In Section 2 a review on active thermal control in literature is given, while in Section 3 guidelines are given how the potential of active thermal control can be estimated. Section 4 presents a thermal controller design and shows the results of the controller on a laboratory setup. Finally, in Section 5 the results are concluded.

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2. Review on active thermal control

In order to achieve high power density and low leakage inductance, semiconductors are assembled in power module configurations. To ensure electrical insulation and good heat dissipation at the same time, several layers of different materials need to be used, which is usually done in the DBC (Direct Bonded Copper) structure [23]. These materials obtain different coefficients of thermal extension [24,25] and consequently temperature gradients and temperature swings caused by the losses of the power semiconductors affect mechanical strain within the module and especially at the interconnections. This mechanism is regarded as the main reason for power modules aging [1] and leads to failures. At the bond wires, which interconnect different chips, the state of the art soldered connection can be improved with improved interconnections, i.e. sintered connections [26]. Also the gel that fills the power module, used to reduce the risk of corrosion and environmental influences [27], can be a source of aging, in particular due to the presence of partial discharges [28]. However, apart from vibration, cosmic rays and humidity caused failures, the failure mechanisms are dependent on the junction temperature and especially the temperature swing [3].

A reduction of the temperature swing increases the lifetime of the power semiconductors. If this is achieved with control actions, it is referred to active thermal control. There are several possibilities to apply active thermal control approaches on different layers of the overall control system, addressing different time periods of thermal cycles, which is summarized in Fig. 1. The short thermal cycles can be addressed with the loss control in the gate driver or the modulator, i.e. with the placement of pulses or the control of the switching frequency. These controllers are application invariant and can only be limited by regulations of hardware limitations. While the loss control acts directly on the hardware, the power electronics controller can modify the electrical parameters (voltage/current), while system controllers can implement longer-term actions by performing the energy managing/routing. In the following, examples from literature for loss control and energy routing are presented.

3. Control of power losses (stress reduction)

Several approaches are reported in literature where the frequency of the pulse width modulation (PWM) for drive application is changed in order to limit the maximum junction temperature [29–31]. The same technique is adopted in [15], where the aim is reducing the thermal cycling. The thermal controller can also influence multiple parameters, i.e., maximum current and switching frequency, while system constraints by means of an electrical machine are taken into account [32].

Changing between continuous and discontinuous 60° PWM to reduce losses was also applied in [16, 33], but needs to be considered carefully for application because of the different impact on the current ripple. A loss reduction can also beneficially affect the lifetime by decreasing the average operating temperature [34]. Furthermore, for grid-connected applications, the modulation strategy was modified to address specific problems, like the low voltage ride through (LVRT) [35], which normally increases the stress of the anti-parallel diodes of the power modules.

The smallest accessible time constants are achieved by gate driver control, which was applied in [10,36–38], mainly to balance the stress between parallel semiconductors. However, the potential to reduce the thermal cycling by increasing the power losses was also exploited.

4. Control of system loading (stress redistribution)

If the system is composed of multiple cells or multiple converters, additional high-level controls can be implemented. In [39] commutation counting was performed to select the cell to switch in a cascaded H-bridge structure. Intelligent management of the power in micro-grid has also been an object of interest in [40]. In [41] the control of parallel converter is optimized for lifetime extension, while the applied lifetime model increased the thermal stress for the components. Another approach to control the thermal cycling with multiple grid-connected inverters in a wind farm was proposed in [42],

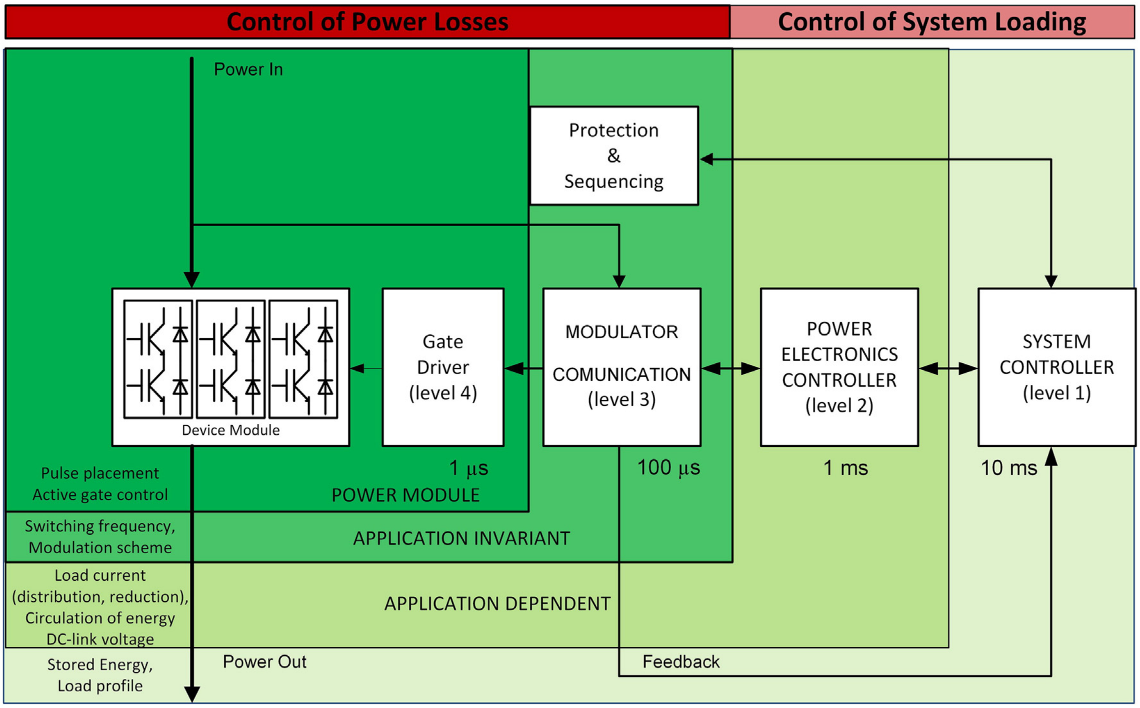

Fig. 1. Active thermal controllers in different layers of a system.

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