Electro-Thermal Modelling and Lifetime Evaluation of Power MOSFETs and Converters

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I would like to dedicate this thesis to my loving parents.

Declaration

I, Tian Cheng declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

Due to the ongoing pursuit of high-density power supplies, thermal management has become one of the most critical issues to consider during the design phase for stable and efficient operation. Therefore, this thesis implements a series of thermally related investigations such as electro-thermal modelling techniques, device lifetime prediction, and reliability assessments on cascaded H-bridge (CHB) converter-based three-phase applications.

Firstly, two electro-thermal modelling techniques are proposed for a converter. Significant efforts and progress have been made in developing electro-thermal models (ETMs) for power semiconductors and passive components individually. However, very few have considered building an ETM for a whole converter to make it more realistic in terms of converter design. Hence, in this thesis, an ETM and an electro-thermal averaged model (ETAM) are proposed for a boost converter as examples. Both the simulation and experimental results are given and compared to verify the proposed solutions. An improved electrical performance estimation and fairly accurate temperature prediction can be achieved for both models.

Secondly, a comprehensive MOSFET model that enables electro-thermal modelling, aging, and lifetime estimation on an LTspice® circuit simulator is proposed. This model is also concise as it eliminates the need for multiple software platforms and is comprised of simple electrical circuits. This work is motivated by the fact that power MOSFETs have relatively low reliability as compared to other power components but have high penetration in current power systems. Therefore, it is essential to monitor their state of health to ensure system reliability. Additionally, the aging of a MOSFET is not considered in most reported

work but has an impact on device lifetime. Based on these concerns, the comprehensive MOSFET model is proposed. High-stress thermal cycling and long-term random mission profiles are applied to verify the correctness of the model. An accelerated aging trend can be observed in the long-term mission profile simulation, which is in agreement with the theory. Additionally, the fast simulation speed indicates that the proposed method is a good simulation/analytical tool to implement a long-term mission profile reliability assessment.

Thirdly, a circuit-based rainflow counting algorithm is elaborated aiming to improve the thermal cycle counting accuracy for the comprehensive MOSFET model proposed above. The rainflow counting algorithm is gaining popularity for its low relative error in fatigue analysis and device lifetime estimation. Nevertheless, the offline operation limits the device in considering other parameters, such as aging and the current state of health in the lifetime estimation, as it requires a complete loading profile to run recursive comparisons. This work proposes to tackle the issue and integrate it into a circuit simulator. Results show that the proposed method improves the counting accuracy, with an averaged error of 3.5% over that of the half-cycle counting which is 24.4% under different load stresses and length conditions, and it can be improved still further.

Finally, with the ETM and the lifetime assessment methodology outlined above, Wye (Y)- and Delta (Δ)-connected 5-level CHB converter-based three-phase systems are compared. The comparisons are from electrical, thermal, and lifespan aspects, particularly when the two systems deal with unbalanced power generation among phases. Recent studies have pointed out the superior power balancing capability of Δ- over Y-connection with zero sequence injection (ZSI). However, few studies have considered this from the reliability point of view, as ZSI has different influences on the two configurations. Reported results have verified that even though the Δ-connection can handle more severely unbalanced power, it will not only lead to an unequalled stress distribution among phases but may also overstress devices in some cases. However, the Y-configuration does not have this issue. Consequently, there is a trade-off between electrical and thermal operation which requires careful consideration when selecting the best configuration to deal with power imbalances.

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