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Converter-level FEM simulation for lifetime prediction of an LED driver with improved thermal modelling

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ABSTRACT

Light-emitting diode (LED) drivers are widely regarded as the weakest link in the solid-state lighting systems. This paper proposes an improved thermal modelling process for the mission profile based lifetime prediction of reliability critical components in a LED driver for the outdoor lighting application. A converter-level finite element simulation (FEM) simulation is carried out to obtain the ambient temperature of electrolytic capacitors and power MOSFETs used in the LED driver, which takes into account the impact of the driver enclosure and the thermal coupling among different components. Therefore, the proposed method bridges the link between the global ambient temperature profile outside of the enclosure and the local ambient temperature profiles of the components of interest inside the driver. A quantitative comparison of the estimated annual lifetime consumptions of MOSFETs and capacitors are given based on the proposed thermal modelling process, and the datasheet thermal impedance models and the global ambient temperature.

1. Introduction

A light-emitting diode (LED) driver is the power supply for a LED lighting system to provide a regulated DC current source. Meanwhile, the LED driver is widely recognized as the weakest link in a lighting system composed of LEDs, LED drivers, and auxiliary components [1], due to an incompatible lifetime with one of LEDs (in the range of 25,000–100,000 h) [2]. In a survey of more than 5400 outdoor LED luminaires, 59% of failures are related to the LED drivers [3]. Among the internal components, electrolytic capacitors and power semiconductor devices are among the vulnerable components which cause the failure due to wear out issues [4,5]. Thus, physics of failure (PoF) understanding and proper lifetime prediction of those critical components are essential to design LED drivers with the fulfilled lifetime target while avoiding over-engineering.

Many research efforts have been made to the PoF based reliability assessment of power converters [6–8]. However, predicting the lifetime of a converter that operates in complex conditions is still a challenge. One of the major limitations of state-of-the-art methods is ignoring the inconformity of the globally environmental ambient temperature and local ambient temperature around components, as shown in Fig. 1. In existing methods, the individual component is always regarded as an impendent thermal network by neglecting the thermal couple from components and the impact of an enclosure. Then the surrounding ambient temperature of a component is empirically estimated. Additionally, a similar local ambient temperature of different components is commonly assumed and adopted to evaluate the component reliability. This may lead to an underestimation or overestimation of component-level thermal stresses, consequently an inaccurate lifetime.

The mission profile shows the operating conditions and functions during the lifecycle of a converter, which is closely related to the stresses of the components. In street lighting applications, the LED driver usually runs in the off mode during the daytime, while in the active mode during the night, as illustrated in Fig. 2. Due to the high latitude, such as at Aalborg, the lighting time of a LED system varies greatly in summer and winter. The thermal stresses of components are completely different due to the power dissipation of power semiconductors and passive components as well as the fluctuation of the environment temperature.

This paper introduces an approach to predict the lifetime of LED driver considering the ambient temperature distribution of the LED driver and its real operating mission profile. In Section 2, Icepak based FEM simulation of the LED driver is described to estimate the temperature contour of an enclosed LED driver. Then, combining the simulation results and the thermal impedance of components, Section 3 analyses the thermal stress of capacitors and MOSFETs during different operating modes. In Section 4, the annual lifetime consumptions of the capacitor and MOSFET are estimated and the predicted lifetime of the LED driver

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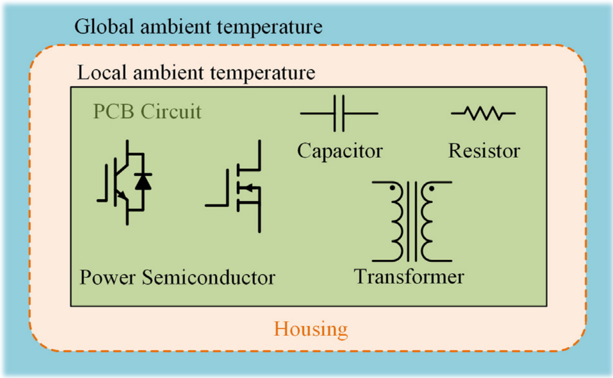

Fig. 1. Inconformity of the global ambient temperature and local ambient temperature.

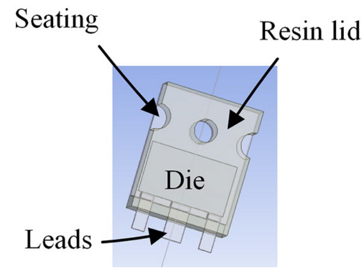

Fig. 3. Approximate geometry model of MOSFET.

is given considering the variations of the evaluated stresses and the lifetime model. Finally, the concluding remarks are given in Section 5.

2. Converter-level FEM thermal simulation of an LED driver

Thermal-related failures extensively exist in power electronics components and the temperature is one of the most important root causes. In this section, converter-level thermal simulation of an enclosed LED driver is carried out by the FEM method.

2.1. Thermal modelling

The LED driver is a single-stage power factor correction (PFC)-based flyback converter and the detailed schematic is illustrated in [9]. On the basis of manufacturer information, most components are simplified by cylinders and cuboids to reduce the computational cost. Except for the MOSFET in TO-247 package, as shown in Fig. 3, it is approximately modelled with a 2D silicon die, a resin lid, a metal seating, and three leads. This allows the FEM model of MOSFETs to be tuned by the heat transfer coefficient. Additionally, to accurate compute the varying orthotropic thermal conductivity of printed circuit board (PCB), the trace and via geometry are modelled according to the electronics computer-aided design (ECAD) data. Finally, the model including its enclosure is shown in Fig. 4. Five points marked in the figure are selected as validation points that are measured by thermocouples and the temperature contour is obtained by an infrared camera.

2.2. Simulation results

The power dissipation of primary components is evaluated by measurement or datasheet based calculation. The LED driver is operating in the condition of natural air convection at 100 W and the ambient temperature of simulation is set as 25 °C. The simulated temperature contour can be seen in Fig. 5. The comparisons between measured temperatures and simulated ones of testing points are shown in Fig. 6. The relative errors of testing points are below 5%. The y-z cut planes of the electrolytic capacitor and the MOSFET, including the surrounding temperature, are shown in Fig. 7. It can be seen that the minimum ambient temperature inside the device is about 12 °C higher than the global ambient temperature, while there is a 17-°C difference of local ambient temperature between the capacitor and the MOSFET, due to the different power dissipation of their adjacent components.

3. Thermal stress analysis of components

After the converter-level thermal simulation, each component can be regarded as an independent thermal system with an input ambient temperature from the simulation. Then, according to the thermal impedance of components, their thermal stress profiles are evaluated.

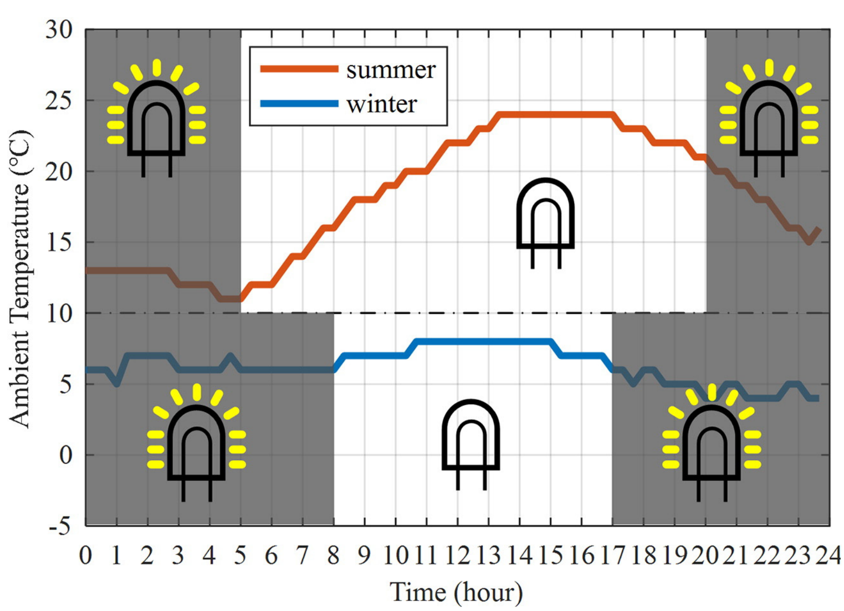

Fig. 2. Two typical daily mission profiles in summer and winter, respectively (sample rate: 20 min).

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