A Lifetime Prediction Method for Solid State Lighting Power Converters Based on SPICE Models and Finite Element Thermal Simulations

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Abstract

Solid State Lighting (SSL) power converters are considered as the reliability bottleneck of a light emitting diode lighting system. This paper proposes a lifetime prediction method for solid state lighting power converter based on SPICE models and finite element thermal simulations. This method consists of four major parts: lifetime meter, components decay models, SPICE simulator and finite element simulator. The estimated lifetime can be obtained by a number of iterations of electronic and thermal performances of the interested power converter.

Key Words: SSL, LED, Power converter, Lifetime, SPICE, FEA

1. Introduction

As the next generation lighting approach, Solid State Lighting (SSL) has great advantages of energy-saving and smart lighting, provides a larger degree of freedom for lighting design than conventional lighting. With the help of new semiconductor materials and technologies, SSL light source, the light emitting diode, has a much longer lifetime than incandescent compact fluorescent lamps. However, due to the limits of cost and operation conditions, SSL power converter is an unreliable power electronic device in a SSL system. According to reports from both academia and industries, SSL power converters are considered as the reliability bottleneck of the whole system.

Firstly, a high performance SSL power converter has a complicated structure and thus a large number of failure modes [4], such as electrolytic capacitor failure, solder cracking, semiconductor device breaking down, etc. Although there are many researches on components' reliability, a few publications reported simulation methods considered reliability models of these components. Secondly, failure of SSL power converter is a multi-physical problem, stresses like voltage/ current, temperature, humidity can damage the SSL power converter, leading a system-level failure. Besides, design for reliability of the SSL system attracts increasing research interesting in recent years, the most significant part of design for reliability is lifetime prediction. Therefore, it is necessary to develop a lifetime prediction method for SSL power converter that could integrate component's reliability models in multi-physical conditions.

This paper proposes a lifetime prediction method for solid state lighting power converter based on SPICE models and finite element thermal simulations. Over three decades' development, the simulation tools for Finite Element Analysis (FEA) and Simulation Program with Integrated Circuit Emphasis (SPICE) are well developed and can provide accurate electronic and thermal simulation results with appropriate models for an SSL power converter. In this method, iterations combine electronic and thermal simulations will be carried out until the performance of the SSL power converter satisfies the failure criteria. With appropriate SPICE models, the heat generation and electronic characteristics of each component can be obtained by SPICE simulations; meantime, the core or junction temperatures of these components can be obtained by finite element thermal simulations. By substitution of core or junction temperatures and operation hours into components' reliability models, the SPICE parameters after degradation can be calculated for next iteration. Finally, the lifetime of the interested SSL power converter is the production of the operation time interval and number of iterations when its performance satisfies the failure criteria. In the following section, this lifetime prediction method for SSL power converters will be discussed in details.

2. The Lifetime Prediction Method

As mentioned in Section 1, this lifetime prediction method for SSL power converters integrates SPICE simulation, finite element thermal analysis, and components' reliability model. Figure 1 illustrates the flowchart of this lifetime prediction method, which consists with four major parts: lifetime meter, components decay models, SPICE simulator and finite element simulator, and two iterations: the major iteration and the secondary iteration. The major iteration consists with lifetime meter, component reliability models and SPICE simulator, which stops when performances of the SSL power converter exceed its failure criteria. The secondary iteration consists with component reliability models, SPICE simulator and finite element simulator, it stops when the SPICE parameters for performance simulations converge at a steady value. Obviously, if the SPICE models contain temperature dependent parameters

978-1-4799-4790-4/14/$31.00 ©2014 IEEE

(TDPs), more than one loop of secondary iteration should be carried out to obtain accurate SPICE parameters.

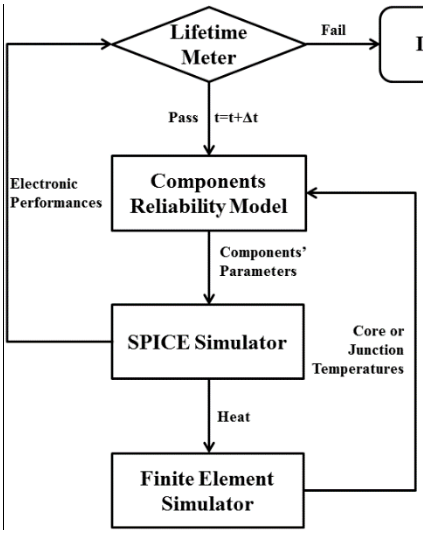


Figure 1: Flowchart of the Lifetime Prediction Method for SSL Power Converters

Although there are various failure modes, failure of SSL power converters are determined by its electronic performances. Essence of lifetime prediction is find the time that electronic performances of the interested SSL power converter have enough deviations which can be considered as failures. The lifetime meter contains a comparator which can compare electronic performances of an SSL power converter after certain hours' operation calculated by the SPICE simulator with their initial value. The operating hours of the target SSL power converter will be increased by a certain step Δt for each loop of the major iteration until its performances exceed their failure criteria. Total operation hours of the target SSL power converter is the production of the operation time interval and number of iterations. All iterations will be stopped when the performances exceed their failure criteria. The lifetime prediction result is between total operation hours of last iteration and the one before last iteration. Obviously, the lifetime prediction accuracy is controlled be the value of Δt.

Similar to other electronic devices, SSL power converter consists with many types of components, such as semiconductor devices, surface mount devices, solder joints, electrolytic capacitors, inductors and transformers, which have disparate operation conditions and failure modes. The decay model for a component which is a set of SPICE parameter distribution model over time and operation conditions, can describe failures of a component. Theoretically, a component decay model has several input variable, includes total operation duration Δt and operation conditions, such as temperature, humidity and etc. And the output of this model is the set of SPICE parameter degradation for the SPICE simulator to calculate the performance of the entire system. This method assumes degradation rate distribution which is determined by operating conditions is stable during each iteration step length Δt, thus the degradation amount of these SPICE parameters follow their own distribution. As a result, one possible estimated lifetime can be obtained at the end of the iteration, and estimated lifetime distribution can be obtained if the number of iterations is large enough.

Theoretically, degradations of all components in an SSL power can be considered in this method, but only major failures and critical components are considered in practice. On one hand, some types of components have a complicated SPICE code, but less impact on the system's performance. On the other hand, some types of failures have tiny possibility and hardened to be described by current reliability models. Hence, this method carries out the FMMEA for an SSL power converter, determining the major failures and critical components, before lifetime prediction.

The failures of an SSL power converter are defined by its electronic performances. Thus, in this method, a SPICE simulator is used for the calculation of its performances. SPICE (Simulation Program with Integrated Circuit Emphasis) is a mature general-purpose analog electronic circuit simulation tool based on electronics and physics, which used to predict circuit behavior in IC or board level. This method firstly establishes the net-list of the SSL power converter circuit by its circuit schematic, and then imports this net-list and SPICE parameters of each component from component decay models into a SPICE simulator which could calculate the performances at last. It is common sense that the junction temperatures or core temperatures of components which are determined by self-heating is significant to system's lifetime. The SPICE simulator can obtain active power which is usually considered as self-generated heat of each component for the junction temperatures or core temperature calculation by the finite element simulator.

Owing to the significant impact on reliability, many methods were developed for junction temperature or core temperature estimation in solid state lighting. The finite element stable-state thermal analysis is one of accurate approaches. In this method, the finite element model of an SSL power converter, consists with component models, is built by the finite element simulator, and then the active powers of each component and boundary conditions were applied to the finite element model to calculate the junction temperature or core temperature of each critical component for a next iteration loop. For SPICE parameters of each critical component were assumed to be stable in one iteration loop, its self-generated heat and thus junction temperatures or core temperatures keep constant during this iteration loop.

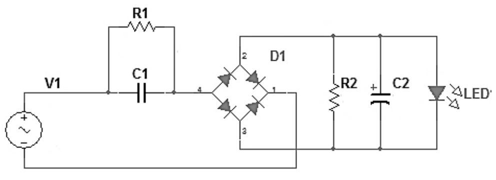
3. Validations and Discussion

(a) (b)

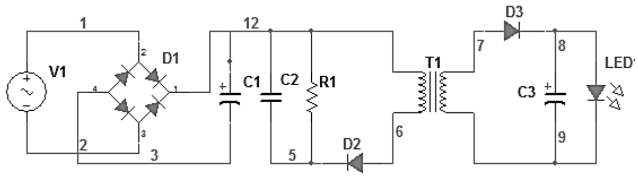
Figure 2 Power Converters for Validation

To validate this lifetime prediction method for SSL power converter, this work concerned with two basic types of SSL power converters: (a) an RC voltage-reducing converter and (b) a fly-back converter, as shown in Figure 2 and 3.

The RC voltage-reducing converter consists with surface mounted resistors, a bridge rectifier and electrolytic capacitors which are the most critical components; the fly-back converter consists with surface mounted resistors, a bridge rectifier, two power diodes, a transformer and electrolytic capacitors. Besides electrolytic capacitors, the transformer is also a critical component of the fly-back converter.



(a) RC Voltage-Reducing Converter



(b) Fly-back Converter

Figure 3 Schematics of Validation Power Converters

(1) Reliability models for critical components

According to industry experiences and academic studies [4, 5], major failure modes in such kind of SSL power converters are degradation of electrolytic capacitors and transformer. Degradation of the electrolytic capacitor at output end may lead current ripple increasing; degradation of the transformer has great impact on output character of a SSL power converter. The previous researches [2, 7] suggest that, as shown in Figure 4, an electrolytic capacitor has two major parameters: capacitance and equivalent series resistance (ESR). The equivalent series inductance is too small to be considered in this work.

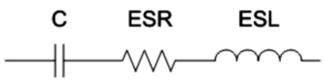


Figure 4 Reliability Models of Electrolytic Capacitor

As shown in Figure 5, for constant core temperature, the degradation of capacitance and ESR follow the model of:

$$C(t) = C_0 - At;$$
$$ESR(t) = ESR_0 \cdot \exp(B \cdot t);$$

Where, t is operation duration, C(t) and ESR(t) are capacitance and ESR at time t, C_0 and ESR_0 are initial capacitance and ESR value, A and B are degradation rates which follow the Arrhenius Equation:

$$R = \alpha \cdot exp(-E_a/\kappa T)$$

Where, E_a is the activation energy, k is the Boltzmann Constant and T is the junction or core temperature in Kelvin.

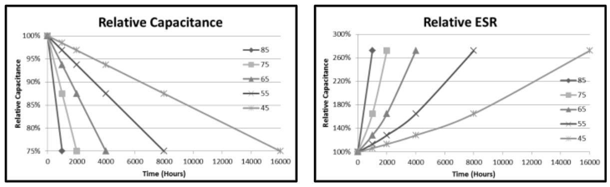


Figure 5 Reliability Model for Electrolytic Capacitors

Similar to an electrolytic capacitor, the major parameter of a transformer is the coupling value. As shown in Figure 6, this work supposes that the coupling value degradation follows the linear model:

$$K(t) = K_0 - At;$$

Where, it is operation duration, L (t) is inductance at time t, L_0 is initial inductance, A is a degradation rate which follow the Arrhenius Equation [8].

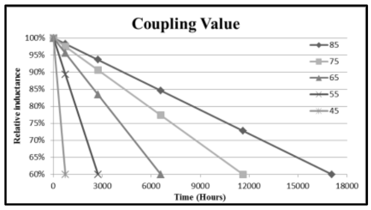
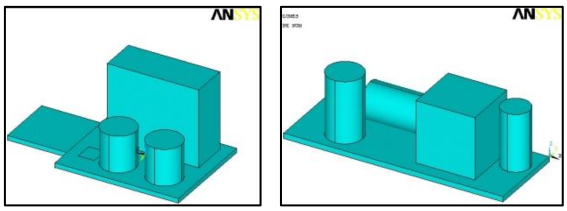


Figure 6 Reliability Model for Transformers

(2) SPICE and FE models for critical components

The SPICE net-lists can be established by their circuit schematics shown in Figure 2 with initial component parameters as circuit design. As shown in Figure 7, the finite element models were established by their system layouts with the material characteristics listed in Table-1.



(a) RC Voltage-Reducing, (b) Fly-back

Figure 7 Finite Element Models of Power Converters Validation

Table-1 Material Characteristics of FE Models

Material	Thermal conductivity
FR4	0.25
Electrolytic Material	3~5e-5
Cu	377
Package Material	1.38～1.73

Considering the real operation condition, we assume the ambient temperature is 45℃. According to current test standards, three performance indicators are considered as the failure criteria for lifetime prediction: output voltage, output current and current ripple, which are significant for these SSL power converters. A power converter with output voltage/ current deviations larger than 10% of the initial value, or ripple content larger than 20% will be considered as failed [6].

(3) Lifetime Predictions

Figure 8 displays the core temperature simulation result of electrolytic capacitors by the finite element simulator. Operation in the system, the core temperature of these electrolytic capacitors increases with its degradation. More importantly, critical components' degradations have significant impact on the system's performance depreciation. Thus, system's lifetime is shorter than the expected lifetime of critical components.

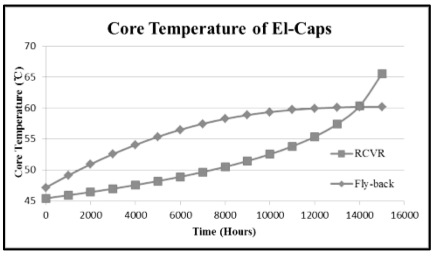


Figure 8 Core Temperatures of Electrolytic Capacitors

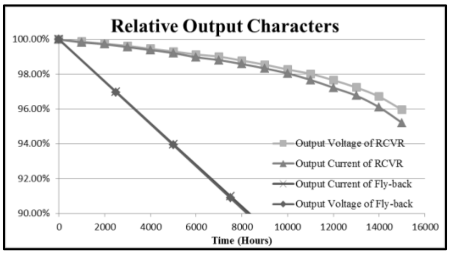


Figure 9 Relative Output Characters Depreciations

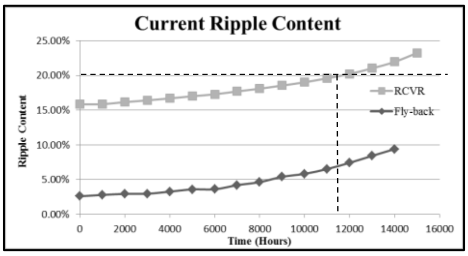


Figure 10 Current Ripple Content Increasing

As shown in Figure 9 and 10, this method well simulated failure modes of these two types SSL power converters. The failure mode of the RC voltage-reducing converter is current ripple increasing lead by degradation of the electrolytic capacitor at output end; the failure mode on the fly-back converter is output depreciation lead by degradation of the transformer. The RC voltage-reducing converter fails after 12'000 hour operation, which is shorter than an electrolytic capacitors' expected lifetime. Meanwhile, the lifetime of fly-back converter is about 8'000 hours. Compare to conservative weakest-link lifetime estimation method, this result is closer to industry experience. Obviously, prediction results by this method depend on the component reliability models. Accurate reliability models can give an estimated lifetimes close to realities. Thus, understanding of failure modes and establishing accurate reliability models are crucial for lifetime prediction of SSL power converter by this method.

4. Conclusions and Future work

This paper proposes a lifetime prediction method for solid state lighting power converter based on SPICE models and finite element thermal simulations. This method focuses on the interaction between electronic and thermal characters of an SSL power converter. According to validation results, this method well simulated failure modes of validation SSL power converters. Compare to conservative weakest link lifetime estimation method, this method gives prediction results closer to industry experience. However, the prediction results depends on the component reliability models. Understanding failure modes and establishing accurate reliability models are crucial to lifetime prediction. There are few data about the degradation of SPICE models of board-level components.

More validations are still undergoing on simulations and tests of more complicated SSL power converters with component reliability distribution models which consider more types of stresses in realities.

Acknowledges

Authors want to thank State Key Laboratory of Solid State Lighting (China) for financial support of this project, and the companies who provide the samples for the validation simulations and tests. The authors also thank to SKL colleagues, Ms. Hongyu Tang and Mr. Zenghui Fan, for the FEA simulations and regular electronic testing.

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