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A Reliability Prediction for Integrated LED Lamp with Electrolytic Capacitor-Free Driver

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***Abstract*—This paper studies the interaction of catastrophic failure of the driver and LED luminous flux decay for an integrated LED lamp with an electrolytic capacitor-free LED driver. Electronic thermal simulations are utilized to obtain the lamp's dynamic history of temperature and current for two distinct operation modes: constant current mode (CCM), and constant light output (CLO) mode, respectively. Driver's mean time to failure (MTTF), and the LED's lifetime in term of luminous flux are calculated. Under CLO mode, the LED's current increases exponentially to maintain the constant light output. As a result, the junction temperatures of LEDs, MOSFETs and power diodes in driver rise significantly, leading to a much shorter MTTF, and faster luminous flux depreciation. However, under the CCM mode, the junction temperatures of LEDs, MOSFETs and diodes change modestly, therefore, the driver's MTTF and LED's luminous flux decay are not affected much by the variation of temperatures during LED's degradation process.**

***Index Terms*— LED Lamp, Electrolytic Capacitor-Free Driver, Electronic Simulation, Thermal Simulation, Catastrophic Failure, Fault Tree, Reliability, Lifetime.**

I. INTRODUCTION

An LED lighting system (lamp or luminaire) is mainly comprised of an LED light source module, a driver, control gears, secondary optical parts, and heat dissipation components [1]. In the past decades, numerous studies have been focusing on the performance and reliability of LED itself [2-11]. A typical LED light source now has a lifetime as long as 25,000 - 100,000 hours in terms of luminous flux maintenance [1, 12]. However, the driver's life is usually much shorter than the light source's, in particular, if electrolytic capacitors are utilized [13-15]. A physics-of-failure (PoF) based reliability prediction methodology has been developed to estimate the failure rate distribution of electrolytic capacitors in LED drivers [13]. In recent years, many electrolytic capacitor-free topologies have been developed with more reliable components [16-18], including thin film capacitors [19] and LC filters [18]. In addition, several new control technologies can also improve the lifetime of electrolytic capacitors, for instance, the resonance-assisted filter [20] and the variable on-time control method [21]. The lifetime of the LED driver may be extended to match the LED light source lifetime [22].

Generally, the lifetime of an LED is given in terms of the expected operating hours until light output has depreciated to 70% of the initial level. The catastrophic failure of an LED driver depends on its critical components and their operation conditions, such as the MOSFETs and power diodes [23-25]. The total rate of catastrophic failures determines the mean time to failure (MTTF) for the driver. There are two distinct concepts of lifetimes involved in an LED system: mean time to failure (e.g. driver), and LED's lifetime in terms of luminous flux depreciation. When these two lifetimes are far different, it is obvious that they do not interact with each other. For example, if driver's MTTF is much less than LED's lifetime, the eventual LED lamp's lifetime is determined by driver's MTTF since the catastrophic failure of the driver will result in the complete light out. However, few study has been conducted to investigate the reliability of LED lamp when the driver's MTTF is comparable to the LED's lifetime.

This paper studies the interaction of driver's catastrophic failure and LED's luminous flux decay for an integrated LED lamp with an electrolytic capacitor-free LED driver. A fly-back converter with an LC filter is used in the present study. The overall catastrophic failure rate of the critical components in the driver are considered as functions of temperature and current. Electronic thermal simulations are utilized for a commercial LED bulb to obtain the lamp's dynamic history of temperature and current. Two distinct operation modes are considered: constant current mode (CCM), and the constant light output (CLO) mode, respectively. The LED's lifetime in terms of luminous flux is calculated using LED's degradation model. A fault tree is applied to calculate the driver's MTTF.

This paper is organized as follows. Section II describes the general methodology. In Section III to V, the circuit models, LED's degradation model, the thermal models and the failure rate models are introduced respectively. Section VI defines different modes and discusses the results. Section VII concludes this work finally.

II. GENERAL METHODOLOGY

Fig.1 displays the general methodology which integrates the electronic thermal simulation with the fault tree method to obtain both the LED's luminous flux decay and driver's probability of catastrophic failures and MTTF. For a given LED system, such as an LED lamp with an integrated driver, electronic simulations are applied to obtain the power distribution of each component in driver and also input power to LEDs. Based on the system's structure and material properties, thermal simulations, which combine both system-level thermal modeling and compact models, are conducted. An iteration process is necessary at each operation time point to determine the state of temperature under operating conditions. Details of the electronic thermal simulation can be found in our previous [13, 26]. Through the electronic thermal simulation, the junction temperature of the LED light source, the current of the driver, and the lumen output can be obtained. LED's luminous flux decay can be calculated based on the calculated results of current and junction temperature using LED's degradation model. The driver's probability of failure and MTTF can also be calculated according to the the failure rate models of critical components. In the following, the details of electronic simulation, the LED's degradation model, the thermal simulation, as well as the MOSFET and diode's failure rate model in driver, are described.

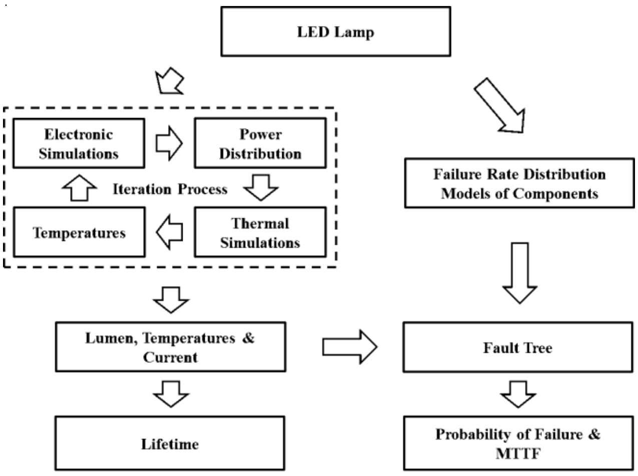

Fig.1 General Methodology of The Proposed Approach

III. ELECTRONIC MODELS

A. Driver Circuit

Fig.2 displays a flyback driver with an LC filter. The LC filter can store energy as capacitors, thus, it is considered as one of the most cost-effective electrolytic capacitor elimination approaches [18, 27]. In this circuit, the models of all components are well validated and verified by manufacturers [28]. The rated input power of the entire driver is 6.3W, and the rated input power is about 5.2W. Ideal feedback units and a current control unit are added, making this driver have two operation modes: the constant current mode (CCM) and the constant light output mode (CLO). In the constant current mode, the current from the driver to the LED light source remains unchanged. The current can be adjusted to achieve invariant light output in CLO mode.

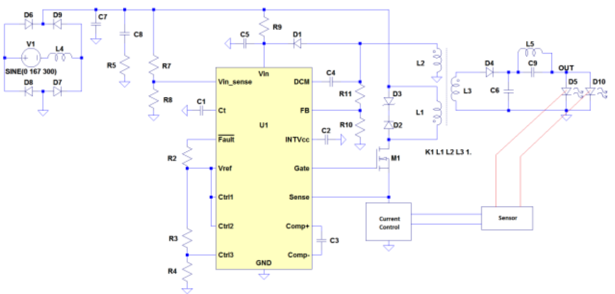

Fig.2 A Fly-Back Driver Circuit with LC Filter

B. LED Light Source

A temperature-dependent model for LED light source is considered in the circuit model in Fig.2. The luminous flux is a function of the ever-changing junction temperature $T_j(t)$ and current $I_{LED}(t)$. Thus the luminous flux $\Phi_{lm}(t)$ can be described by the following function:

$$\Phi_{lm}(t)=\begin{cases}\eta_0\cdot\dfrac{B_e I_{LED}(t)^2}{A_e+B_e I_{LED}(t)+C_e I_{LED}(t)^2}\cdot V_f\cdot e^{-\int_0^t \beta[T_j(x)]\cdot dx} & (T_j<T_{MAX})\\ 0 & (T_j\geq T_{MAX})\end{cases} \quad (1)$$

where η_0 is the basic efficacy, A_e and C_e are the linear and the 3rd-order non-radiative recombination rates, B_e is the radiative recombination rate, V_f is the forward voltage, and β is the depreciation rate that follows the Arrhenius equation [15]:

$$\beta(T_j)=A_\beta\cdot e^{-\frac{E_{a,\beta}}{\kappa\cdot T_j}} \quad (2)$$

The performance of an LED light source can be described by the following function [29]:

$$V_f[I(t),T_j(t)]=N\cdot\kappa\cdot T_j(t)\cdot\ln[\frac{I(t)}{I_s}+1]+R_s\cdot I(t) \quad (3)$$

where, N is the ideality factor, κ is the Boltzmann constant; I_s is the saturation current, R_s is the equivalent series resistance of the LED. The R_s, I_s and N can be described by the following functions [29-31]:

$$N[T_j(t)]=\frac{T_j(t)}{A_N\cdot T_j(t)+B_N} \quad (4)$$

$$R_s[T_j(t)]=R_{s0}\cdot[1+A_s\cdot T_j(t)] \quad (5)$$

$$I_s[T_j(t)]=I_{s0}\cdot T_j^2(t)\cdot e^{-\frac{A_I}{T_j(t)}} \quad (6)$$

The details of the LED models mentioned above can be found in the literature [26, 32].

IV. THERMAL SIMULATION

A commercial LED bulb is selected as the carrier of the present study. As shown in Fig.3, it consists of a bulb cover, LED light source, heat sinks, a driver and other relevant parts. The light source of this lamp includes 24 LED packages mounted on a metal board. The original driver in this lamp is replaced by the electrolytic capacitor free driver shown in Fig.2 for the purpose of the study in this paper.

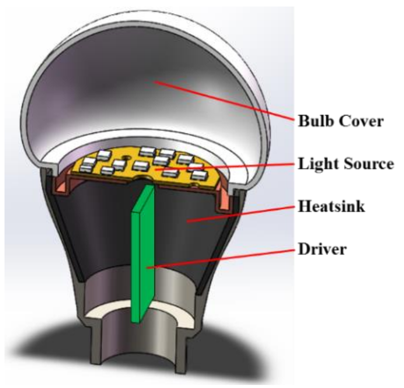

Fig.3 The Model of the selected LED Lamp.

The heat sources come from the LEDs and the driver's components. System level thermal simulations are conducted to calculate the LEDs' junction temperature T_{LED} and air temperature around the driver T_D. The driver (the green part in Fig.3) is considered as homogenous material with heat from the driver distributed evenly on surface. The lamp operates in room temperature (298K) with a natural convection condition. Table I lists material properties used in system level thermal simulations.

Table I Thermal Material Properties

Part	Thermal Conductivity
Bulb Cover	0.2W/(m·K)
LED Board	12W/(m·K)
Heatsink	110W/(m·K)
Driver	0.15W/(m·K)
LED Package	5W/(m·K)

The thermal compact model of each critical component in the driver is applied to find their junction temperature:

$$T_{j,i} = T_D + R_{th,i} \cdot P_{th,i} \tag{7}$$

where $T_{j,i}$ is the the junction temperature of the component, $R_{th,i}$ is the thermal resistance from junction to surface of the component which is usually provided by components' datasheets, $P_{th,i}$ is the thermal power of the component.

To validate the system level thermal simulation, temperature distribution of the lamp is tested. The lamp is place in the room temperature (298K) and natural convection condition. The temperature at each point is measured by a thermocouple system. Fig.4 displays the simulation results, and Table II compares the test and simulation results. Errors between the simulation and test results are less than 1K.

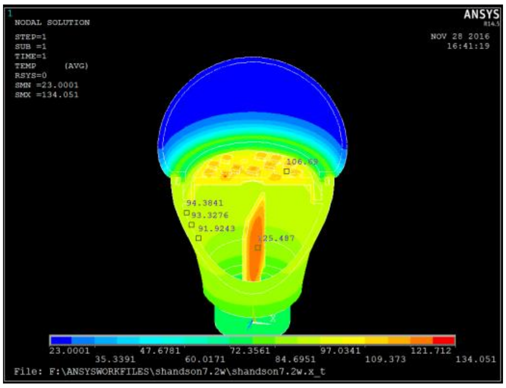

Fig.4 Temperature Distribution from Finite Element Analysis

Table II Simulation and Test Results

Position	Simulation Results		Test Result	Error
Light Source	379.7K	106.7℃	379.4K	0.290K
Heatsink 1	367.4K	94.4℃	367.1K	0.264K
Heatsink 2	366.3K	93.3℃	366.0K	0.268K
Heatsink 3	364.9K	91.9℃	365.5K	0.596K
Driver	398.5K	125.5℃	398.6K	0.103K

V. FAULT TREE AND FAILURE RATE MODELS

The catastrophic failures of the MOSFET M1 and the Diode D4 in the circuit shown in Fig.2 are considered. Assuming that the failures of M1 and D4 are independent to each other, the probability density of the catastrophic failure of the driver can be described by the following function:

$$f_{Driver}(t) = f_M(t) + f_D(t) - f_M(t) \cdot f_D(t) \tag{8}$$

where $f_{Driver}(t)$ is the failure probability density of the driver at time t, f_M is the failure probability density of M1, f_D is the failure probability density of D4. Eq.(8) is described by a fault tree shown in Fig.5.

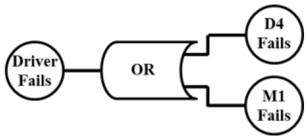

Fig.5 the fault tree of the LED driver

The failure probability density of a MOSFET can be described by the inverse power law [34]:

$$f_M(t) = f_M[I_M(t), T_M(t)] = f_{M0} \cdot [\frac{I_M(t)}{I_{rated}}]^p \cdot e^{-\frac{E_{a,M}}{k}[\frac{1}{T_M(t)} - \frac{1}{T_A}]} \tag{9}$$

where $I_M(t)$ is the average current of the MOSFET at time t, $T_M(t)$ is junction temperature of the MOSFET at time t, f_{M0} is the failure probability density of the MOSFET in rated current I_{rated} and typical ambient temperature T_A=298K, p is the current accelerated coefficient and $E_{a,M}$ is the activation energy of the MOSFET.

The failure probability density of a diode can be described by the Arrhenius equation [34]:

$$f_D(t) = f_D[T_{Di}(t)] = f_{D0} \cdot e^{-\frac{E_{a,D}}{k}[\frac{1}{T_{Di}(t)} - \frac{1}{T_A}]} \tag{10}$$

where, f_D is the failure probability density of the diode, $T_{Di}(t)$ is junction temperature of the diode at time t, f_{D0} is the rated failure probability density of the diode in typical ambient temperature T_A =298K, $E_{a,D}$ is the activation energy of the diode.

The conditions $I_M(t)$, $T_M(t)$ and $T_{Di}(t)$ at each operation time point can be obtained by the electronic thermal simulations, and thus, the failure probability densities f_M, f_D and f_{Driver} at each time point can be calculated by Eq.(8) to (10). Then, the mean time to failure (MTTF) of the driver can be calculated by the following equation:

$$MTTF = t_{MAX} / \int_0^{t_{MAX}} f_{driver}(t) \cdot dt \tag{11}$$

where t_{MAX} is the total operation duration. In order to simply the calculation, this work selects 1000 hours as the time increment. Between two time points, the integrating region is assumed to be a trapezoid.

VI. CASE STUDIES AND RESULTS

A. *Selection of LED and Driver*

The LED light source is preselected with the activation energy and pre-factor of $E_{a,\beta}$ =0.3eV and A_{β} =0.2829, according to previous test results [32]. The other parameters that appear in Eq.(1) to (6) are listed in Table III. Those data were extracted experimentally from previous studies [26, 32].

Table III Physical Parameters of The LED Light Source

Parameter	Values	Parameter	Values
R_{s0}	5.914×10^{-1}	A_s	6.699×10^{-4}
A_I	1.274×10^{-1}	I_{s0}	4.786×10^{5}
η_0	1.456×10^{2}	A_n	1.240
B_n	-2.882×10^{2}	A_e	9.990×10^{-1}
B_e	1.406×10^{3}	C_e	2.138×10^{3}
C	4.087×10^{-3}	T_{Max}	423 K

According to the electronic thermal simulation at the initial state during operation, the LED's junction temperature is about 340K. Based on the parameters defined above, the LED's lifetime in terms of luminous flux decay is about 25000 hours at the constant temperature 340K and with a current of 400mA, by Eq.(1) and (2).

For the driver, the empirical values [35] of model parameters for the MOSFET M1 and Diode D4 shown Eq.(9) and (10) are selected as p of 2.0, $E_{a,M}$ and $E_{a,D}$ as 0.7eV respectively. According to the simulation results, the initial junction temperature values of $T_M(0)$ for M1 and $T_{Di}(0)$ for D4, are about 357K and 344K respectively. Assume that the driver's MTTF at the initial state equals to 25,000 hours, f_{M0} =4.12 × 10^{-7}, f_{D0} =2.74 × 10^{-7}. Since temperatures in the lamp and the current during operation will change over time, the actual LED's lifetime in terms of luminous flux decay and the MTTF for driver will be different from the pre-selected values. The details of the results will be discussed below.

B. *Constant Light Output (CLO) Mode*

Fig.6 displays the LED current curve at the CLO mode. The LED's current increases exponentially, e.g. from the initial 400mA to 910mA in 16000 hours. Such an increase in current mainly compensates the luminous efficacy degradation of the LED to maintain the constant light output.

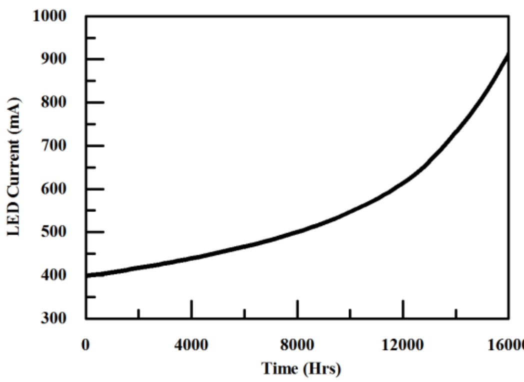

Fig.6 LED Current in The CLO Mode

Fig.7 displays the LED junction temperature as a function of time. Due to the elevated current, the LED's temperature increases greatly. At 16000 hours, the junction temperature of the LED light source increases by about 84K and exceeds 423K.

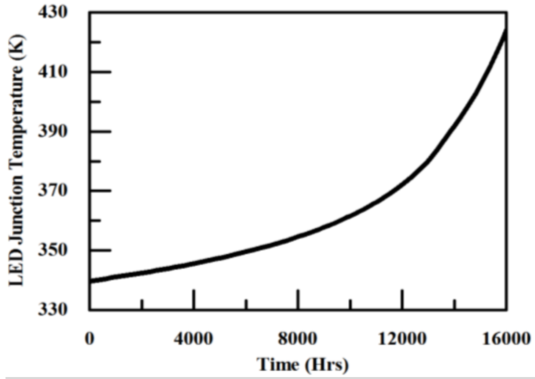

Fig.7 LED Junction Temperature in The CLO Mode

Fig.8 shows the history of the junction temperatures of M1 and D4 at the CLO mode. In 16,000 hours, the junction temperatures of M1 increases from 357K to 452K, and the junction temperatures of D4 rises from 344K to 432K. Fig.9 shows the cumulative failure rate of M1 in different conditions of the CLO mode. In the constant temperature and current of the M1, the cumulative failure rate is about 47% at 16000 hours. If M1's junction temperature increase only is considered, the failure rate accumulates to 100% around 12000 hours. If M1's current increase only is considered, the cumulative failure rate is about 98% at 16000 hours. If both of junction temperature and current of M1 in CLO mode are considered, the failure rate of M1 accumulates to 100% in about 10000 hours. The increased junction temperature has larger effects on the failure rate.

Fig.10 displays cumulative failure rate of the driver for the CLO mode in comparison with a constant temperature and a constant current, same as the initial ones. In the ever-changing temperature and current operation condition, the driver's failure rate accumulates to 100% in about 8700 hours. In the constant temperature and current condition, the failure rate accumulates about 64% in 16000 hours. As discussed above, the driver's failure rates are greatly increased due to the significant increase of driver's temperature and current. Thus, the driver in the CLO mode has a much shorter MTTF than in constant condition.

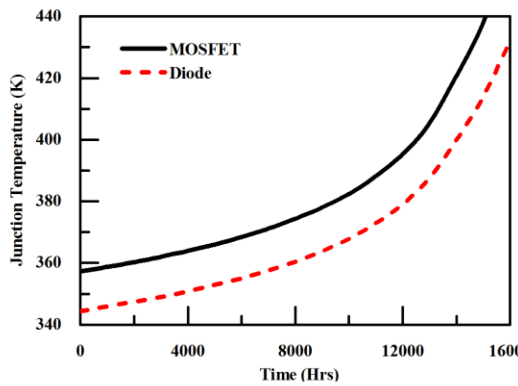

Fig.8 Junction Temperature of M1 and D4 in The CLO Mode

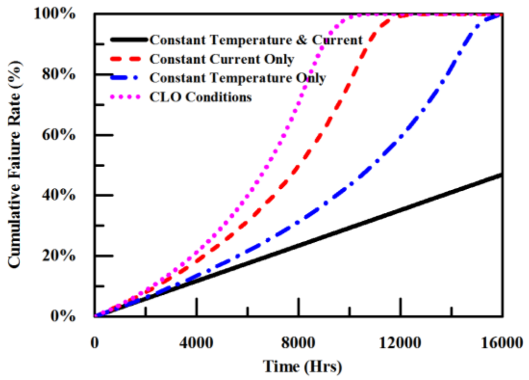

Fig.9 Cumulative Failure Rates of M1 in The CLO Mode

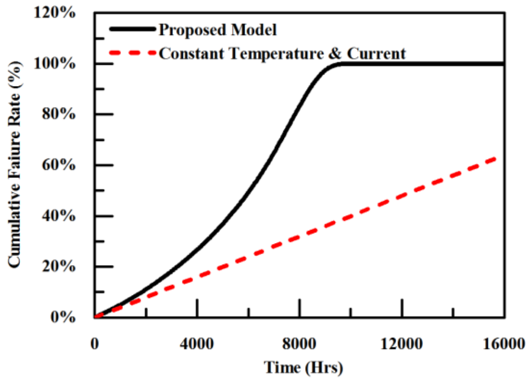

Fig.10 Cumulative Failure Rates of The Driver in The CLO Mode

C. Constant Current Mode (CCM)

Fig.11 displays the LED junction temperature in CCM mode. After 25000 hours, the junction temperature of the LED light source only increases by about 6K. As the LED degrades, more thermal power is generated, leading temperature increase for the entire lamp modestly. However, such rise is much less than that in CLO mode.

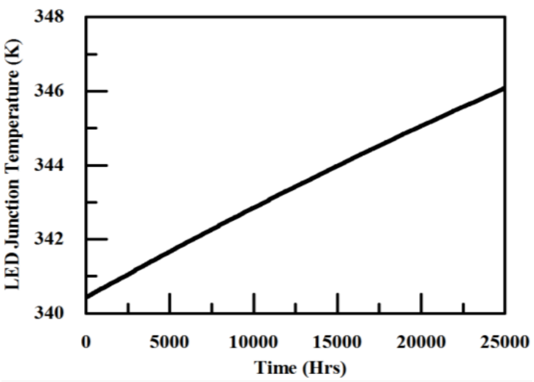

Fig.11 LED Junction Temperature in The CCM Mode

Fig.12 displays the normalized luminous flux maintenance under CCM mode. The LED's lifetime is redcued to about 20000 hours, 20% shorter than in the constant temperature and current.

Fig.13 shows the history of the junction temperatures of M1 and D4 in the CCM mode. The junction temperature of M1 increases from 357K to 364K, and D4's junction temperature rises from 344K to 349K in 25000 hours. Compared with the CLO mode, the junction temperature of M1 and D4 increase slightly.

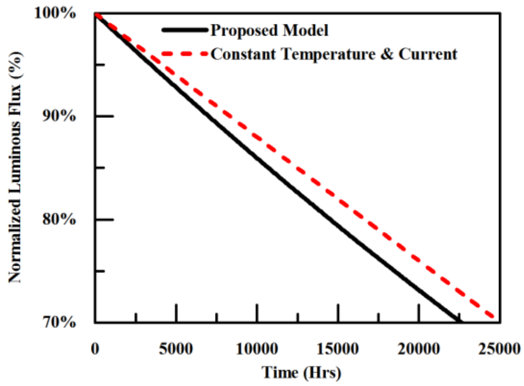

Fig.12 Normalized Luminous Flux in The CCM Mode

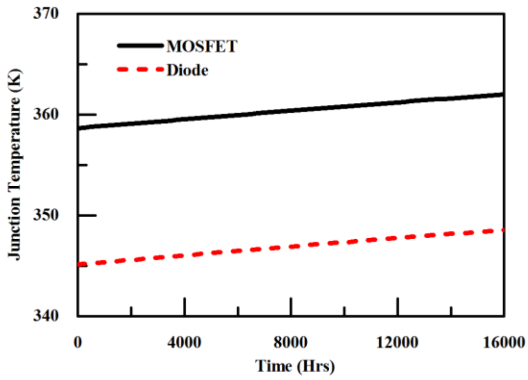

Fig.13 Junction Temperatures of M1 and D4 in The CCM Mode

Fig.14 displays cumulative failure rate of the driver in different conditions of CCM mode. The LED driver's failure rate accumulates to 100% in about 22500 hours, compared to 25,000hours at the constant temperature and current. This implies that the driver's failure rate in CCM mode does not change dramatically, as seen in CLO mode.

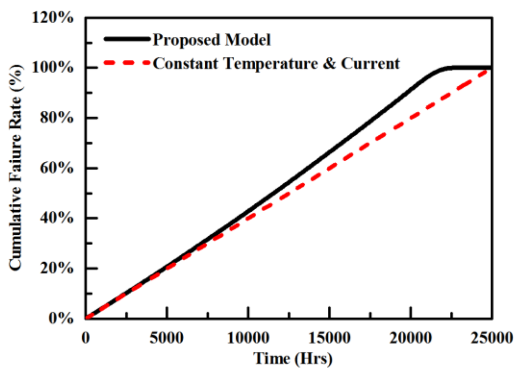

Fig.14 Cumulative Failure Rates of The Driver in The CCM Mode

Table IV summarizes LED's lifetimes in terms of lumen output and the driver's MTTFs for CLO and CCM modes. It is seen that even the preselected driver and LED both have a lifetime of 25,000 hours at the initial respective junction temperatures and operating current conditions, the actual lamp's lifetime can be significantly shorter in CLO mode. This is because that the current continually increases in LEDs for the CLO mode, which will increase the LED's junction temperature greatly. Since the driver is integrated together with LED, the driver's M1 and D4 junction temperatures also increase significantly, leading to a much early failure. In the CLO mode for the lamp studied here, since the LED's lifetime in terms of luminous decay is 16,000 hours, the catastrophic failure will occur first. It means that the whole lamp will have a lifetime of 8,700 hours.

In the CCM mode, the luminous flux decay lifetime is slightly shorter than the driver's MTTF, thus, the lamp will fail first due to the unacceptable luminous flux output. However, since both MTTF and luminous flux decay time are very close, it is also possible that the lamp will fail first by catastrophic failure. In either case, the lamp's actual lifetime is still less than the designed target of 25,000 hours.

Table IV Lifetime and MTTF

Case	Lifetime (Hrs)	T_j (K)	MTTF (Hrs)	T_D (K)
Initial Status	25'000	340	25'000	336
CLO	16'000	Varying	8'700	Varying
CCM	20'000	Varying	22'500	Varying

VII. CONCLUSIONS

This paper studies the interaction of catastrophic failures of a driver and the LED light source on the actual lifetime of the lamp. There are two distinct concepts of lifetimes involved in an LED lamp: driver's MTTF in terms of catastrophic failure, and LED's lifetime in terms of luminous flux output. The actual LED's lifetime is taken from the smaller one of these two values. LED's lifetime in terms of luminous flux decay depends on the history of LED's junction temperature and current. Driver's MTTF depends on the history of junction temperatures of key components, such as MOSFET and diodes in the driver. Electronic simulations were conducted first to obtain the power distributions among components and the current passing through LEDs. Then system-level thermal simulation and compact model were applied to obtain the temperature distributions. Since the LED's degradation is a continuous process, such electronic and thermal simulations need to be carried out throughout whole time domain.

In the present study, a fly-back converter with an LC filter is used. Two distinct operation modes are considered: the constant current mode (CCM), and the constant light output (CLO) mode, respectively. Under the CLO mode, LED's current increases exponentially. As a result, the junction temperatures of LEDs, MOSFET and diode rise by about 84K, 95K and 88K respectively in about 16,000 hours. The constant light output mode eliminates lumen depreciation at the expense of the LED lamp's reliability. Since the MTTF of the driver in the CLO mode is much shorter than the LED's luminous flux decay lifetime, the catastrophic failure of the driver will occur first.

For the CCM mode, since the current is forced to remain unchanged, the junction temperatures of the LED, the MOSFET and the diode rise modestly about 6K, 7K and 5K respectively, leading the lifetime drops to about 20000 hours, and the MTTF drops to about 22500 hours. Since the LED's lifetime and driver's MTTF in this mode are comparable, either catastrophic failure or the excessive lumen depreciation may occur first.

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