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A PoF and Statistics Combined Reliability Prediction for LED Arrays in Lamps

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Abstract- **In this work, a physics-of-failure (PoF) reliability prediction methodology is combined with statistical models to consider the interaction between the lumen depreciation and catastrophic failures of LEDs. The current in each LED may redistribute when the catastrophic failure occurs in one of LEDs in an array, thus affecting the operation conditions of the entire LED array. A physics-of-failure based reliability prediction methodology is combined with statistical models to consider the interaction between the lumen depreciation and the catastrophic failure. Electronic-thermal simulations are utilized to obtain operation conditions, including temperature and current. Meanwhile, statistical models are applied to calculate possibilities of the catastrophic failure in different operation conditions.**

Key Words: MOSFET, Electrolytic Capacitor-Free LED Driver, Reliability

1. Introduction

Compare with incandescent lamps and fluorescent lamps, LED lamps have many unique advantages, including its superior energy efficiency, environmental friendliness, and long lifetime. The LED light source often has a lifetime as long as 25,000 - 100,000 hours [1, 2]. Numerous studies have been focusing on the lifetime prediction of LED light sources [3-8]. Although lumen depreciation is one of the major failure modes, catastrophic failures of LEDs cannot be neglected. However, few study takes the catastrophic failure of the LED light source into consideration.

In an LED lamp, many light sources are LED arrays, which is consisted of several LED strings. The LEDs' catastrophic failures will result in zero light output and open circuit of the entire LED string [1, 9]. Thus, the lumen depreciation and the catastrophic failure of LEDs electronically and thermally interacts with each other during operation condition. When the catastrophic failure occurs on LEDs in an array, the current in each LED may redistribute, thus affecting operation conditions of the entire LED array. Therefore, the lifetime distribution of an LED array is no longer determined by the lumen depreciation, but effects by the interaction between the lumen depreciation and the catastrophic failure. However, the current reliability prediction methods for LED arrays neglect this interaction, overestimating the system reliability of an LED lamp.

This paper focuses on evaluating the reliability of an LED array when two failures co-exist: the lumen depreciation and the catastrophic failure. A physics-of-failure (PoF) based reliability prediction methodology is combined with statistical models to consider the interaction between the lumen depreciation and the catastrophic failure. Electronic-thermal simulations are utilized to obtain operation conditions, including temperatures and current. And then, LED's catastrophic failure rate is considered as functions of temperature and current. A temperature- and time-dependent lumen depreciation model and a lumen-probability distribution are used to obtain the probability of the lumen depreciation and the catastrophic failure.

2. Systematic Reliability Assessment Approach

A. General Methodology

This paper considers two different types of failure modes, LED's lumen depreciation and catastrophic failure, co-existing in an LED array. The lumen depreciation depends on time, LEDs' junction temperature and current. The catastrophic failure is determined the LEDs' junction temperature, and can be predicted by statistical models. The catastrophic failure of a LED will make an open circuit of the entire LED string, and result in current redistribution in the rest of working LED strings. Thus, these two types of failure modes interact physically with each other. As a result, a physics and statistics combined methodology is required to predict both of these two kinds of failures.

The proposed methodology integrates the physical prediction method and the statistical prediction method. The physical based method uses the electro-thermal simulations to obtain major system conditions with consideration of the lumen depreciation process at each time point, including LEDs' junction temperature, driver's output current and lumen output of the lamp. A series of iteration processes between electronic simulations and thermal simulations are needed to find the balance between the electronic performance and temperatures. Once the lumen output and junction temperature of LEDs exceed failure criteria, the lifetime of the LED lamp can be obtained. Details of the electro-thermal simulation method can refer to Literature [10].

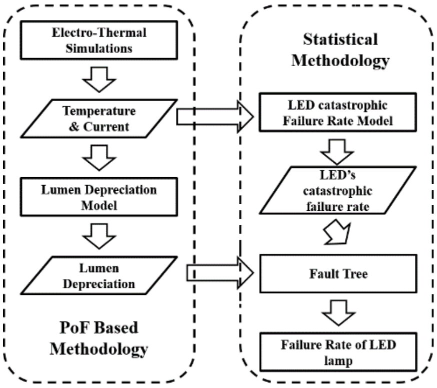

Fig 1 General Methodology of Proposed Approach

With operation conditions obtained by physical simulations, the statistical prediction method is used to calculate LEDs' catastrophic failure rate.

B. LED Degradation Model

A commercial LED bulb lamp is selected as a carrier of the prediction. The light source of this lamp consists of a 3×2 LED array. This work considers the effect of the lumen depreciation of LED light source to the entire lamp. The lumen depreciation an ever-changing junction temperature $T_j(t)$ and current $I_{LED}(t)$ can be described by the following function:

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

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 which follows the Arrhenius Equation [11]:

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

The performance of an LED light source can be described by the following function [9]:

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

where, N is the ideality factor, 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 [9, 12, 13]:

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

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

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

The parameters of this model are listed in Table 1. The details of derivations, validations and parameters extractions of the LED Degradation Model is introduced in Literature [14]. By performing the electronic simulations, the lumen output of the entire lamp, and the thermal power of each device can be obtained.

Table 1 The LED Model Parameters

Parameter	Value	Parameter	Value
$\boldsymbol{\eta_0}$	1.456×10^2	$\boldsymbol{A_e}$	0.999
$\boldsymbol{B_e}$	1.406×10^3	$\boldsymbol{C_e}$	2.138×10^3
$\boldsymbol{R_{s0}}$	5.914×10^{-1}	$\boldsymbol{A_s}$	6.699×10^{-4}
$\boldsymbol{I_{s0}}$	4.786×10^5	$\boldsymbol{A_I}$	1.274×10^{-1}
$\boldsymbol{A_n}$	1.240	$\boldsymbol{B_n}$	-2.882×10^2
$\boldsymbol{E_{a,\beta}}$	0.3eV	$\boldsymbol{A_\beta}$	0.2842
$\boldsymbol{T_{MAX}}$	423K	$\boldsymbol{T_A}$	298K

Fig.4 displays the theoretical lumen maintenance. Due to the increased current and temperature, when an LED string fails, the lumen maintenance drops to a lower level. The lamp's lifetime is a function of string failure time x. Suppose the lifetime of the lamp if a string fails at time x can be denoted by $G(x)$. If $x = 0$, the lifetime of the lamp is labeled as t_{min}; If $x = \infty$, the lifetime is labeled as t_{max}; For the minimum $x = G(x)$, it defines $x = G(x) = t_{LD}$. The function $G(x)$ can be obtained by simulations.

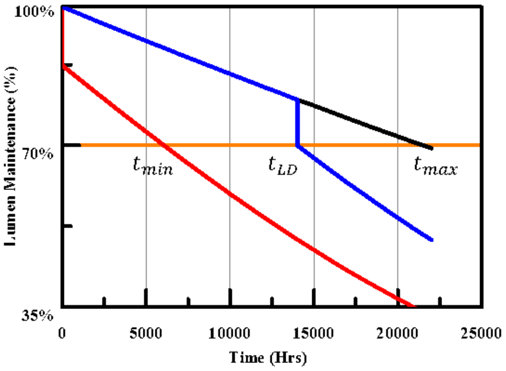

Fig.2 The Theoretical Lumen Maintenance

C. Failure Rate Models

The selected LED light source has three LED strings. The catastrophic failure of a LED will make an open circuit of the LED string with the failed LED, and lead to current redistribution in the rest of working LED strings. If none or one string fails, the LED light source can be still functional. Hence, the lumen depreciation probably occurs in these two statuses. If two strings fail, the working will burn out rapidly due to exorbitant junction temperature. If all three strings fail, the entire light source is considered open circuit. As a result, calculation of the rate of each failure mode becomes calculation of the rate of each status.

The probability density of catastrophic failure of an LED string f_{LED} depends on its junction temperature:

$$f_{LED}[T_j(t)] = f_{l0} \cdot e^{-\frac{E_{a,\beta}}{\kappa}[\frac{1}{T_j(t)} - \frac{1}{T_A}]} \tag{7}$$

where f_{l0} is the basic failure probability density at ambient temperature T_A. If one LED string fails at time

x, from 0 to time y, the failure rate of a working LED string $F_{LED}(x,t)$ is:

$$F_{LED}(x,y) = \int_0^x f_{LED}[T_{j,3}(t)] \cdot dt + \int_x^y f_{LED}[T_{j,2}(t)] \cdot dt \quad (8)$$

where $T_{j,3}(t)$ and $T_{j,3}(t)$ are the LED junction temperatures when none and one LED string fails respectively. Particularly, when none of LED string fails, the failure rate is:

$$F_{LED}(\infty, y) = \int_0^y f_{LED}[T_{j,3}(t)] \cdot dt \quad (9)$$

At this time, the reliability is:

$$R_{LED}(x,y) = 1 - F_{LED}(x,y) \quad (10)$$

The reliability of the entire light source is:

$$R_{LD0}(y) = R_{LED}^3(\infty, y) \quad (11)$$

The probability of one-string-fails status is

$$R_{LD1}(y) = 3 \cdot \int_0^y f_{LED}[T_{j,3}(x)] \cdot R_{LED}^2(x,y) \cdot dx \quad (12)$$

Thus, for the light source, the failure rate of catastrophic failure:

$$F_C(y) = 1 - R_{LD0}(y) - R_{LD1}(y) \quad (13)$$

For the 0-string-fails status, the lumen depreciation occurs when the aging duration y exceeds t_{max}, thus:

$$F_{LD}(y) \cdot P_{LD0}(y) = \begin{cases} 0 & (y < t_{max}) \\ P_{LD0}(y) & (y \geq t_{max}) \end{cases} \quad (14)$$

Fig 7 displays the lumen maintenance from 0 hours to different time y. For the 1-string-fails status, there are no lumen depreciation occurrence if $y \geq t_{min}$; And the lumen depreciation rate and the lifetime are functions of failure time x when $t_{min} < y < t_{max}$. The lumen depreciation rate for the 1-string-fails status can be described by:

$$F_{LD}(y) \cdot P_{LD1}(y) = 3 \cdot \int_0^{G(y)} f_{LED}[T_{j,3}(x)] \cdot R_{LED}^2(x,y) \cdot dx \quad (15)$$

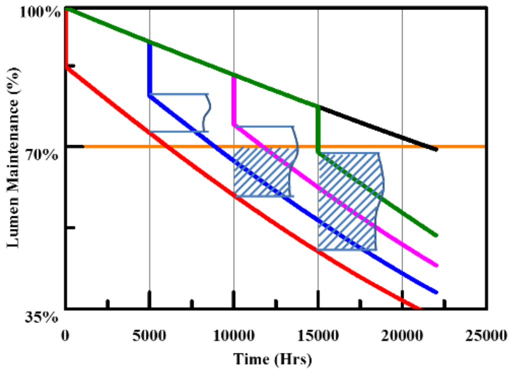

Fig.3 The Lumen Maintenance Curves

3. Case Study

Definition of Scenarios

To estimate the catastrophic failure of the LED light source, the MTTF of an LED string is preselected as 30000 hours when the ambient temperature of the lamp is 55C. As a result, the basic failure probability density of an LED string is f_{l0}=3.13×10^{-6}. Those data were extracted experimentally from previous study [24].

This work considers two scenarios. Scenario S1 considers the catastrophic failure and the lumen depreciation of the light source by proposed method. Scenario S2 and S3 consider the catastrophic failure by the conventional method described by [29]. In this method, if any LED string fails, the entire light source is considered as fails. Meanwhile, S2 and S3 obtain the rate of the lumen depreciation only from Eq.(16), the 1-string-fails status is excluded from their consideration. Compare with Scenario S3, S2 uses ever-changing temperatures to calculate the failure rate of the light source, while S3 uses constant temperatures before lumen depreciation.

Table 2 Scenario Design

Scenario	Temperatures	Failure of The Light Source
S1	Varying	Depends on the lumen depreciation
S2	Varying	One LED fails, entire light source fails
S3	Constant	One LED fails, entire light source fails

Results and Discussions

Table 3 lists the junction temperature and current of working LED string for each status. Before lumen depreciation, the rated LED current is about 350mA and junction temperature in this current is about 343.7K. If one of three LED string fails, the rest two LED strings still working, but LED current jump to 525K and the junction temperature jump to 374.5K. If two of three LED strings fail, the current of the rest LED string will increase to 1050mA, pushing the junction temperature up to 496.3K. In such high temperature, the LED will be burned immediately. According to results above, it needs to consider the 0-string-fails status and the 1-string-fails status for lumen depreciation predictions.

Table 3 Junction Temperature and Current for Each Status

Number of Failed String(s)	$T_j(0)$	$I_{LED}(0)$
0	343.69K	350mA
1	374.55K	525mA
2	496.30K	1050mA

Fig.8 displays the LED junction temperature distribution with different one string failure time (time x) and aging duration (time y). Generally, the LED junction temperature increases with the lumen depreciation process. After 22000 hours' aging, the junction temperature increases to higher than 386K. When an LED string fails, the junction temperature of other strings jumps up about 11K. After a string failure, the light source degradation faster than before, due to the higher junction temperature. Before the string failure, junction temperature increases about 4K in 10000 hours; after the string failure, junction temperature increases about 11K.

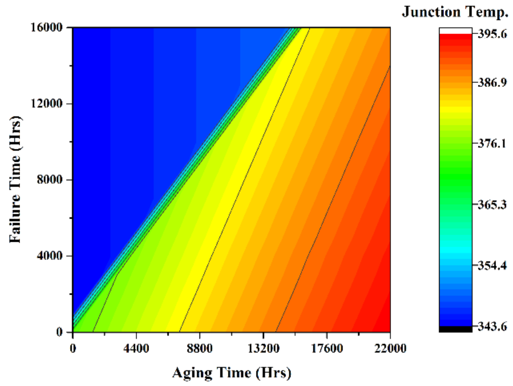

Fig.4 LED Junction Temperature Distribution

Fig.5 shows the lifetime curve $G(x)$ as a function of the string failure time x. As shown in Fig.9, t_{min} is about 6070 hours, t_{max} is about 21550 hours, and t_{LD} is about 14070 hours. With the help of $G(x)$, the rate of the lumen depreciation can be found.

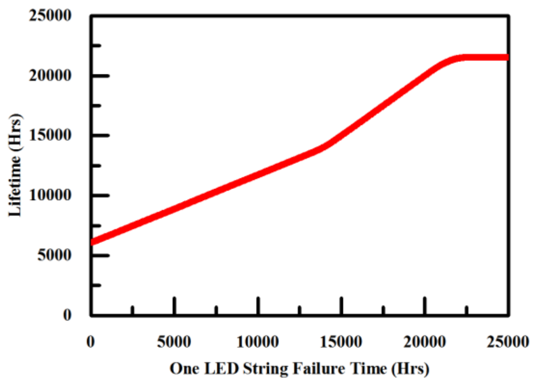

Fig.5 The Lifetime Vs 1-String-Failure Time

Fig.6 displays the accumulated rate curves of catastrophic failure, lumen depreciation and total failure of the light source. As shown by red curve, the accumulated catastrophic failure rate increases exponentially. In 22000 hours, the catastrophic failure rate accumulates to about 58%.

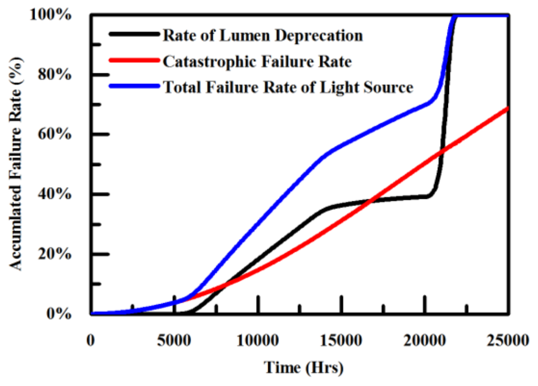

Fig.6 Accumulated Rate Curves

The black curve shows the accumulated rate of lumen depreciation. From t_{min} to t_{LD}, the lumen depreciation only occurs in a part of the one-string-fails status, and the ratio of lumen depreciation increases rapidly with aging duration. From t_{LD} to t_{max}, 100% of the 1-string-fails status has the lumen depreciation, thus the accumulated lumen depreciation rate increases slowly with probability of 1-string-fails status. After t_{max}, the lumen depreciation occurs in both 0-string-fails status and 1-string-fails status, and thus total lumen depreciation rate jumps to 100%. Under impact of the lumen depreciation rate, slope of the total failure rate curve of the light source changes at t_{min} and t_{LD}, and jump to 100% at t_{max}, as shown in Fig.6.

Fig.7 compares the light source's failure rate curves of each scenario. The light source's failure rates of Scenario S2 and S3 accumulate 53% and 32% at time t_{LD}, and 73% and 33% at time t_{max}. The 1-string-fails status is considered as failed by Scenario S2 and S3, but as survival by Scenario S1 before to time t_{min}. Thus, the Scenario S1 has a lower failure rate of the light source than S2 and S3 before t_{min}. During time t_{min} to t_{LD}, Scenario S2 overestimates the failure rate of the light source due to lack of the consideration of the lumen deprecation rate of the 1-string-fails status. Even in ever-changing temperature, the conventional method still has significant error in this period. The failure rate curves of S1 and S2 coincide with each other after time t_{LD}, since 100% of the 1-string-fails status is considered as failed by Scenario S1. Compare with S1 and S2, predicted failure rate of Scenario S3 has a significant error, because of the constant temperature assumption.

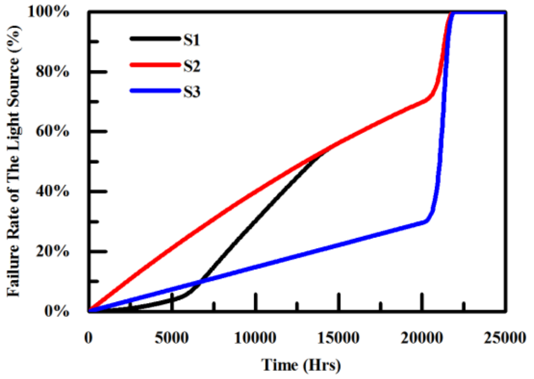

Fig.7 Failure Rate Curves

4. Conclusions

This paper evaluates the reliability of an LED lamp when two failures co-exist: the lumen depreciation and the catastrophic failure of the LED light source. Electronic-thermal simulations are utilized to obtain operation conditions, including the lumen maintenance, temperatures and current. With these operation conditions, catastrophic failure rates of the LED light source are obtained by the failure rate models.

When two of three LED strings fail, the remaining LED string will fail immediately due to the high junction temperature. When one LED string fails, the junction temperature of two remaining strings jumps to a higher level, leading to the faster lumen depreciation. The one string failure time x determines the lifetime of entire lamp. When $0 < x < t_{LD}$, lifetime of the LED lamp increases from t_{min} to t_{LD} linearly; When $t_{LD} < x < t_{max}$, the lamp's lifetime equals to 1-string-fails time x; When $x > t_{max}$, the lamp's lifetime fixes at t_{max}. For the selected lamp, t_{min} is about 6070 hours t_{max} is about 21550 hours, and t_{LD} is about 14070 hours. The accumulated catastrophic failure rate increases exponentially. The rate of lumen depreciation increases rapidly during t_{min} to t_{LD}, rises slowly during t_{LD} to t_{max} and jump to 100% at t_{max}.

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