Accelerated Lifetime Test for Isolated Components in Linear Drivers of High-Voltage LED System

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Abstract

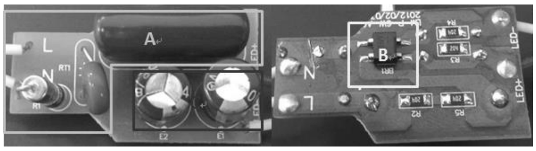
This paper proposes an isolated component accelerated lifetime testing of high-voltage SSL driver. In this method, the most critical component(s) will be isolated from the rest, and critical stress will be applied to these components to estimate the lifetime. Although circuit modification is unavoidable, this testing method can minimize failure interactions between components and testing duration for the system. Thus, compared to the conventional accelerated testing method, this method could achieve shorter test duration. In the configuration of high-voltage LED, the electrolytic capacitors have been selected from the linear driver configuration. As one of most significant failure mechanisms, the effects of high temperature degradation of electrolytic capacitors to the entire system were investigated in this test. To quantify these effects, the changes in luminous flux and power consumption over time were measured. By analysis of all these output data, the relationship between the system's outputs and temperature of electrolytic capacitor can be found. For the high-voltage LED system, this relationship is a required condition for the accurate system reliability prediction.

Abstract: Accelerated lifetime test; high-voltage LED; linear driver; electrolytic capacitor, Solid State Lighting

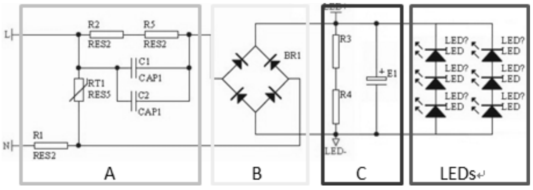
1. Introduction

In order to provide stable voltage and current to the LEDs, various driver topologies have been implemented in the Solid State Lighting (SSL) systems. However, since SSL driver is a kind of power electronic gear use in lighting products, it presents unique reliability problems for both power electronics and lighting. Firstly, as a significant part in such long life products, SSL drivers are required to have a lifetime as long as LEDs for avoiding becoming the weakest link in the entire system. Secondly, working along with lighting products, operation environment of SSL drivers is quite complicated, such as unstable operation temperature, high humidity or other harsh condition, which have a serious impact on drivers' reliability. Finally and unfortunately, due to the limit of total cost, reliability usually is not the first priority during the trade-off of driver designing. Thus, it is a common viewpoint that SSL driver is a reliability bottleneck of entire system according to both industry experiences and research results.

Although research on components and subsystems of SSL driver attract more and more attention since US DoE released its Multi-Year Planning Program for Solid State Lighting, only a few studies have tried to investigate the impact of critical component degradation in the whole system by accelerating test [1]. Therefore, it is reasonable and necessary to develop the accelerated life test method for isolated critical component from others in the test.



(a) Linear Driver Structure



(b) Linear Driver schematic

Fig1: the linear driver (a) Structure and (b) Schematic

Within different kinds of drivers, a relative economic one is a linear driver as shown in Fig.1. The main linear driver schematic contains: A) a resistance-capacitance step-down stage, B) a full-wave bridge rectifier and C) one or more electrolytic capacitors at the output stage. These electrolytic capacitors are significant for reliability of the whole system, their functions as rectifier, filter and buffer are crucial for shielding the LEDs from the ripple and noise of the input power. Without these capacitors, the LEDs can still be lighted on, but have serious flicker and therefore poor reliability owing to serious current ripple. Industry experiences suggest that, besides the solders, the electrolytic capacitor at the output end is the weakest link in the driver. Due to the limited number, solders are more reliable than electrolytic capacitors whose liquid electrolyte is so sensitive to temperature that it is easy to evaporate out, leading the degradation of electrolytic capacitors. Thereby, such degradation has serious impact on the driver's and the entire system's output. Thus, as shown in Fig 3, the electrolytic capacitors have been selected as the isolated part of the configuration of linear driver. As one of most significant failure mechanisms, the effects of high temperature degradation of electrolytic capacitors in the entire system are investigated in this test.

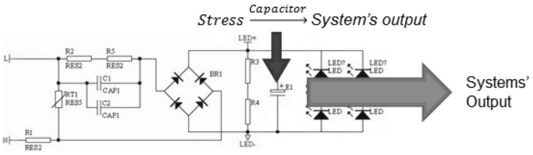


Fig 3: Isolated Accelerated Lifetime Test Method

2. Accelerated Lifetime Test

As mentioned before, this work proposes an isolated component accelerated lifetime testing of high-voltage LED driver. In this method, a critical component(s) will be isolated from the other components in the system, and critical loading will be applied to these components to investigate its degradation. In the linear driver in this work, the critical components are the electrolytic capacitors at output end due to its crucial functions and short lifetime. In another word, the degradation of electrolytic capacitors may lead to the failure of whole systems. As one of most common and significant failure mechanisms of electrolytic capacitors, its electrolyte could volatilizes from cylinder at high temperature. According to a larger number of previous researches [1~9], such degradation leads its capacitance decreasing and Equivalent Series Resistance (ESR) increasing. However, for the linear driver in this work, capacitance decreasing has larger impact on the driver's performance.

Theoretically, electrolytic capacitors' lifetime in these temperatures can be calculated by:

$$L = L_0 \cdot f(T_a) \cdot g(\Delta T_j)$$

In the equation above, L is the lifetime expectancy in these conditions; L_0 is basic lifetime or guaranteed lifetime, usually provided by the data sheet. Known as the double every 10℃ law, the ambient temperature acceleration coefficient f (T_a) is a function of maximum operation temperature T_{max} and actual operation ambient temperature T_a:

$$f(T) = 2^{(T_{max} - T_a)/10}$$

Similarly, the ripple current acceleration coefficient g (ΔT_j) is a function of the internal temperature rise when actual ripple current is applied ΔT_j and internal temperature rise when maximum permissible ripple current is applied ΔT_{jo}:

$$g(\Delta T_j) = 2^{\left[\frac{\Delta T_{j0}}{10 - 0.25 \cdot \Delta T_{j0}} - \frac{\Delta T_j}{10 - 0.25 \cdot \Delta T_j}\right]}$$

Where, ΔT_{jo} is a constant which usually provided by the data sheet. However, the internal temperature rise is hard to measure, so the ΔT_j can be estimated by electrolytic capacitors' surface temperature rise ΔT_c:

$$\Delta T_j = \alpha \cdot \Delta T_c$$

In the equation above, α is the ratio of internal temperature rise to surface temperature rise which provide by the data sheet.

Table 1 Main Parameters of Electrolytic Capacitor

Parameter	Value
L_0	1000Hrs
T_{max}	105℃
ΔT_{j0}	10℃
α	1.1

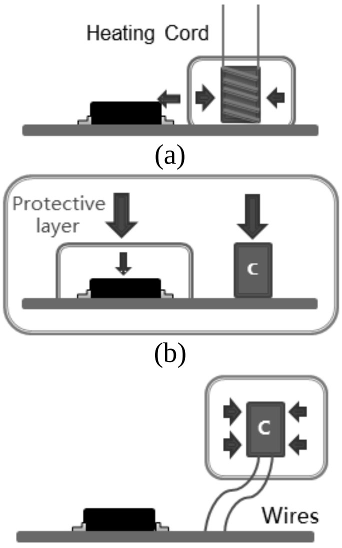
Table 1 gives the main parameters of the electrolytic capacitors in this work. For the electrolytic capacitors in this work, the measured ΔTc is around 2.97°C no matter what ambient temperature it is. Therefore ΔTj = 3.27°C, and obtained from equation (5), g(ΔTj) equals to a constant 1.97. As listed in Table-2, the lifetime of this type electrolytic capacitor operating in 145℃ is about 130 hours, much shorter than the lifetime in 105℃ and 55℃. Although all components of the luminaire, including LEDs and the rest of the driver, degrade during operation, compare to any other component, it is obvious that electrolytic capacitors have much shorter lifetimes and more remarkable degradation during hundred hours aging. In consequence, electrolytic capacitors' degradation has severer influence on the system performance changes than the rest of system during the test.

Table 2 Theoretical Lifetime of Electrolytic Capacitors

Temp. (℃)	Lifetime (Hrs.)
55	63000
105	1970
145	130

3. Test Set-up & Error Estimation

For the purpose of accurate lifetime estimate, several methods were designed to isolate critical components or subsystems and apply stresses to them while working, such as local stress, component isolating, component protection method, as shown in Fig.4.



(a)

(b)

(c)

Fig.4 Isolated Accelerated Lifetime Test Method Options: (a) Local Stresses; (b) Component Protection(c) Component Isolation

As illustrates in Fig.4 (a), component protection method is developed in this work from conventional accelerated test methods. In this method, a protective layer or device was added into the driver, shielding the accelerated stresses from an environment where the entire driver was placed in during aging. However, such method cannot use for thermal experiment due to self-heating of components. Take the electrolytic capacitor aging as an example, the local stress method need to install a tiny heating cord and protective layer if necessary on the driver's PCB, controlling the temperature around the electrolytic capacitor as illustrated in Fig.4 (b). This method suits for the driver has enough space between the heated electrolytic capacitor and other components; otherwise it may impact the components close to the electrolytic capacitor.

Considering accurate controlling of high temperature, the component isolation method was developed, in which the electrolytic capacitor is placed into an oven and connects to rest of the driver with a pair of high temperature wires. Before testing, the electrolytic capacitors were removed from the drivers, and wires were connected in between electrolytic capacitors' pins and pin through holes in the PCB.

After circuit modification, parts of this high-voltage luminaries were assembled together and working in room temperature except its electrolytic capacitors are aged in an oven which applies a constant high temperature. At intervals of a certain period of time, the electrolytic capacitors were removed from the oven after switch off, and performances of the luminaries were measured when they restore a thermal equilibrium state during this interval. In this work, 3 different temperature conditions were selected as aging conditions, where 55℃ is the regular operating ambient temperature in luminaires; 105℃ is the maximum operating temperature; 145℃ is the accelerated temperature in this work.

As mentioned above, by the component isolation method, the electrolytic capacitor connects to rest of the driver with a pair of high temperature wires. Although extra resistance and capacitance will be introduced into the driver circuit by such modification, it is so small compared to origin parameters of the sample linear driver that has little influence to drivers' output. According to the definition of resistance, extra resistance can be obtained by:

$$R = \frac{\rho \cdot l}{s}$$

Where, R is resistance, copper resistivity ρ is 2.2 uΩ•cm, l is the wire length and s is the wire cross section which is about 2.5 mm^2. Considering the worst situation, the two wires can be seemed as a plate capacitor for the calculation of its coupling capacitance. Hence, extra capacitance can be obtained by:

$$C_c = \varepsilon \frac{\varepsilon_0 \cdot S}{d}$$

Where, C_C is the coupling capacitance, ε is the dielectric constant of wire cover material which is about 3.0~3.2 in this work, dielectric constant in vacuum equals to 8.86pF/m, d is the distance between wires which is about 2mm. In the worst situation, the capacitor's area S is considered as the surface area of a wire. As a result, theoretical unit resistance is 0.0088Ω/m, unit capacitance is 6.65pF/m. Meanwhile, the measured unit resistance is less than 0.05Ω/m and measured unit capacitance are less than 1pF/m. Both of them can be ignored in practice.

4. Test Result

For purposes of the investigating such effect, a series of electrolytic capacitors, which have identical brand, same type, approximate other specifications except capacitance, were connected into driver before electrolytic capacitors aging. By measuring luminaires' performance difference with each capacitance, the influence of capacitor degradation can be quickly found. According to table 3, luminous flux decreases with capacitance decreases, while power consumption increases.

Table 3Perfermence Change vs Capacitance

C (uF)	P (%)	Φ_L (%)
9.66	1	1
6.35	+0.6%	-1.4%
5.11	+1.4%	-2.9%
3.33	+3.7%	-3.6%

According to table 3, luminous flux of the linear driver based system decreases with capacitance decreases as other types of driver mentioned in previous research [1].

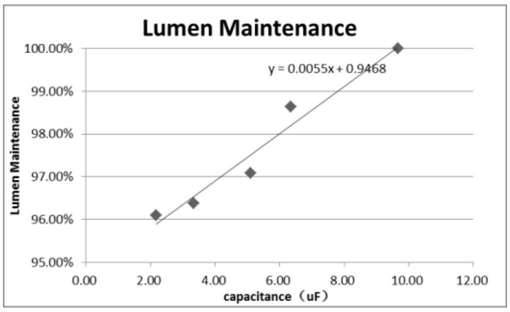


Fig.5 Lumen Maintenance vs Capacitance

As illustrated in Fig.5, lumen maintenance and capacitance degradation almost have a linear relation, so that the lumen maintenance at the time of capacitors exceed their lifetimes can be estimated. However, for this linear driver based system, luminous decreasing cause by canpacitance degradation is slight. When the capacitance drops to 75% of the initial value, at which point a capacitor is usually considered exceed its lifetime, and the luminous flux drops about 1.335%. Considering the capability of measuring, error of luminous measuring is about ±1%. So luminous decreasing caused by capacitor degradation in the accelerated test is hard to be detected.

As illustrated in Fig.6, similar to lumen maintenance, at the time of capacitors exceed their lifetimes, power consumption reduce about 0.5%, but compares to the ±0.01% accuracy of electrical measuring, it is much more accurate to be measured. Therefore, in this work, power consumption and power factor are considered as the indicator of capacitor degradation instead of lumen maintenance.

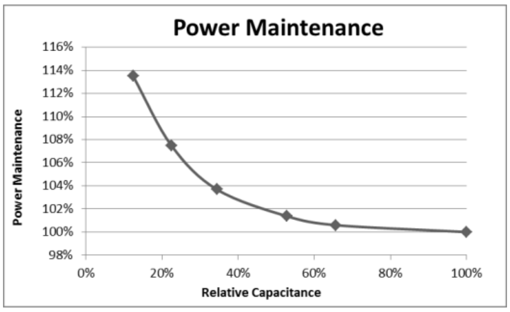


Fig.6 Power Maintenance vs Capacitance

In this accelerated test, the electrolytic capacitors in the linear drivers are put in 55℃, 105℃ and 145℃. As mentioned above, an electrolytic capacitor degrade much faster in 145℃ than in 55℃ and 105℃, so in the first 300 hours of aging, the electrolytic capacitors in 145℃ had already exceeded their lifetime, while the electrolytic capacitors in other condition are still operating well within their lifetime.

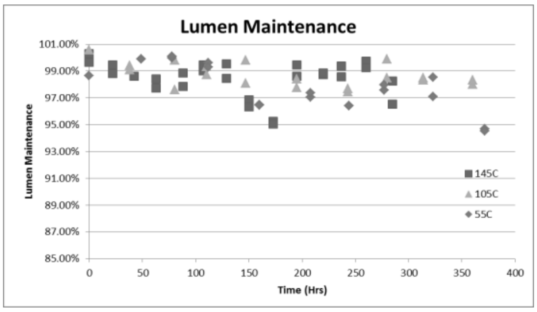


Fig.7 Relative Lumen Flux Trend

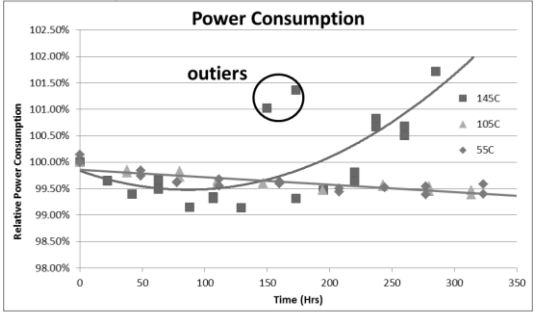


Fig.8 Relative Power Consumption Trend

As the most significant indicator, shown in Fig.7, lumen maintenance of systems with electrolytic capacitors in 55℃, 105℃ and 145℃ fluctuate between 97% to 100%, even that the electrolytic capacitors in 145℃ exceed their lifetime. Consider the ±1% measurement error, the lumen maintenance of the systems remains relatively. In consequence, it can validate previous analysis that lumen maintenance decreases with but is insensitive to capacitor degradation, and thus, hard to be detected due to the limits of measurement.

Fig.8 shows the power consumption curves of 55℃, 105℃ and 145℃. For the systems with electrolytic capacitors place in 145℃, the input powers of the electrolytic capacitors in 145℃ decrease slowly during the first 150 hours, Meanwhile, compare to electrolytic capacitors in 145℃, power consumption of the systems with electrolytic capacitors in 55℃ and 105℃ decrease continuously nearly in same rate. Hence, it is support that within the lifetime of electrolytic capacitors, high temperature has little influence on system's power consumption. But after exceeding the electrolytic capacitors' lifetime which is around 150 hours in this work, power consumption turns to an increasing trend. As a result, more and more heat produced in the LEDs or their driver, this heat may greatly shorten the system's lifetime. In comparison with lumen maintenance, power consumption can be a better indicator for the lifetime of electrolytic capacitors in the linear drivers of the high-voltage LED system

On the basis of electrolytic capacitor nature, the degradation rate of an electrolytic capacitor depends on the ambient temperature. According to Fig.8, it is obvious that the ratio of power decreasing rates in various ambient temperatures does not follow the ratio of degradation rate of an electrolytic capacitor. Thus, the same decreasing trend should not be attributed to electrolytic capacitor but other parts in the luminaire. Furthermore, the preliminary test result also support that the capacitance degradation causes power consumption increase. However, it is possible that this slow decreasing trend can be accelerated or amplified in conventional overstressing accelerated test, counteracting the impact of electrolytic capacitor degradation on power consumption. Therefore, isolated accelerated lifetime test method successful avoids interaction between electrolytic capacitor and other parts of the system.

4. Conclusions

This paper proposed an isolated accelerated lifetime test method for the linear driver in a high-voltage LED application. In the configuration of this application, the electrolytic capacitors have been isolated from the linear driver, and the temperature loading has been applied in order to trigger the failure mode of the degradation of electrolytic capacitors. By this new overstressing lifetime test, the influence of electrolytic capacitors in a linear driver of a high-voltage system can be found: 1) After the electrolytic capacitors exceeding their lifetime, the high-voltage system's power consumption of this linear driver turns from decreasing to increasing trend. Different with other types of driver, its lumen maintenance slightly decreases; 2) In comparison with lumen maintenance, power consumption can be a better indicator for the lifetime of electrolytic capacitors in the linear drivers of a high-voltage LED system; 3) Although circuit modification is unavoidable, this test method can minimize failure interactions between components in the system.

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