A Degradation Model of Aluminum Electrolytic Capacitors for LED Drivers

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Abstract

The failure of aluminum electrolytic capacitors is considered as one of major failure modes of the LED drivers. This paper propose a degradation model of aluminum electrolytic capacitors considers impacts of operation time and temperature.

1. Introduction

It is generally found that the driver is the weakest part within a LED luminaire [3]. According to the field test results of DoE, USA, more than 70% of the failures of tested LED luminaires come from their driver failures [8]. Such high failure rate is caused by several major reasons: (1) limitation of cost; (2) harsh working conditions; (3) long expected lifetime [9, 15]. That makes the reliability issue of the driver needs to be carefully examined for a LED luminaire.

As revealed in many researches [1-6], the electrolytic capacitor is considered as the weakest component of many power electronics. Therefore, many researchers regard the lifetime of the electrolytic capacitor as the lifetime of the driver. According to literatures [1, 2, 4], the output smoothing electrolytic capacitors have the highest rate of failure and account for over 50% of the failures in switch mode power supplies. Thus, reliability assessment of the electrolytic capacitor is a significant issue for reliability of LED drivers and LED luminaires.

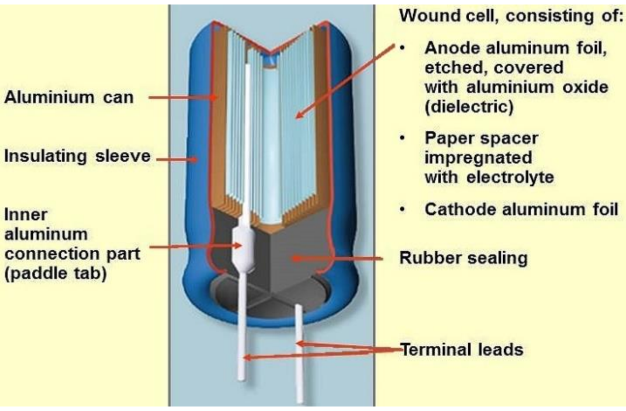

Fig. 1. Construction of Aluminum Electrolytic Capacitors [10]

As shown in Fig.1 [10], an aluminum electrolytic capacitor is composed of several parts: an aluminum can, wound cell, rubber sealing and terminal leads. The core part, the wound cell is consisted with cathode aluminum foil, electrolytic paper and an aluminum oxide dielectric film on the anode foil surface as shown in Fig. 2 [10].

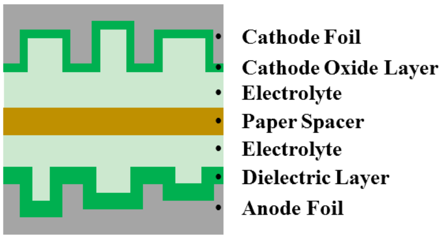

Fig. 2. Foil Structure of Aluminum Electrolytic Capacitors [10]

As shown in Fig.2, the foils of the wound cell forms a high dielectric constant, high dielectric strength and low resistivity layer. Compare with other capacitors, aluminum electrolytic capacitors have larger capacitance-voltage production per volume and excellent withstand voltage per thickness. Thus, aluminum electrolytic capacitor is one of most common used capacitors in LED drivers.

However, aluminum electrolytic capacitors have several shortcomings. For instance, the performance of the electrolyte material of an electrolytic capacitor is sensitive to temperature. An electrolytic capacitor has different performance when its core temperature is different. Besides, degradation rates of the performance of an electrolytic capacitor are also influenced by its core temperature during long term of operation. In an elevated temperature, an electrolytic capacitor have about several thousand hours lifetime, which is shorter than most of other components.

As introduced above, evaluating impact of core temperature on performance and degradation rates are significant to reliability assessment of an electrolytic capacitor in LED drivers. This paper proposes a degradation model of aluminum electrolytic capacitors which considers performance and their degradation rates of an electrolytic capacitor in different temperature.

2. Theories

For quantitative analysis, an electronic model of an electrolytic capacitor is commonly used, as shown in Figure 3 [16]. In this model, an electrolytic capacitor has three major parameters: capacitance, equivalent series inductance (ESL) and equivalent series resistance (ESR). This work focus on the capacitance and ESR of an electrolytic capacitor in long term of operation.

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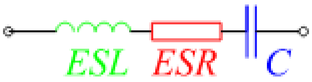


Fig. 3. Equivalent Circuit of an Aluminum Electrolytic Capacitor

For aluminum electrolytic capacitor, ESR is about several ohms. According to literatures [2, 14, 18], it is experimentally found that capacitance of an electrolytic capacitor decreases with time and increase with temperature. Meanwhile, an opposite tendency is showing on its ESR.

According to literatures [1-5], performance of an aluminum electrolytic capacitor is determined by three major factors: degradations with time, core temperature and operation frequency. Frequency LED drivers seldom shift, hence this work considers a fixed frequency during long term operation. Currently, conventional model is usually assumes that core temperature of an electrolytic capacitor stay constant. However, the degradations of capacitance and ESR will increase the power loss on a capacitor, resulting in a rise of the core temperature and degradation rate of the capacitance and ESR in turn. Therefore, the assumption of constant temperature or constant degradation rate used in the currently available models may bring large error in predicting capacitance and ESR. Considering impact of temperature on performance and degradation rates, the model is given by Eq. (1) and Eq. (2) as follows:

$$CAP(T,\ t) = F_1(T,\ t) \cdot F_2(T) \qquad (1)$$

$$ESR(T,\ t) = E_1(T,\ t) \cdot E_2(T) \qquad (2)$$

where, $CAP(T, t)$ and $ESR(T, t)$ are capacitance and ESR as functions of the temperature T and time t, $F_1(T,\ t)$ and $E_1(T,\ t)$ are degradation functions of capacitance and ESR, $F_2(T)$ and $E_2(T)$ are shifting functions for capacitance and ESR. In literature [4, 11-13], the degradation of capacitance and ESR are calculated by the following Eq. (3) and Eq. (4):

$$F_1(T,\ t) = 1 - \int_0^t A[T(t)] \cdot dt \qquad (3)$$

$$E_1(T,\ t) = \int_0^t C[(T(t)] \cdot dt \qquad (4)$$

where, $A[T(t)]$ and $C[T(t)]$ are degradation rates at temperature T. Further, $A[T(t)]$ and $C[T(t)]$ are described by the Arrhenius form as Eq. (5) and Eq. (6):

$$A[T(t)] = A_0 \cdot e^{\left(-\frac{E_{a1}}{\kappa \cdot T(t)}\right)} \qquad (5)$$

$$C[T(t)] = C_0 \cdot e^{\left(-\frac{E_{a2}}{\kappa \cdot T(t)}\right)} \qquad (6)$$

where, E_{a1} and E_{a2} are the activation energies of the capacitance and ESR, $T(t)$ is the temperature in Kelvin. According to chemical properties of the dielectric materials, the capacitance shifting function $F_2(T)$ and ESR shifting function $E_2(T)$ are described by Eq. (7) and Eq. (8):

$$E_2(T) = \frac{ESR_0}{1+D \cdot T(t)} \qquad (7)$$

$$F_2(T) = CAP_0 \cdot e^{B/T(t)} \qquad (8)$$

By combining Eq. (3) to Eq. (8), the degradation model of an electrolytic capacitor is eventually calculated as:

$$CAP(T,\ t) = CAP_0 \cdot e^{\frac{B}{T(t)}} \cdot \{1 - \int_0^t A[T(t)] \cdot dt\} \quad (9)$$

$$ESR(T,\ t) = \frac{ESR_0}{1+D \cdot T(t)} \cdot exp\{\int_0^t C[T(t)] \cdot dt\} \quad (10)$$

The parameters A_0, B, E_{a1} for capacitance and C_0, D, E_{a2} for ESR need to be extracted from experiments which will be discussed in the next section.

3. Experiments

For parameter extraction of the electrolytic capacitor degradation model, three different experiments were carried out orderly. One of most frequent types of electrolytic capacitor from a top capacitor manufacturer was selected as test objects of this work. Before tests, all samples passed a 48-hours' burn-in screening test.

Fig. 4 displays the set-up of parameters determination tests which consists with 4 major equipment: thermal couples, an aging oven, a LRC meter and a programmable power source. The thermal couples are used to measure case temperature of each sample for calculation of core temperature, the aging oven is used to provide a stable ambient temperature to test samples, the LRC meter is used to measure capacitance and ESR of each sample, the programmable power source is used to apply and measure voltage ripple and power to these electrolytic capacitor.

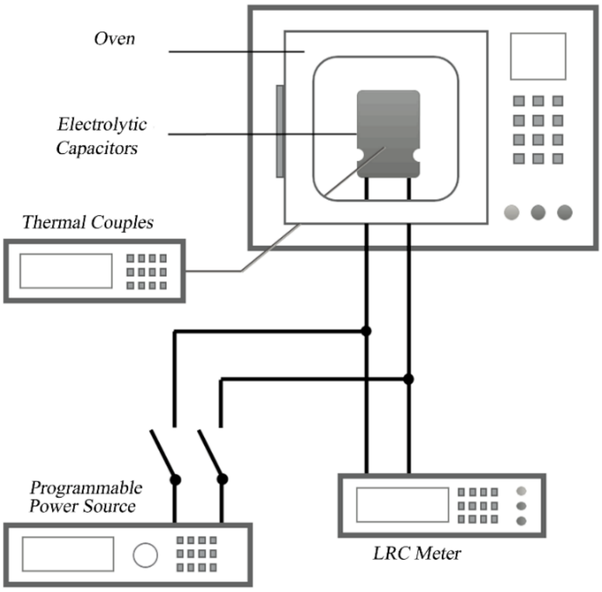


Fig. 4. Set-up of Parameters Determination Tests

To measure A_0, C_0, E_{a1} and E_{a2}, four groups of electrolytic capacitors were aged in different temperatures: 399K, 389K, 355K and 339K. Each group has more than 10 samples. During this test, samples is placed in an oven whose temperature is continuously adjusted to keep temperature fluctuation of samples less than 1℃, and applied rated voltage and ripple. After a period of aging, the capacitance and ESR of each sample is measured in 25℃ by a LRC meter. With help of the least square method, the test results will be fitted by Eq. (3) and Eq. (4) to obtain the degradation rates $A[T]$ and $C[T]$. And then, these degradation rates are fitted by Eq. (5) and Eq. (6), to obtain A_0, C_0, E_{a1} and E_{a2}.

To determine B and D, two groups of electrolytic capacitors were tested in a series of temperatures by same test platform of above tests. During this test, temperature, capacitance and ESR of each sample ware measured directly in ambient temperatures from 35℃ to 105℃. Case temperature is measured by a thermal couple attach on top side of the samples. Due to no electrical load is applied, case temperature of each sample equals to core temperature. The test results are fitted by Eq. (7) and Eq. (8) to obtain B and D.

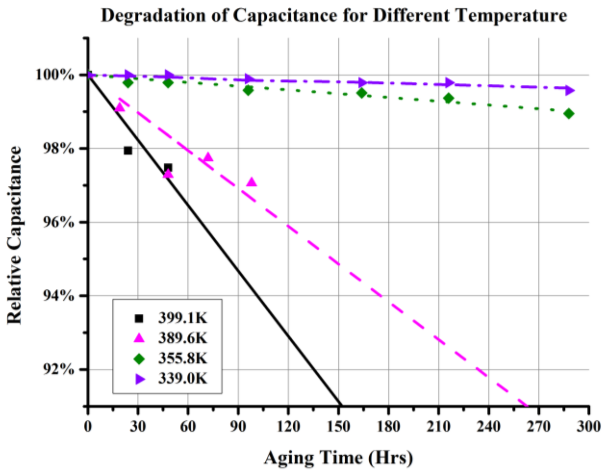
The major settings of these parameter determination tests are listed in the Table I.

TABLE I. Major Settings of Parameter Determination Tests

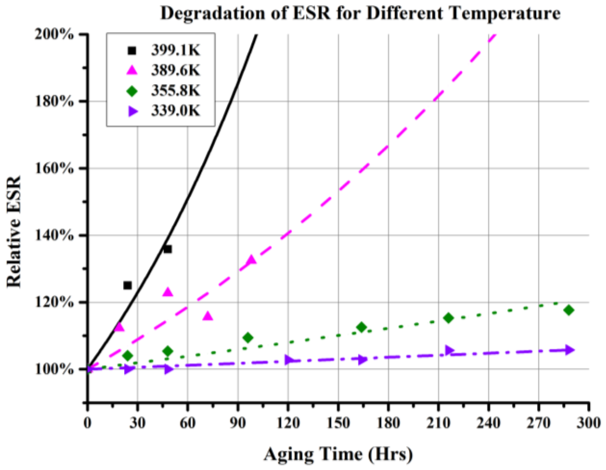
	Test 1	***Test 2***
Sample Size	4×10	2×10
Target Parameters	A_0, C_0, E_{a1}, E_{a2}	CAP_0, ESR_0, B, D
Core Temperature for Aging	339K\ 355K\ 398K\ 339K	-
Core Temperature for Testing	298K	308K to 378K
Aging Duration	0 to 300 Hrs	0 Hrs
Voltage and Ripple Level	Rated	OFF

4. Results and Discussions

In Fig. 5, the test results of the (a) capacitance and (b) ESR degradations at four different temperatures are shown by the markers, and fitted using Eq. (3) and Eq. (4) in different types of lines respectively. Obviously, decreasing of capacitance and increasing of ESR were accelerated by temperature.



(a) Relative Capacitance Degradation



(b) Relative ESR Degradation

Fig. 5. Degradations at Different Temperature

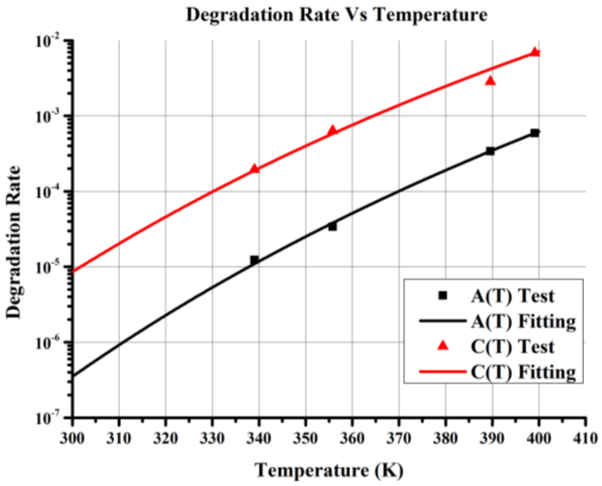
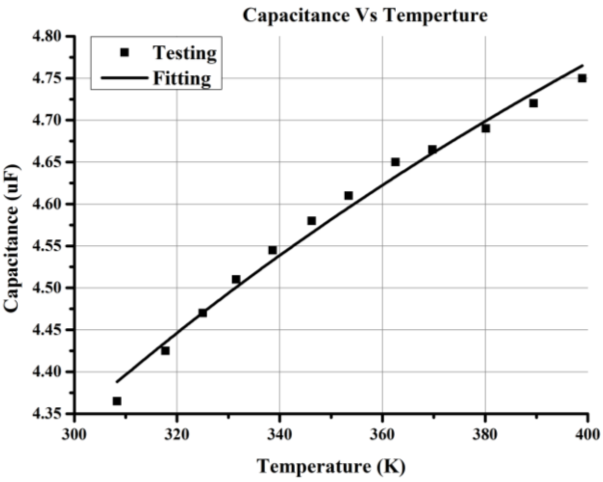
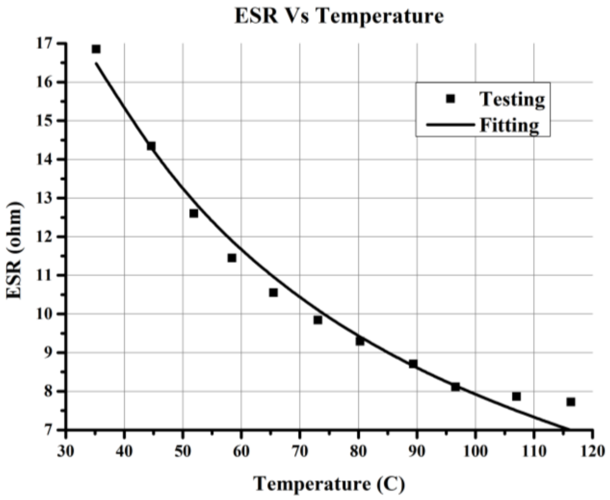


Fig. 6. Degradations Rates of Capacitance and ESR vs Temperature

Fig. 6 displays the degradation rates obtained from fitting results shown in Fig. 5 by the markers. These degradation rate are fitted using Eq. [9] and [10] in different types of lines, and thus A_0, C_0, E_{a1} and E_{a2} are calculated and listed in Table II.



(a) Capacitance in Different Temperature (@100Hz)



(b) ESR in Different Temperature (@100Hz)

Fig. 7. Parameters in Different Temperature

The capacitance and ESR of the selected electrolytic capacitors in different temperature are shown in Fig. 7. These testing results are fitted by using Eq. (7) and Eq. (8), and B and D, is calculated and listed in Table II.

TABLE II. parameters of degradation model of the selected capacitors

Capacitance			
CAP_0 (@100Hz)	***E_{a1}***	***A_0***	***B***
6.3074uF	0.773eV	3.462×10^6	-1.118×10^2
ESR			
ESR_0 (@100Hz)	***E_{a2}***	***C_0***	***D***
40.07ohm	0.694eV	3.9994×10^6	4.067×10^{-2}

5. Conclusion and Future Work

In this work, a degradation model of electrolytic capacitor is derived from physics of capacitor and experiments. This model considers the impacts of time and temperature on capacitance and ESR of a selected electrolytic capacitor shown in Eq. (5), Eq. (6), Eq. (9) and Eq. (10). With this model, performance of an electrolytic capacitor with different operation duration and different temperature can be predicted, providing a powerful tool for reliability assessment for LED drivers.

In future study, this model will be applied to reliability assessment of real LED drivers.

Acknowledgments

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