

Developing Highly Reliable LED Luminaires for High Temperature Applications Using AC-direct Driving LED Technology

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Abstract— The paper is to develop highly reliable LED luminaires for high-temperature applications, which are often needed in hush or hazardous industrial environments. An improved MIL-HDBK-217F method is introduced to study the reliability and predict the lifetime of different LED driving technologies, and confirmed by accelerated life testing results in order to optimize the design towards high reliability and long lifetime. Based on the analysis results of a AC-direct driving LED driver and a switched-mode LED driver, the paper demonstrates that the AC-direct driving technology is a better driving solution for LED luminaires used in high-temperature environments due to its capability to operate at higher temperatures and longer lifetime at the same temperature compared to the traditional switched-mode driving technology. Also, the paper has some discussions on optimizing the design of the AC-direct driving circuits for long lifetime in high temperature applications. As a result, a 4000+ lumen AC-direct driving LED luminaire is developed, which has achieved 2-3 times longer lifetime at 65 °C ambient and can operate safely up to 80 °C ambient (15 °C higher) compared to its switched-mode counterpart.

Keywords—LED driver; reliability; lifetime; AC-direct driving; high temperature

I. INTRODUCTION

As an energy-efficient lighting solution, solid-state lighting (SSL) has experienced rapid growth in recent years. Compared to convention lighting sources, LED luminaires provide significant energy saving, much longer life span, greater eco-friendliness, and equal or better quality of light. They are applied in a wide range of lighting applications including residential lighting, industrial lighting, and sign and obstruction lighting, etc.. LED luminaires are also safer with low maintenance costs due to the fact that they operate at relatively lower temperature, and are free of maintenance or has low replacement frequency because of the long lifetime. Thus, SSL becomes the mainstream illumination solution in some hush or hazardous industrial environments, where caustic chemicals, flammable materials, extreme temperatures, or combinations thereof may be present. A common requirement of LED luminaires in such kinds of industrial applications is the capability to operate at high ambient temperature. For example, in paper mill industry, the ambient temperature of a light fixture in dryer areas is as high as 65 °C. In this paper, a reliable LED luminaire is developed for such kind of high temperature applications using AC-direct driving LED technology. Reliability and lifetime study is

conducted based on the improved MIL-HDBK-217F and confirmed by accelerated life testing results in order to identify the critical components to optimize the design towards high reliability and long lifetime. The advantages of AC-direct driving LED technology for high-temperature and long-lasting applications are demonstrated as compared to traditional switched-mode driving technology. Based on these discussions, the paper also points out some critical design considerations in order to make the best of these benefits, including MOSFET and capacitor selection and thermal management.

II. OVERVIEW OF LED DRIVING TECHNOLOGIES

Switched-mode LED drivers have been adopted widely due to high efficiency. They are basically switched-mode power supplies, except for mostly current-controlled. Different topologies can be selected based on power level, power factor (PF), efficiency, size, and cost target [1-4]. In general, flyback topologies are used widely in the designs less than 100 W. To achieve higher efficiency, quasi-resonant flyback are also used at this power level. For designs over 100 W, typically two-stage layout (boost converter followed by a resonant converter) is employed. It is also very often to use multiple drivers at high power levels. Overall, flyback drivers are dominant in present LED driving market due to low cost, less part count, compactness and being easy to design. Compared to switched-mode LED drivers, linear LED drivers are low cost, less noises, and simple to implement but has low efficiency. They are often used for low power applications such as battery-powered systems until recent development of AC-direct driving LED technology [5-10]. Simply saying, AC-direct driving LED technology is to segment the rectified AC input voltage and connect different numbers of LEDs to the input power according to the specific segment voltage values in order to achieve approximate constant current flowing through each LED. The connection of LEDs to the input is controlled by semiconductor switches operating at a relatively low frequency. The current through these LEDs is regulated by a linear current regulator, and therefore AC-direct driving LED technology is essentially a linear technology modified by switching technology. It can be used for high power applications, and possible to achieve a comparable efficiency and inherent better Total Harmonic Distortion (THD) than a switched-mode LED driver, and at the same time retains the benefits of low cost and less noises. Particularly as shown as in this work, the AC-direct driving LED

technology has high reliability and superior performances at high temperatures so that it is also suitable for high temperature applications, low cost designs, or long lasting applications.

III. RELIABILITY AND LIFETIME

Unlike conventional light sources, LEDs do not fail catastrophically. The light output of LEDs is the highest at the first use, and then declines gradually over time. Thus, their lifetime is defined as the time when the light output is reduced to certain percentage from its initial value. For example, L70 lifetime is specified as the time when the light output is reduced to 70% of its initial value. Currently, IES LM-80-08 and TM-21-11 methods are widely accepted for single LED testing and lifetime prediction. Based on top-brand white LED manufacturers' LM80 and TM21 data [11-14], most of mid-power and high-power packaged LEDs has L70 lifetime around 42,000+ ~ 60,000+ hours at the specified operation temperature range. However, the LED luminaires are more than just a single LED. They have many other components, such as drivers, optics, thermal management, electrical connections and mechanical assembly, etc. Among all these components, LED drivers have the shortest lifetime, especially at higher temperatures. For the typical industry temperature range from -40° C to 55 °C, considering proper cooling and reasonable cost, the corresponding highest operation temperature of a LED driver is about 75 °C - 85 °C. Based on driver manufacturers' specifications, most of off-shelf LED drivers in the market today have a life span less than 30,000 hours at these temperatures, which is about half the life of LEDs. Thus, in high temperature applications, the LED driver lifetime dominates the luminaire lifetime. In the following sections, the paper will focus on the discussions of LED driver lifetime in order to extend luminaire life span by designing a long-lasting LED driver.

A. MTBF/MTTF and Lifetime Calculations

Reliability is defined as the probability that a certain number of units will pass (or fail) within a specified period at a given failure rate. It is measured by Mean Time Between Failures (MTBF, for serviceable products) or Mean Time To Failures (MTTF, for non-serviceable products). MTBF/MTTF can be used to estimate lifetime with a proper distribution model. Like many other manufactured products, the failure regions of electronic and semiconductor devices can be divided into three periods of time: early life region, random failure region (useful life), and wear out region. The time-dependent trend of the failure rate in each period is represented by the bathtub curve in Fig. 1 [15]. The reliability of a product is studied in the useful life region (the bottom of the curve), where the failure rate, λ , is constant, and the reliability distribution can be fitted into the exponential model (a special case of Weibull distribution) [16]. Under this model, the relationship of reliability r and lifetime t can be represented by (1), where $\lambda=1/MTTF$. The driver lifetime in this work is defined at $r = 90\%$ (90% driver survive rate). Then, the lifetime is calculated by equation (2).

$$r(t) = e^{-\lambda t} \quad (1)$$

$$t = 0.10536 / \lambda \quad (2)$$

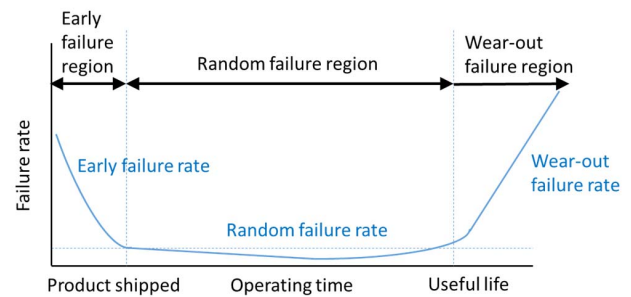


Fig. 1. General Manufactured Product reliability Curve

B. Failure Rate Calculations

Parts stress analysis prediction method is used in this work. The main concept of part stress analysis is that the overall driver failure rate is equal to the sum of individual failure rate of each component. Even the failure rate of an individual component varies a lot depending on the topologies, operation modes, control algorithms, and environmental factors, the failure rate of the same type of components under the same conditions are similar and responses similarly to the same kind of stress. Thus, it is reasonable to introduce a base failure rate for each type of component at typical stress level and a stress factors to reflect an actual level of stress. Then, the individual component failure rate can be calculated by multiplying its base failure rate with the stress factors corresponding to the specific stress which the individual device is subjected to. The base failure rates and stress factors are empirical values or values based on the measurement on practical drivers, which can be found in MIL-HDBK-217F reliability handbook [17]. Besides, in order to determine the actual stress level, power losses and case temperature may need to be measured or estimated.

Due to numerous assumptions and dated database, MIL-HDBK-217F method yields very conservative estimations. It cannot provide an exact figure for reliability. In order to obtain more realistic estimations, instead of using MIL-HDBK-217F method, the failure rates of critical components in LED drivers are replaced by the specific manufacturer's data or calculated by more accurate methods using the specific manufacturer's data pertaining to the exact components. The critical components include aluminum electrolytic capacitors, switching components, and controller ICs, which are identified as the components have the most impact on the lifetime of LED drivers [18 - 19]. Take aluminum electrolytic capacitors as an example, due to the dry-out effect inside these capacitors, the capacitance of these capacitors degraded as time going. Typically, the lifetime of the capacitors is defined at the point when the change of capacitance reaches $\pm 25\%$ of its initial value, and the lifetime at rated conditions is specified in manufacturer's datasheets. For a capacitor not operating at rated conditions, the impact of operation temperature and current ripple on the lifetime needs to be considered in order to derive the lifetime for applied operating condition [20 - 21]. Then, this lifetime can be used to calculate the capacitor failure rate by (2). The resultant failure rate can be used in the part stress analysis. Similar process can be performed for other critical components.

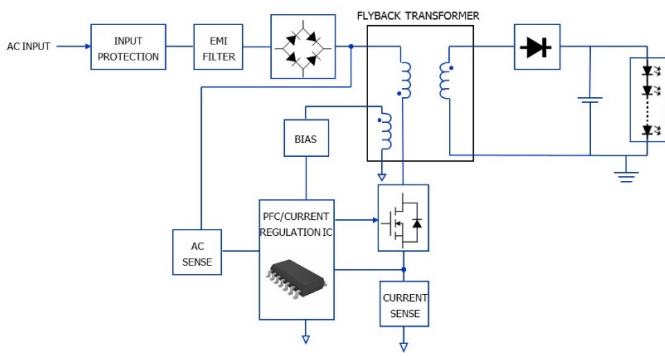


Fig. 2. Topology of the switched-mode LED driver

In the work, this method is applied to a LED driver (its topology is shown in Fig. 2) to estimate its lifetime. The results are shown in Fig. 3 and compared to the lifetime obtained using an accelerated testing method (ALT). As shown in the Fig. 3, there is a good match between the two set of results, which demonstrates the accuracy of the proposed method (improved PSA) in this work.

C. Reliability and lifetime estimations of LED Drivers

An AC-direct driving light engine (driver plus LEDs) is developed, which can deliver 4000+ lumen light output at a rated input voltage of 120 VAC. Its topology is shown in Fig. 4. Applying the method introduced in the previous subsections, the lifetime of this driver can be estimated, and compared to that of the switched-mode driver (SMD) with a similar power rating shown in Fig. 2. The lifetime at 90% reliability of both drivers are plotted in Fig. 5. As seen from Fig. 5, the lifetime of AC-direct driving LED driver is about 2-3 times longer than the switched-mode driver at the same temperature from 25 °C to 65 °C ambient, and above 65 °C, the switched-mode driver is not able to handle due to some component temperatures exceeding the design limits, while the AC-direct driving driver can operate with reasonable lifetime up to 80 °C.

Further, the failure rate by component groups for both drivers are plotted in Fig. 6. For both driver technologies, the failure of capacitors dominates the driver failure and limit its

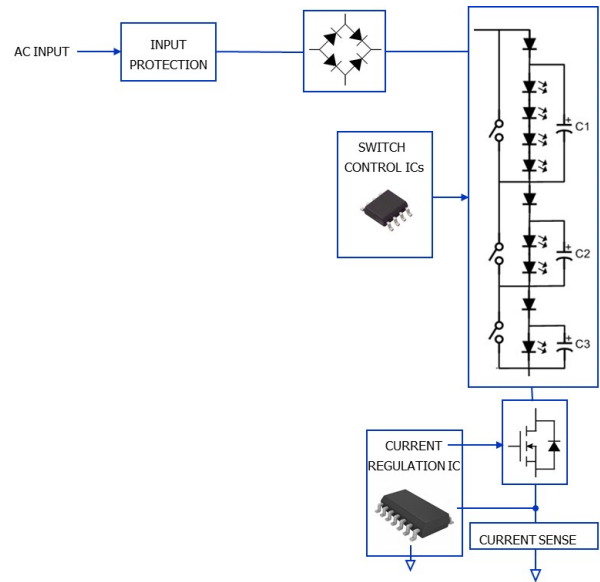


Fig. 4. Topology of the AC-direct driving LED driver

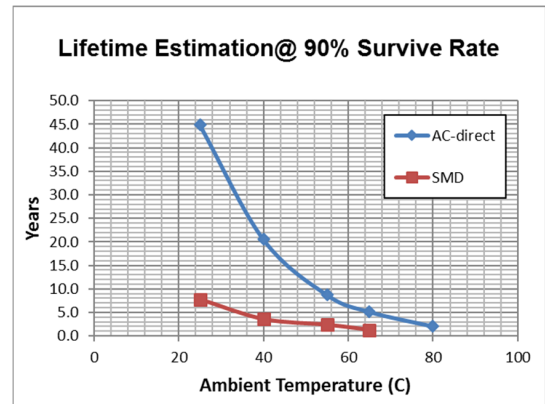


Fig. 5. Lifetime of the LED drivers

lifespan, especially at high temperatures. Thus, select long-lifetime capacitors can help extend driver lifetime. Unlike switched-mode drivers which need bulky filter capacitors and typically implemented by aluminum electrolytic capacitors, the capacitance value required by AC-direct-driving technology is relatively small and can be realized with long-lifetime aluminum electrolytic capacitors or solid electrolytic capacitors. The capacitor values can be determined by flicker requirements. For the design in this work, aluminum electrolytic capacitors with the best available lifetime are selected. For the AC-direct driving light engine in this work, the lifetime of the selected capacitors is 5000 hours @ 125 °C, and 10,000 hours @ 105 °C for the switched-mode driver. The capacitor values and failure rates of these capacitors are presented in Table I. It can be seen that the failure rates of the capacitors in the AC-direct driving light engine are much smaller, which significantly increases its lifetime.

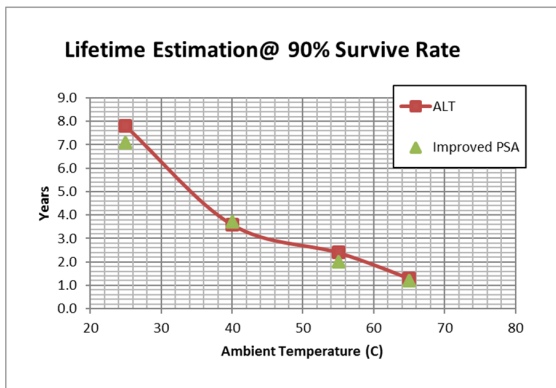
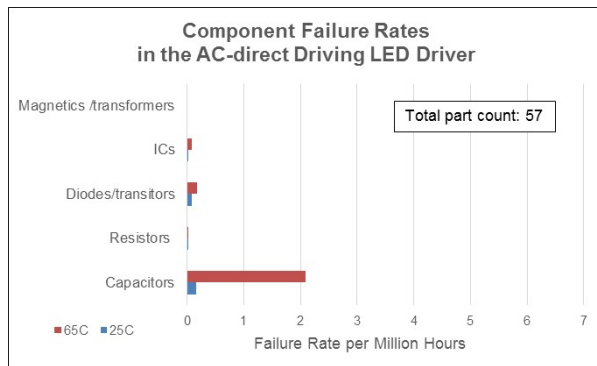
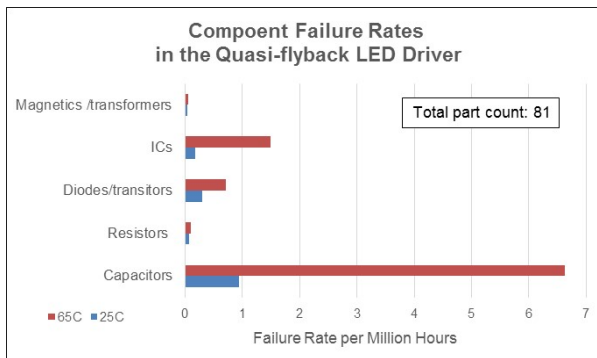


Fig. 3. Comparison of estimated lifetime to testing results



(a) AC-direct Driving LED driver



(b) Switched-mode LED driver

Fig. 6. Failure rates of LED driver components

TABLE I. CAPACITORS AND FAILURE RATE ESTIMATION

| Parameters | | Failure Rate | | |
|------------|-----------------------------|--------------|-------|-------|
| | | 25 °C | 40 °C | 55 °C |
| C_1 | 100V/33 μ F \times 2 | 0.049 | 0.145 | 0.411 |
| C_2 | 50V/220 μ F \times 1 | 0.039 | 0.118 | 0.334 |
| C_3 | 25V/470 μ F \times 1 | 0.041 | 0.122 | 0.342 |
| C | 100V/330 μ F \times 3 | 0.240 | 0.679 | 0.960 |

IV. HIGH TEMPERATURE APPLICATION EXAMPLE AND DESIGN CONSIDERATIONS

The power losses of a AC-direct driving LED driver almost concentrate on a single component — the MOSFET in the current regulator, which operates in linear mode. As shown by the test results in Fig. 7, the power losses of the MOSFET account for 82% - 97% of the total driver losses over the input voltage range. Thus, it is preferred to select MOSFETs with high allowable maximum power dissipation and low thermal impedance. Extended thermal pad and local heatsink can also help improve high temperature performance and increase reliability and lifetime. Since the MOSFET operates in linear mode at a low switching frequency, the MOSFET power losses are approximately equal to its conduction loss, which is determined by the product of its average voltage and average current, and almost constant at all temperatures (see Fig. 7).

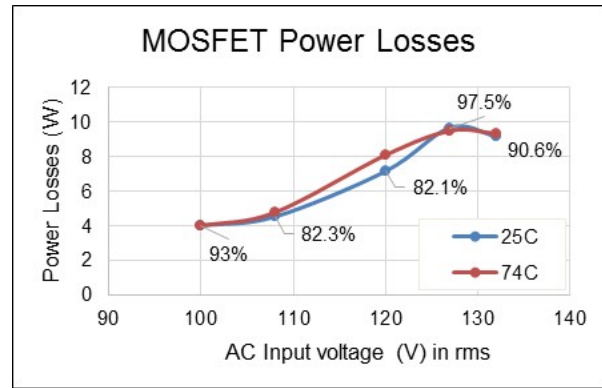


Fig. 7. Power losses of the MOSFET

Thus, the power loss estimation at ambient temperature is sufficient for the thermal design across the operation temperature range.

With the proper selection of the MOSFET and thermal design on driving circuit layout combined with the application of long-lifetime capacitors, the AC-direct driving light engine in Fig. 3 is developed into a luminaire with 4000+ lumen light output at a rated input voltage of 120 VAC. It has achieved ~106 lm/W of efficacy, 0.99 power factor, 1.62% THD, and < 30% flicker percentage (controlled by the capacitors C1-C3 in Fig. 4). The thermal tests have confirmed its proper operation at an ambient temperature up to 80 °C. Compared to a luminaire driven by the switched-mode drivers in Fig. 4 with similar light output and a maximum operation temperature of 65 °C ambient, the light engine cost is reduced by 60%, plus 13% enclosure cost saving (due to the simplified design with integrated driver circuits and LED circuits), which leads to an overall lumen per dollar improvement of 62%. Based on the lifetime estimation in Fig. 5. The luminaire is expected to have 2-3 times longer lifetime and additional 15°C operation range above 65 °C ambient compared to its counterpart with switched-mode drivers.

V. CONCLUSIONS

In general, compared to the traditional switched-mode driving technology, AC-direct driving technology has higher power factor, lower THD, lower cost, less complexity, and is more compact and easier to be scaled up. In addition to these advantages, through the reliability analysis and the design example, this work demonstrates that, with proper selection of components and thermal design, the AC-direct driving LED technology can achieve a luminaire capable to operate at a higher temperature with a longer lifetime at comparable efficacy and lower cost in terms of lumen per dollar. Thus, AC-direct driving technology is a good choice for high temperature and/or long lasting applications. As another way to take advantage of this technology, designs can be optimized towards low cost, which makes AC-direct driving technology also a solution for low-end luminaire products.

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