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A return on investment analysis of applying health monitoring to LED lighting systems

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ABSTRACT

LED lighting systems have become desirable because of their environmental and energy-saving advantages. The lack of information regarding LED reliability is a barrier to the further expansion of LED use, especially in large-scale applications such as street lighting and traffic lights, and safety-related applications such as automotive headlights. Prognostics and health management (PHM) techniques can be utilized to provide LED reliability information to remove this barrier. However, the return on investment (ROI) for LED lighting systems has been of concern. To reduce life cycle cost, a PHM maintenance approach with system health monitoring (SHM) is considered as a means of providing early warning of failure, reducing unscheduled maintenance events, and extending the time interval of maintenance cycles. This paper presents the ROI from a PHM maintenance approach with SHM in LED lighting systems compared with the unscheduled maintenance approach based on different exponential and normal failure distributions. Three different exponential distributions with 10%, 20%, and 30% failure rates were used to investigate how ROI changes with different failure rates. For each failure rate, the mean times to failure (MTTFs) were 41,000 h, 20,500 h, and 13,667 h, respectively. Three normal failure distributions with the same MTTFs as those of the exponential distributions were utilized to compare the results with the exponential distributions. ROI results showed that the PHM maintenance approach with SHM is required for cost savings in the exponential failure distributions. In case of the normal distributions, the PHM maintenance approach with SHM shows ROI benefits when MTTFs are less than 30,000 h. The PHM maintenance approach with SHM needs to be considered in industrial applications based on the reliability of LED lighting systems to maximize the ROI benefit when the total life cycle cost of the system employing the unscheduled maintenance is greater than the total life cycle cost of the system employing the PHM maintenance approach with SHM.

1. Introduction

LEDs have been used in a wide variety of applications, including display backlighting and general illumination [1–3]. An LED consumes less electrical energy (LED power requirements are usually less than 4 W per LED) than an incandescent bulb or a fluorescent lamp because its luminous efficiency (i.e., the ratio between the total luminous flux emitted by a device and the total amount of electrical power) is higher than the luminous efficiencies of incandescent bulbs and fluorescent lamps. Typical value of luminous efficiency (lm/W) of LEDs is 100 lm/W for public lamp and maximum efficiency of LEDs is 180 to 200 lm/W in industrial applications. Incandescent lamp is 15 lm/W; fluorescent is around 100 lm/W; and Na lamp is up to 180 lm/W. Critical key values judging the quality of white light produced by phosphor converted LEDs are known as the color rendering index (CRI) and the correlated color temperature (CCT) [1,3]. CRI of LEDs can be more than 90 as close as CRI of the incandescent lamp. LEDs range from a narrow spectral band emitting light of a single color to a wider spectral band light of white with different distribution of luminous intensity and spectrums and shades depending on color mixing and package design.

LED lighting systems have differentiated themselves from traditional lighting systems (e.g., incandescent bulbs and fluorescent lamps) in terms of flexible lighting control and energy savings. Flexible lighting control means that an LED lighting system can give off light beneficial to human wellbeing by using artificial intelligence-based color and light output control [4]. An LED lighting

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system can provide comfortable white light close to the color of sunlight, which is considered beneficial to human biological rhythms and human psychology (by producing appealing colors that appear in nature) [4]. In addition to comfortable white light, LED lighting technology achieves digital convergence—the convergence of information technologies, telecommunication, consumer electronics, and entertainment into one conglomerate. LED usage is also compliant with environmental regulations for hazardous substances (e.g., the Kyoto Protocol, RoHS, and WEEE).

The LED industry, despite exciting innovations driven by technological advances and environmental/energy-saving potential, still faces challenges to widespread adoption. With the adoption of LED systems in Europe and the US, the LED industry is optimistic about the global LED street lamp market, but the reliability and, thus, the life cycle costs remain a concern. Tao [5] reported that failures of LED modules (i.e., an LED board with an electric driver) include case cracks, driver failures, and ESD failures [6]. Failures at the luminaire level (i.e., a complete lighting unit that includes a lamp or lamps, optics, ballasts or drivers, power supplies, and all other components necessary to have a functional lighting solution) include fractures due to vibrations, moisture-related crack failures, electrolytic capacitor failures, current imbalance failures in parallel LED strings, corrosion due to water ingression, and deposition of out-gassing material on the optics [5,7,8]. The electrolytic capacitor serves as an energy buffer between the pulsating input power and constant output power, without causing flickering while taking up the minimal volume. The electrolytic capacitor is a major failure component, as is cooling fan failure in power supplies [7]. Software failures, damage from strong winds, lens breakage, and electrical compatibility issues have been found at the lighting system level (i.e., a street light with a luminaire) [5,8].

To ensure the proper operation of LED lighting systems in applications that are safety–critical or involve operation in a harsh environment, it is necessary that optical degradation, current sharing, open and short circuit faults, and thermal tracking of LEDs be monitored, especially for high-power applications such as street lighting. Prognostics and health management (PHM) is an extension of condition-based maintenance of critical systems [9,10]. Prognostics is the ability to extrapolate the health condition of a product forward to predict its remaining useful life (RUL). Health management is based on system health monitoring (SHM). System health monitoring is defined as the ability to determine the instantaneous condition of a product through in-situ performance monitoring. The purpose of applying PHM is to assess the degree of deviation or degradation from an expected normal operating condition for a product, such as an LED lighting system [9,10]. The goals of using PHM include providing advance warning of failures, minimizing unscheduled maintenance, extending the time duration of the maintenance cycle, reducing the life cycle costs of equipment, and improving qualification and the design and logistical support of future products [10].

Freddi et al. [11] developed a fault diagnosis and prognosis methodology for LED lighting systems based on system health monitoring with a light sensor, motion sensor, temperature sensor, and current sensors that are controlled by a communications control system. They developed a fault diagnosis and prognosis supervision module integrated into a smart lighting system to detect and isolate faults. This module also provides an estimate of the remaining useful lifetimes of LED lighting systems for industrial and domestic applications. Sutharssan et al. [12] performed LED anomaly detection based on Euclidean distance (ED) and Mahalanobis distance (MD). They collected applied voltage, current, light, and temperature in real time for system health monitoring (SHM). The detection thresholds were identified at the point where the light output started to decrease. Furthermore, real-time system health monitoring was conducted based on data from a voltage sensor and a temperature sensor to monitor board temperature and forward current to predict the remaining useful life of LED lighting systems in the field using prognostics algorithms [13]. Fan et al. [14] monitored chromaticity coordinates u' and v' in real time to detect anomalies based on MD values. Two inputs (voltage and ambient temperature) and two outputs (current and body temperature of the light engine) were monitored to control LED current to a constant value with variation of the ambient temperature for ensuring stable optical output from LEDs [15].

Return on investment (ROI) is the monetary benefit derived from having spent money on developing, changing, or managing a product or system. ROI is a common economic measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. ROI is the ratio of gain to investment, often given by the equation

$$\mathrm{ROI} = \frac{return - investment}{investment} \quad (1)$$

An ROI of 0 represents a break-even situation, i.e., the monetary value gained is equal to the monetary value invested. If the ROI is <0 there is a loss, and if the ROI is >0 there is a gain, i.e., a cost benefit.

Studies have been conducted to evaluate the benefits of LED lighting systems as replacements for conventional lighting systems (such as high-pressure sodium (HPS) lighting systems [16–18], metal halide lighting systems [19], fluorescent lighting [20], mercury lamp lighting [21], and incandescent lamp lighting [22]). ROI research on LED lighting systems [16–22] has assumed that LED lighting systems are successfully maintained over long lifetimes (e.g., 100,000 operating hours [22]). These results have shown that LED lighting systems have financial benefits when compared to conventional lighting systems.

Recent ROI research on LED lighting systems has shown that ROI can be maximized with an interface with a wireless sensor network and by considering the optimal year for replacement of the conventional lighting systems [23,24]. Kathiresan et al. [23] implemented an interactive LED lighting interface using a wireless sensor network to adjust the illumination level of individual lamps to lower maintenance costs and provide higher energy savings for LED lighting systems. Potential energy savings using the smart lighting interface were reported as 3 SGD (Singapore dollars) per year per street light. Ochs et al. [24] developed a model to predict the optimal year for the most cost-effective replacement of HPS lighting systems with LED lighting systems. Delaying the purchase resulted in additional financial benefit because the cost of LEDs continues to decrease, and LED efficiency continues to increase. The proposed method recommended delaying adoption by an average by an average of 6.8 years, as compared to a traditional net present value (NPV) analysis. This delay resulted in an average life cycle savings of 5.37 percent over a 50-year life cycle when compared to the life cycle costs incurred by adopting LED streetlights in the first year that these streetlights were shown to have a positive NPV.

Even though previous ROI research on LED lighting systems assumed that LEDs are good replacements for conventional lighting systems, reliability issues with LED streetlights must be resolved to reduce life cycle costs caused by failures of LED modules, fractures due to vibrations, moisture-related crack failures, electrolytic capacitor failures, current imbalance failures, corrosion, and deposition of out-gassing material on the optics [5–8], as discussed earlier. A PHM approach using SHM can be used to improve the availability and achieve cost benefits when LED streetlights are installed. However, little research has been conducted on the determination of ROI to verify how PHM maintenance using SHM can be cost-effective and applicable to the LED lighting industry.