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Prognostics-based qualification of high-power white LEDs using Lévy process approach

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ABSTRACT

Due to their versatility in a variety of applications and the growing market demand, high-power white light-emitting diodes (LEDs) have attracted considerable attention. Reliability qualification testing is an essential part of the product development process to ensure the reliability of a new LED product before its release. However, the widely used IES-TM-21 method does not provide comprehensive reliability information. For more accurate and effective qualification, this paper presents a novel method based on prognostics techniques. Prognostics is an engineering technology predicting the future reliability or determining the remaining useful lifetime (RUL) of a product by assessing the extent of deviation or degradation from its expected normal operating conditions. A Lévy subordinator of a mixed Gamma and compound Poisson process is used to describe the actual degradation process of LEDs characterized by random sporadic small jumps of degradation degree, and the reliability function is derived for qualification with different distribution forms of jump sizes. The IES LM-80 test results reported by different LED vendors are used to develop and validate the qualification methodology. This study will be helpful for LED manufacturers to reduce the total test time and cost required to qualify the reliability of an LED product.

1. Introduction

High-power white light-emitting diodes (LEDs), with the advantages of high inherent reliability, long service life, high energy efficiency, fast switching speed, small size, and environmental friendliness, have been applied in many fields, including general illumination, automotive lamps, display backlighting, communications devices/networks, and medical applications [1–5]. The requirements of high reliability and long lifetime pose new challenges in research and development (R&D), production, and the application of LED lighting.

Similar to other new electronic devices, qualification testing is an essential part of the product development process to ensure the reliability of a new LED product before its release. Reliability qualification refers to the process of demonstrating that a product is capable of meeting the specified reliability requirements, usually by testing in accelerated conditions and proven models [6,7]. While anomaly detection is a related concept similar to product qualification, it refers to the process of identifying when a product does not conform to its expected performance or functional requirements during normal

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operating conditions [8–10]. Even though there are some similar points between these two concepts, there are still some differences between them. The biggest difference is that reliability qualification mainly concentrates on exporting reliability parameters, such as reliability function, mean time to failure (MTTF), while in anomaly detection, the current value of a certain performance characteristic is compared with the rated value (usually called criterion), so the status of a product/system can be detected. The reliability related parameters usually cannot be obtained in anomaly detection.

In general, the rated lumen maintenance lifetime ($L_p/L_{50}/L_{70}$), recommended by the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), is the most popular characteristic used to qualify the performance, life, and reliability of LED lighting [11]. Nowadays, the IES-TM-21 standard approved by IESNA (Illuminating Engineering Society of North America), is the most commonly used by many LED manufacturers in the LED industry to qualify LED light sources [12]. The collected lumen maintenance data is based on 6000 h (or more) of testing following the IES LM-80 standard [13]. For system-level LED products, such as lamps or luminaires, the recently released IES-TM-28 is used to project long-term luminous flux maintenance [14]. Similarly, the required data can be obtained using approved methods according to IES-LM-84 standard [15]. The exponential regression model and least-squares regression (LSR) approach are employed in IES-TM-21 and IES-TM-28. However, in practical applications, both IES-TM-21 and IES-TM-28 will generate large errors caused by different types of uncertainties such as those in design, materials, manufacturing processes, and operational conditions (e.g., driven current, temperature, humidity). In addition, these standard require a long testing time (usually more than 6000 h) and costly testing processes [1]. Thus, it is necessary to develop an accurate and effective method for LED manufacturers to perform product reliability qualification testing using anomaly detection and remaining useful life (RUL) prediction in a shortened/acceptable testing time (e.g., less than 1000 h) and with reduced/affordable testing cost.

Prognostics refers to the process of predicting the future reliability or determining the RUL of a product by assessing the extent of deviation or degradation from its expected normal operating conditions [16–20]. Sun et al. [21] discussed the potential benefits, challenges, and opportunities associated with system prognostics. Li et al. [22] proposed an improved exponential model to overcome the shortcomings exist in the RUL prediction of rolling element bearings. Prognostics enables LED developers and users to obtain many benefits, such as improvement of the accuracy of reliability prediction and useful lifetime assessment, optimization of LED system design, reduction of qualification test time, availability of condition-based maintenance for LED-based systems, and feedback of information for return on investment analysis.

Several previous studies have been conducted on anomaly detection or qualification in LEDs. Jeong et al. [23] proposed a screen method that can be used for screening LEDs with leakage problems in mass production, which will cause brightness degradation. Sutharssan et al. [24] detected anomalies based on Euclidean Distance (ED) and Mahalanobis Distance (MD) measurement techniques. The RUL of LEDs was estimated by considering light output degradation failure. Dong et al. [25] proposed a photosensor system based estimation approach to diagnose the lumen depreciation failure of individual LEDs in LED lighting systems. Fan et al. [26,27] used a data-driven method based on a multivariate MD distance measure to detect the chromaticity shift anomaly of high-power white LED after aging tests. Chang et al. [28,29] developed a technique, called the similarity-based metric test, to identify anomalies. This study mainly deals with the color shift failure of LEDs by extracting the features from the spectral power distributions (SPDs), calculating the ED from the test data point to the centroid of each cluster, and comparing the ED with a predetermined threshold. Meanwhile, studies aimed at shortening the qualification testing time have also been conducted. For example, Fan et al. [30] conducted a wet high temperature operation life (WHTOL) test on a typical mid-power LED. The results of the lumen degradation trend indicated that the WHTOL test can be used for the prediction of LED lumen maintenance lifetime in a relatively short period of time. Yang et al. [31] designed an accelerated aging test, considering only the effect of temperature on high-power LEDs. The experimental results show that the unstable period of an LED can be clearly shortened by applying high-temperature conditions.

However, the above mentioned studies have been carried out mainly using the anomaly detection method, without providing detailed reliability information. In actual fact, the reliability information with respect to lifetime or RUL of LEDs is of great significance to manufacturers, as well as to the potential users. In addition, the above studies have focused on anomaly detection at a certain moment, without reliability estimation capability and prognostics capability for future operating conditions. The prognostics method based on the stochastic process model is an important part of the current LED reliability qualification. Park et al. [32] utilized the gamma process to describe the lumen flux degradation, and the results showed that the gamma process works well in modeling the gradual and continuous degradation process. Hao et al. [33] used the gamma process to model the LED lumen degradation and chromaticity shift process respectively, and the dependency of these two performance characteristics (PCs) was described by a Frank copula function. Finally a dual PCs model for LED degradation was constructed and the experimental results indicated that the built model is more accurate than a model that just considers one PC. The gamma process is a gradual and continuous process, which usually can be used to describe the continuous degradation process, such as wear and corrosion. In practice, few products/systems experience a pure gradual degradation process. Due to the effect of various random factors, the actual degradation process of LEDs is characterized by random sporadic small jumps. As a result, a novel model combining the gamma process and the compound Poisson process is presented, as the new model takes sporadic jumps of LEDs degradation into consideration and describes the degradation process more precisely. The reliability qualification results produced by this model can be more accurate than the model based on the gamma process only.

A method for conducting reliability qualification based on the prognostics of LEDs is presented in Section 2. The lumen flux is selected as the degradation indicator. A Lévy subordinator of a mixed Gamma and compound Poisson process is used to describe the actual degradation process of a high-power white LED characterized by random sporadic small jumps. Then,