International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 335

OPTIMAL MAINTENANCE PLAN WITH LUMEN DEGRADATION FAILURE FOR ENERGY EFFICIENCY LIGHTING RETROFIT PROJECTS

Alice Ikuzwe*, Xiaohua Xia, Xianming Ye

Centre of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, 0002 Pretoria, South Africa

ABSTRACT

An optimal lighting maintenance plan that considers the lumen degradation failure is proposed for energy efficiency lighting retrofit projects. In lighting retrofit projects, lamp population is subject to decay, resulting in reduction of the project performance. The decay of lamp population is mainly caused by the burnout failure or lumen degradation failure. In the previous studies, lighting maintenance plan is investigated by modelling the burnout failure. In this study, we present an optimal lighting maintenance plan by modelling the lumen degradation failure. The effectiveness of the formulated maintenance plan is demonstrated by a practical residential light-emitting diode (LED) lighting retrofit project.

Keywords: Energy efficiency lighting system, lumen degradation failure, optimal maintenance.

1. INTRODUCTION

Electric light sources undergo two main failure modes; burnout (catastrophic) failure and lumen degradation failure. The burnout failure is mostly caused by defective materials, deviations in the manufacturing process or by incorrect handling and operation by the customer [1], and the lumen degradation failure is based on increased wearing and aging of the material [2]. In lighting retrofit projects, the failure of retrofitted lights leads to the reduction of illumination level and energy savings if proper maintenance is not carried out.

For energy efficiency lighting retrofit projects registered under different incentive programmes such as Clean Development Mechanism (CDM), a penalty factor to the energy savings is applied, which restricts that no rebate will be given to the implemented project when 50% of the initial population is failed during the project crediting period [3]. In consideration of lumen degradation, the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), found that 70% lumen degradation is close to the threshold at which the human eye can detect a reduction in light output, and recommends 70% lumen degradation threshold to determine the useful life of LEDs for general lighting applications [4]. Therefore, for LED-based lighting retrofit projects, 70% lumen threshold criteria might be considered to maintain both visual comfort and energy savings.

In the literature, various models of lamp population decay have been proposed. The AMS-II.J CDM guideline suggested a linear population decay for compact fluorescent lamps [5]. This model has been applied in [6] for optimal sampling design for measurement and verification (M&V). The Polish efficient lighting project (PELP), conducted by the World Bank through the international finance corporation, presented a logistic curve for a population of 1.2 million lamps [7]. Carstens et al. [8] proposed a model derived from existing biological population growth equations for modelling the decay of compact fluorescent lamps over time. The lighting maintenance plans developed in the literature studies [9],[10] are mainly based on burnout failure. However, lighting maintenance plans considering the lumen degradation failure are still unexplored.

The main contribution of this study is the formulation of an optimal lighting maintenance plan that takes lumen degradation failure into account. In existing studies, lumen degradation failure was not considered in formulation of optimal lighting maintenance plans. Lumen degradation when neglected can not only cause energy savings reduction but also lead to an inadequate

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

illumination level, which can affect the quality of work, specifically in situation where precision is required, and overall productivity.

In this study, lumen degradation failure is modelled by analysing the statistical properties of degradation rates. The formulated lumen degradation failure model is incorporated into the optimization problem to estimate the survival population and energy savings. The optimal maintenance plan is formulated to maximize the energy savings and minimize the maintenance cost. The optimization problem is solved using Mixed Integer Distributed Ant Colony Optimization (MIDACO) solver in MATLAB R2017b.

The remainder of this paper is organized as follows: Lumen degradation failure model is formulated in Section 2. Formulation of the lighting maintenance into an optimization problem is elaborated in Section 3. A case study is given in Section 4. Simulation results are given in Section 5, and Conclusion is presented in Section 6.

2. LAMPS FAILURE MODELLING BASED ON LUMEN DEGRADATION

In the literature, the lumen degradation of LEDs is modelled using the exponential decay model as

$$\phi(t)=\phi(0)\exp\left(-\beta t\right), \tag{2.1}$$

where $\phi(0)$ is the initial luminous flux (lm) and β is the degradation rate.

The lumen degradation of LEDs is accelerated or lessen by the degradation rate. The degradation rate may vary among LEDs due to operating conditions, variance in materials, or different manufacturing processes. In this study, the lumen degradation failure of LEDs is modelled by analysing the statistical properties of the degradation rates.

The data used to model the lumen degradation failure are obtained from IESNA LM-80 test report of Philips Lumileds [11]. In this report, lumen degradation of 25 LEDs LUXEON rebel, Lumileds Philips are tested in compliance with LM-80-08 standard.

The following assumption are applied for modelling:

- Lumen degradation L_p is measured on sample test units at every pre-specified time t , $t=1,2,\dots,K$. The observed degradation measurement in i unit at time t is represented by $L_{p,i}(t)$, $i=1,2,\dots,n$.
- Lumen degradation threshold ($L_{p,th}$) of 70% is considered. When $L_{p,i}$ at time t reaches $L_{p,th}$, the lighting unit is deemed as failed.

The cumulative failure distribution function is expressed as

$$F(t)=P\left[\epsilon\le t\right], \tag{2.2}$$

where ϵ is the lifetime of LED. Assume the degradation rate of LED is known and $L_{p,th}$ is set, ϵ can be expressed as

$$\epsilon=\frac{\ln\left(L_{p,th}\right)}{-\beta}. \tag{2.3}$$

Substituting (2.3) in (2.2), we obtain

$$F(t)=P\left[\frac{\ln\left(L_{p,th}\right)}{-\beta}\le t\right]. \tag{2.4}$$

By using the non-linear least squares method, the degradation rates are estimated for each test unit. Regression analysis is used to examine the relationship between time and luminous flux. It is found that the data used are characterised by exponential models with R^2 between 0.97 and 0.99. To determine the statistical distribution that best fits the degradation rates, the probability distribution fitting method is used. 57 probability distributions were tested to find the best distribution fit, and Generalized Extreme Value (GEV) distribution was found to be the best fits and is used to estimate $F(t)$.

β_i follows the GEV distribution with shape parameter ι, location parameter ν, and scale parameter κ. $\beta\sim\text{GEV}\ (\iota,\nu,\kappa)$, the GEV cumulative distribution is given as

$$F(t)=\exp\left[-\left(1-\left(\frac{\frac{\ln\left(L_{p,th}\right)}{-t}-\iota}{\nu}\right)\times\kappa\right)^{\frac{-1}{\kappa}}\right]. \tag{2.5}$$

Distribution parameters ι , ν and κ are estimated using the L-moment estimators. It is found that the GEV distribution of the degradation rates is characterized by

$\iota = 1.386\times10^{-5}$, $\nu = 4.001\times10^{-6}$, and $\kappa = -0.286$. The distribution fit for degradation parameters is tested at 95% confidence level using Kolmogorov Smirnov, Anderson Darling, and Chi-Squared goodness of fit tests.

By using Kaplan-Meier method the survival population is calculated as

$$N(t+1) = N(t)\prod_{j=1}^{t}\left(1-\frac{d(j)}{N(j)}\right), \quad (2.6)$$

where $d(j) = N(j-1)F(j)$ is the number of LEDs failed (with luminous flux below threshold) at time j.

3. OPTIMIZATION FORMULATION

The number of replaced lamps over the evaluation period is considered as the design variable of the lighting maintenance optimization problem. Let $u(t)$ denote the number of lamps to be replaced at time t, the set of design variable over the evaluation period K is given as

$$X = \left[u(1), u(2), ..., u(K)\right]^T. \quad (3.1)$$

The optimization problem has two objectives; maximize energy savings and minimize maintenance costs. The weighed sum method is used to translate multi-objective optimization into a single objective optimization problem as

$$\min \ J = -\alpha_1\frac{W}{\overline{W}} + \alpha_2\frac{M_c}{\overline{M_c}}, \quad (3.2)$$

where W and M_c are the energy savings (kWh) and maintenance cost (R), respectively, over the evaluation period, α_1 and α_2 are the weighting coefficients which are in range $[0,1]$, and $\alpha_1+\alpha_2$=1. $\overline{M_c}$ and $\overline{W}$ are the maximum values of maintenance cost and energy savings, respectively, which are used to normalize the objective function.

$$W = \sum_{t=1}^{K} ES\times N(t),$$

(3.3)

where ES is the energy savings (kWh) per retrofit unit. By considering the maintenance, the survival population Equation (2.6) is expressed as

$$N(t+1) = N(t)\prod_{j=1}^{t}\left(1-\frac{d(j)}{N(j)}\right)+u(t). \quad (3.4)$$

The maintenance cost over the evaluation period is expressed as

$$M_c = \sum_{t=1}^{K}\sigma\times u(t), \quad (3.5)$$

where σ is the retrofit price (R) per bulb. The objective function (3.2) is constrained by survival population and maintenance cost constraints expressed in the following equations:

$$0.7N(0)\le N(t)\le N(0), \quad (3.6)$$

$$M_c \le \sigma\times N(0). \quad (3.7)$$

4. CASE STUDY

The formulated model is used to plan an effective strategic maintenance for large-scale lighting retrofit projects. LED lighting retrofit project under Eskom's residential mass rollout programme is taken as the case study. In this project, LED light bulbs in several provinces of South Africa replaced halogen bulbs. 207,693 LUXEON-based LED light bulbs with rated power of 10 W and lumen output of 800 lm replaced 207,693 Halogen light bulbs of rated power of 50 W and lumen output of 800 lm. Light bulbs are assumed to operate 10 hours every day over the evaluation period K = 10 years.

5. RESULTS ANALYSIS

The proposed lighting maintenance plan is applied to the lighting retrofit project in the case study. To obtain the optimal solution, the optimization problem is solved using MIDACO solver. The solver determines the optimal number of failed lamps to be replaced at each sampling interval. Energy savings and maintenance cost are treated equally, thus the weighting coefficients in the objective function are equal ($\alpha_1 = \alpha_2$ =0.5). Results show that 143,456 failed lamps will be replaced over the evaluation period. Energy savings of 282.2 x 10^3 MWh can be achieved in 10-year period. Figure 1 shows the number of survived and replaced lamps. The maintenance cost is R 8,176,992 over the evaluation period.

Although the lighting maintenance optimization model proposed gives the advantage of planning the effective maintenance plan, the optimization results are subject to uncertainties. Uncertainties associated with parameters used in the optimization include weighting coefficients, lights daily usage, and lighting population size are analysed. The weighting coefficients are selected depending on the project developer's preferences, the higher weighting coefficient, the more preference is given to the attached objective. For example, for α_1

=0.5, and α_2 =0.5, 143,456 failed lamps will be replaced, while for α_1 = 0.7, and α_2 = 0.3, 145,532 failed lamps will be replaced. Results show that when the operating hours increase, the number of lamps to be replaced increases, and when the operating hours decrease, the number of lamps to be replaced decreases. Results also show that the optimal number of lamps to be replaced increases when the initial population increases and decreases when the initial population decreases.

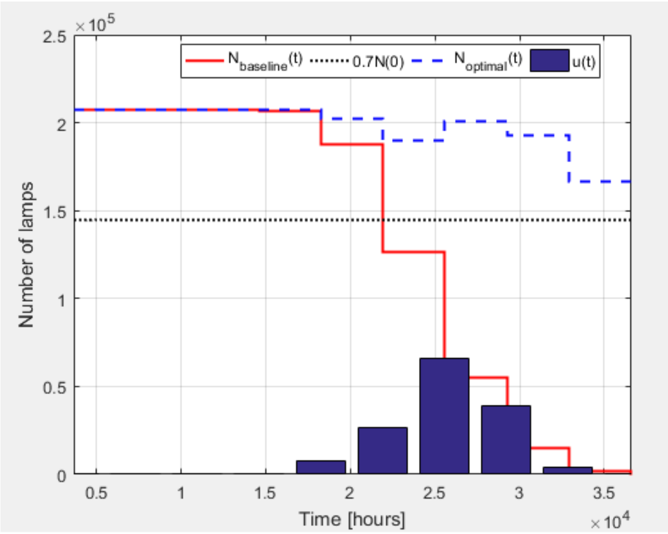

Figure 1: Number of survived and replaced lamps.

6. CONCLUSION

Optimal maintenance plan that considers lumen degradation failure is formulated for LED lighting system. The lighting maintenance optimization problem is formulated to maximize energy savings and minimize maintenance cost. A case study carried out shows that, in 10-year period, the optimal lighting maintenance plan would save up to 58.6% of lighting energy consumption with acceptable maintenance cost. The lumen degradation failure should be considered when investigating the performance of lighting retrofit projects, as it can not only affect the savings, but also reduces the level of illumination, which can lead to visual discomfort.

ACKNOWLEDGEMENT

This work is supported by the Organization for Women in Science for the Developing World (OWSD), Swedish international development cooperation agency (Sida), and the National Hub for Energy efficiency and Demand Side Management at the University of Pretoria.

REFERENCES

[1] W. D. van Driel and X. Fan, *Solid state lighting reliability: components to systems*, vol. 1. Springer Science & Business Media, 2012.

[2] F. Wang and Y. Lu, “Microelectronics Reliability Useful lifetime analysis for high-power white LEDs,” *Microelectron. Reliab.*, vol. 54, no. 6–7, pp. 1307–1315, 2014.

[3] UNFCCC, “Approved baseline and monitoring methodology, distribution of efficient light bulbs to household,” 2007.

[4] W. D. Van Driel, X. Fan, and G. Q. Zhang, *Solid State Lighting Reliability Part 2: Components to Systems*, vol. 3. Springer, 2017.

[5] CDM, “AMS-II.J: Demand-side activities for efficieny lighting technologies.”

[6] X. Ye, X. Xia, and J. Zhang, “Optimal sampling plan for clean development mechanism energy efficiency lighting projects,” *Appl. Energy*, vol. 112, pp. 1006–1015, 2013.

[7] M. Botha-Moorlach and G. Mckuur, “A report on the factors that influence the demand and energy savings for Compact Fluorescent Lamp door-to-door rollouts in South Africa,” *Eskom Energy Res. Centre, Cape T.*, 2009.

[8] H. Carstens, X. Xia, and X. Ye, “Improvements to longitudinal Clean Development Mechanism sampling designs for lighting retrofit projects,” *Appl. Energy*, vol. 126, pp. 256–265, 2014.

[9] B. Wang and X. Xia, “Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives,” *Energy Build.*, vol. 96, pp. 299–308, 2015.

[10] X. Ye, X. Xia, L. Zhang, and B. Zhu, “Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach,” *Control Eng. Pract.*, vol. 37, pp. 1–10, 2015.

[11] Philips Lumileds, “IESNA LM-80 Test Report,” 2012.