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Light output stabilisation of LED based streetlighting luminaires by adaptive current control

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ABSTRACT

Temperature dependence of LED operation is often not fully considered during the design of solid state lighting products. If temperature dependence is not carefully considered, solid-state lighting products are typically overdesigned to be too robust enough to fulfil the requirements under any possible environmental conditions. Temperature dependent nature of LEDs though, could even be a new benefit if properly considered. Overdesign means designing for the worst case that is the highest possible environmental temperature when LED efficiency/efficacy is low. With a control scheme resulting in constant emitted total luminous flux significant electrical power saving can be achieved since at lower temperatures, due to increasing efficiency/efficacy less electrical power, thus, lower forward current levels are sufficient. This paper describes different methods to specify the so called iso-flux control of LEDs' operating point, in which effect of temperature changes on light output characteristics is compensated by adjustment of the forward current. Parameters for an automated temperature compensation can be identified with the help of multi-domain LED models. This paper describes our LED multi-domain model based approach applied to the design of the light output control of an existing street-lighting luminaire. During the design of the control scheme real, archived meteorological temperature data set was considered. Based on our model we implemented the temperature compensated iso-flux control of a luminaire and the planned operation was validated by actual measurements. The verified luminaire model was further investigated with multi-domain models of aged LEDs obtained during an LM-80 standard compliant aging of a set of LEDs, characterizing LEDs up to 6000+ h of operating life time.

1. Introduction

Significance of LED based solutions is rapidly increasing both in indoor and outdoor lighting applications. While at present indoor “LEDification”, projects are frequently based on retrofit LED light sources, thermal design is hardly ever considered on application level (In these cases the thermal environment of the later application is usually unknown; it is still an issue but this topic is out of the scope of this article). In outdoor applications however, such as in streetlighting installations retrofit approaches are less common therefore thermal considerations can be better accommodated.

To fully exploit higher efficacy and longer expected product life time of modern high-power LEDs careful thermal design on module and luminaire level is a must: properly designed module and luminaire level thermal management of LED applications assures that critical temperature limits of LEDs are not exceeded therefore predicted LED lifetime in terms of lumen maintenance is typically guaranteed. A further step towards a still reliable but smarter luminaire level design is to consider the temperature dependence of the operating parameters of LEDs that helps assure avoiding possible overdesign, thus help reduce product cost. Such a design process needs accurate data on LED operation that can be well characterized (see e.g. the LED thermal testing standards of JEDEC [1,2,3,4]) with measurements and with so called multi-domain models of LED chips [7,8].

Operation of LEDs is highly sensitive to the temperature of the pn-junction; at a constant forward current, with the increase of the junction temperature, the forward voltage, the efficiency and the efficacy decreases, altogether decreasing the total emitted radiant and luminous flux of the device. Therefore, the minimal emitted total flux of a streetlighting luminaire must be designed according to the foreseen highest possible ambient temperature that can occur (i.e. the hottest summer night). Such considerations however, will make the design too robust over the rest of the year (e.g. during the cold winter nights), especially at geographical locations where the average temperature is much lower. Keeping the light output characteristics at a constant level over the year and at any geographical location would significantly increase the efficiency of outdoor solid-state lighting (SSL) products. Furthermore, operating LEDs at lower levels of forward current results in increased product lifetime.

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Besides minimising electric power costs, primary purpose of any novel streetlighting improvement should be enhanced reliability for better personal, property and transport protection [9]. Various adaptive dimming technologies have been available long time ago, both for incandescent and for retrofit LED light sources. Although, drive current controlling techniques in LED based solutions serve not only the purpose of controlling or regulating the illumination level, but can also enhance device reliability and safety by preventing the LEDs from excess temperature. Anthony Catalano describes an adaptive system with thermal fold-back [10]. According to the method described in his paper the forward current of the LED is reduced under high temperature conditions, in order to avoid elevated pn-junction temperatures where LED degradation speeds up dramatically. The paper also mentions that the observers will notice significant dimming in case of dramatic over-temperature; which should not be a case in critical applications. The modelling and dimming technique described in this article aims to enable appropriate thermal and electrical designs which also ensure reliable and well stabilised light output characteristics.

By monitoring the ambient temperature, a smart adaptive system can fix the light output values through a controlled current source or through pulse-width modulation (PWM) based dimming with variable duty-cycle while maintaining a constant forward current. Such a solution is also known as *constant light output* (CLO) design.

Practical realization of a CLO or *iso-flux* control would require a pre-specified look up table (LUT) of required forward current/duty cycle vs. ambient temperature. Obtaining such LUTs e.g. for PWM-based dimming is not easy; for the calculation the pulsed thermal resistance, the effective heating power and the actual temperature dependence of LEDs' luminous flux need to be known.

An analog control scheme with variable forward current of LEDs is a less complicated approach, though, it requires detailed knowledge about the so called iso-flux characteristics (set of operating points providing constant radiant/luminous flux values under any environmental conditions) of the applied LEDs. Look up tables containing required forward current vs. ambient temperature pairs to be used for such a control can be obtained by properly set up simulations using a chip level multi-domain model of the LEDs to be controlled.

Besides the temperature dependent light output characteristics of power LEDs, end-of-life conditions of SSL products are also different from the end-of-life conditions of classical light sources. Catastrophic failure is no longer the primary failure mode but total luminous flux depreciation should be the main reason for SSL device replacements. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) recommends maximum light output degradation to 50% for decorative lighting and display applications (L50) and to 70% for general lighting applications (L70) [11] as end-of-life criteria of the LED product in question, while a limit of 90% maintenance (L90) or even stricter regulations may be necessary in case of specific applications (such as automotive or emergency lighting). IES LM-80-08 [12] is an approved method for testing total luminous flux maintenance of power LEDs, while the technical memorandum IES TM-21-11 [13] supplies with standardized method for lifetime estimation, based on the LM-80-08 measurement data (see also in [14]). There are well detailed LM-80 based LED testing results published by academic sources (see e.g. [15]) and LED vendors also perform such tests and release such test data as well as data on lifetime estimations, but still there is a lack of approved modelling methods and practical solutions with which total luminous flux depreciation could be considered already in the design stage of any streetlighting luminaire. The smart adaptive system proposed in this article could be a solution not only for temperature compensation to achieve constant light output operation but also for assuring long term lumen maintenance of the luminaires (keeping light output at constant level throughout the product lifetime; where it is the first step towards a perfect luminaire level CLO operation during the useful product life span). In this paper we deal with the issue on the level of LED packages only, but for a complete luminaire level approach it is also necessary to consider the transmission degradation of the optical parts.

2. Technical background

Characterisation and simulation of power LEDs is a multi-domain task due to the strong interactions between the operating parameters; characteristics of an LED in the electrical, optical and thermal domains must be investigated simultaneously. The JEDEC JESD51-5x family of standards [1,2,3,4] provides appropriate recommendations for measurements of LED packages. Though the major focus of such JESD51-5x compliant measurements of LEDs is to provide thermal resistance/thermal impedance data of LED packages, as a "by product" of JEDEC JESD51-51/51-52 compliant combined thermal and radiometric (photometric) measurements, temperature dependence of the major operating LED characteristics can be easily obtained.

Commercial implementation of the abovementioned LED testing standards is available from Mentor Graphics MicReD: the T3Ster and TeraLED test equipment [5,6]. The most recent operating software of these equipment provides automatic control of the ambient temperature in order to reach pre-defined junction temperature values allowing the measurement of the isothermal I-V-L characteristics of LEDs, providing forward current–forward voltage and forward current–radiant/luminous flux value pairs while the LED junction temperature is kept constant. Such measured characteristics of a Luxeon Z test LED [16] are shown in Figs.1, 2 and 3.

Considering the total radiant flux of an LED is essential since a significant part of the consumed electrical power leaves the package in the form of light; the measured electrical power needs a correction by the total emitted radiation to get the proper heating power data when measuring/calculating thermal resistance or thermal impedance. Measuring luminous flux values is not indispensable for correct electro-thermal simulations but highly desirable when design of a lighting application is the ultimate goal.

Measured radiant and luminous flux values may be handled by various ways during coupled electrical, thermal and optical simulations. The most commonly used quantities are:

- *Radiant efficiency* (of an electric light source) "is the ratio of the radiant flux of the emitted radiation to the power consumed by the source" (symbol is η_e; unitless) [17].
- *Luminous efficacy* (of an electric light source) is the "quotient of the luminous flux emitted by the power consumed by the source" (symbol is η_v; unit is [lm/W]) [18].

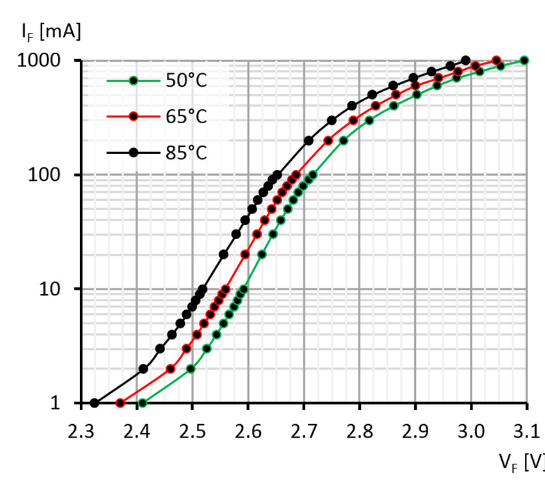

Fig. 1. Isothermal forward voltage–forward current characteristics of a test LED at $T_J = 50$ °C, 65 °C and 85 °C.

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