LED-Based Electronic System to Support Plant Physiology Experiments

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Abstract — **This paper proposes an electronic system intended to provide a simplified and efficient alternative for plant physiology experiments, as well as to be used in greenhouse conventional processes. The text starts with a description regarding the interaction between artificial lighting and cultivation of vegetables, either for agricultural-oriented purposes or to help the interpretation of plants behavior in botanical studies. This first study helps to characterize the main radiometric quantities of interest, with a predominant orientation for growing vegetables when artificial lighting is used as a supplement or as a sole lighting source. Hence, based on some previous works, it is proposed a standalone system intended to drive a lighting fixture consisting of white power LEDs or mixed-color LED unities. Moreover, the paper also includes some preliminary radiometric experiments concerning a possible commercial LED, which is intended to be used in association with the proposed lighting fixture. The results should indicate if the LED brands are enough to excite a good photosynthetic response. Hence, the most relevant parameters are measured, such as the photosynthetic photon flux, luminous flux, lamp color rendering and color correlated temperature. It is expected that the developed prototype be able to present features that add flexibility, automation and radiometric relevance to some selected vegetable crops.**

Keywords—LEDs, artificial lighting, electronic systems, photosynthetic photon flux.

I. INTRODUCTION

The interaction between light and plants is something known by humans since ancient times [1]. However, the use of (artificial) grow lighting may be considered a more recent alternative for plant cultivation. A grow light or plant light is an artificial light source (electrical, in general), designed to stimulate plant growth by emitting an electromagnetic spectrum appropriate for efficient photosynthesis [2]. Grow lights are used in applications where there is either no naturally occurring light or where supplemental light is required. For example, in the winter months when the available hours of daylight may be insufficient for the desired plant growth, lights are used to extend the timespan during which the plants receive light. So, artificial light is generally used to provide high intensity light, when the natural sunlight available is not sufficient to provide optimal plant growth, or to extend the hours of natural daylight or to provide a night interruption to maintain the plants on long-day conditions. When light is provided at optimal levels, where it was lacking before, it can significantly increase the health, strength, growth rate and crop yield of plants. Supplementing natural sunlight in a backyard greenhouse allows for the virtual elimination of seasonal and geographical restraints. In addition, by extending the day length with supplemental lighting, it is possible to enhance the growing success. Many conventional lamp models have been employed for this purpose, such as incandescent bulbs, HID lamps, tubular and compact fluorescent fixtures etc. [3]. Nowadays, newer and highly efficient lamp technologies, including solid-state lighting, have started to be considered in this field.

The use of light-emitting diodes (LEDs) as a radiation source for photosynthetic growth of plants has been evaluated since 1990 [4]. This kind of technology (sometimes called solid-state lighting, SSL) is a promising lighting alternative from various important aspects. For example, modern LEDs can save high amounts of energy either for interior or exterior applications. They may experience long lifetime and are produced in relatively small packaging. Moreover, LEDs can emit in wavelengths, which are consistent with the absorption spectrum of higher plant photosynthesis. LEDs do not come with toxic substances (such as mercury) inside their packaging and contain no electrodes, which prevents them of premature failures in comparison with incandescent or fluorescent bulbs, which must be periodically replaced and may also consume much energy.

Nowadays, in respect of lighting sources, LEDs are considered one of the best and important alternatives for light production, being also possible to achieve luminous quality and energy efficiency of about 80% to 90% [3]. When compared to other lamp technologies, SSL could reduce the global CO_2 gas emissions to at least 50%. In this way, LEDs can be considered as green products [5].

Thus, the use of LEDs in crop production has been stimulated owing to minimize damages to the plants and the problems related to greenhouse temperatures. Therefore, as light output increases and device costs decrease, LEDs continue to move toward becoming economically feasible for even large-scale horticultural lighting applications [6].

Due to the importance and growing interest of LEDs in plants development and agriculture, this work proposes an LED-based electronic system intended to help plant physiology studies as well as to be used in greenhouse installations. The paper is organized as follows: Section II presents a brief review concerning protected plant growth environments and the

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relevant radiometric variables, highlighting the typical photosynthetic plants response and the magnitudes of interest. In Section III it is proposed an electronic system to control the lighting fixture, which should be composed of white or monochromatic LEDs. This section also shows some preliminary tests which have been performed with respect to a commercial LED module, in order to evaluate their main features concerning a specific crop growing (artificial) environment. The main conclusions are presented in Section IV.

II. LIGHT AND PLANTS INTERACTION BASICS

In order to develop with health and quality, living organisms need some kind of energy, normally derived from the sun. In general, higher plants usually harvest this energy by means of a photoreaction process called photosynthesis. The term photosynthesis literally means "synthesis using light." Photosynthetic organisms use the sun's energy to synthesize carbon compounds that cannot be formed without an input of energy. More specifically, luminous energy drives the synthesis of carbohydrates from carbon dioxide and water with the generation of oxygen. Energy stored in these molecules can be used later to power cellular processes in the plant and can serve as the primary energy source for all forms of life. This process begins with the excitation of chlorophyll and culminates in the synthesis of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) [7 - 8], which are basic molecules that can be considered essentials for the maintenance of the cell chemistry.

As already stated, one of the main concerns for researchers, producers and engineers, who are involved with agriculture, botanical studies and plant development, is to know the amount of artificial light to be used as a supplement for daylight regarding several types of crops. In the last decade, a huge number of scientific studies have been published concerning the effect of artificial light sources for the photosynthesis process during the cultivation of plants, revealing the importance and timeliness of this subject [3], [9 - 11].

In order to evaluate the effect of light on plant growth, biologists know that it is preferable to consider the number of photons emitted by a given light source instead of its energy [12]. Moreover, it is also known that most all photosynthetic activity is driven by photons in the 400 nm to 700 nm wavelength range. Therefore, this convention had resulted in the definition of the Photosynthetically Active Radiation (PAR) as the incident quantum flux in the 400 nm to 700 nm range [13]. PAR quantum flux is also considered a power measurement, which could be given in W/s or moles/s. Moreover, PAR is sometimes understood as just a wavelength region, leading to some confusion of unities, quantities and meaning in this field.

Fortunately, the most important quantity in plant physiology and plant growth inside chambers or greenhouses is the Photosynthetic Photon Flux Density (PPFD), E_q, sometimes called PAR rate or just PPF. This quantity is normally expressed in terms of the number of moles of photons (quanta of light) in the radiant energy between 400 nm and 700 nm, per square meter per second. In this case, 1 mole of photons is close to 6.022 x 10^{23} photons, which is the Avogrado's constant, N_A. PPF can be expressed by means of equation (1).

$$E_q = \int_{400}^{700} E_{q,\lambda}\ d\lambda. \tag{1}$$

Where $E_{q,\lambda}$ is the spectral quantum irradiation of a given grow light source and is given in (µmol.m^{-2}.s^{-1}.nm^{-1}) and λ is the radiation wavelength, given in nm. So, E_q is given in (µmol.m^{-2}.s^{-1}). $E_{q,\lambda}$ can be linked to the equivalent radiometric quantity by means of equation (2), that comes from Stark-Einstein law [1] .

$$E_{q,\lambda} = \frac{E_{e,\lambda}\,\lambda}{N_A\,h\,c} = \frac{E_{e,\lambda}\,\lambda}{0.1196}. \tag{2}$$

Where, $E_{e,\lambda}$ is the irradiance in W/m^2, h is the Planck's constant and c is the speed of light.

For good crop health and optimal plant growth, it is necessary to know the quality of the incident light, since the plants have variable sensitivity within the range of luminous radiation spectrum, similarly to the human eye. However, the plant response in the PAR region is very different from humans as seen in Fig. 1. The photosynthetic efficiency response of higher plants and some algae is sometimes called Relative Quantum Efficiency (RQE), as indicated by its respective curve in Fig. 1 along with the human eye visual response, which is usually called Luminosity Function. By analyzing the photosynthetic response, one can observe that sensitivity peaks occur in red (610 nm) and blue (430 nm) wavelengths.

When PPF is weighted by the RQE response, the flux rate is referred to as the Yield Photosynthetic Photon Flux Density (YPFD or just YPF) [14], [15]. In this case, equation (1) could be modified by the integral given by equation (3), which can be considered a more accurate way of evaluating RQE-based PAR quantities.

$$E_q = \int_{400}^{700} E_{q,\lambda}\,.\,P(\lambda)\ d\lambda. \tag{3}$$

Where $P(\lambda)$ is the RQE response of higher plants (see Fig. 1), being dimensionless.

Since the RQE-weighted integral is a mathematical function that is difficult to solve analytically [16] and since $P(\lambda)$ and $E_{q,\lambda}$ in general cannot be expressed by simple mathematical functions, equation (3) could be rewritten in its discrete form, as given by (4) [16].

$$E_q = \sum_{\lambda=400}^{700} E_{q,\lambda}\,.\,P(\lambda)\ \Delta\lambda \tag{4}$$

Typical supplemental lighting levels in some plant physiology studies range from 30 to 600 µmol.m^{-2}.s^{-1} [17]. High Pressure Sodium (HPS) lamps are found very commonly as grow lights due to their high luminous efficacy and because their monochromatic spectrum is near the peak of RQE curve. Besides, their cost is relatively low nowadays. However, LED lamps are gaining special attention in this field since it is easy to have commercial models designed to cover the red, blue or both wavelengths as commonly found in phosphor-converted white LEDs.

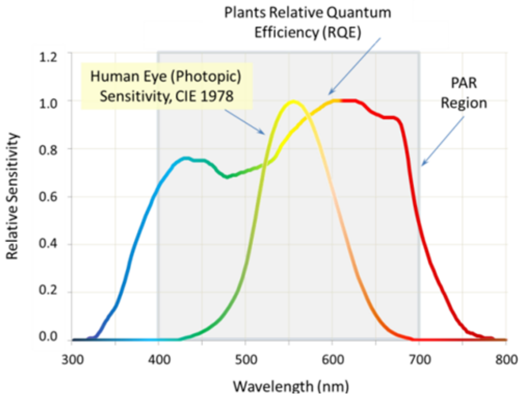

Fig. 1. Comparison between the light sensitivity of the human eye (photopic vision, CIE 1978) and higher plants.

Additionally, LEDs are experiencing an important reduction of cost during the last years, what could contribute even more to their application as grow lights. Reference [18] has shown that LED fixtures can be a very energy efficient alternative to HPS lamps. The same reference shows that cool white phosphor converter LEDs, warm-white LEDs and monochromatic (red and blue arrangement) of LEDs present very good relative efficacy values among several current lamp technologies, either regarding radiometric measures, quantum or newly proposed measurement methods.

In this work, PPF quantities are obtained (measured) by means of the SpectraSuite software (PAR) of Ocean Optics. A specific LED module is going to be evaluated inside a black box by using an optical measurement setup including a cosine corrector adapter and CDS 610 spectrometer (see Section III.A).

III. ELECTRONIC SYSTEM PROPOSAL AND DESIGN

Fig. 2 shows a simplified schematic of the proposed electronic system. As can be seen, the whole system is composed by a high power factor (PFC) front-end AC-DC pre-regulator that provides a fixed (regulated) DC voltage to LED drivers. Each LED driver should be able to provide a controlled output current to feed the LED strings.

In order to generate the required transistor pulses for both LED drivers and PFC pre-regulator it would be possible to employ a microcontroller-based control unity, as shown in same figure.

To offer more flexible functionalities in grow lighting, the lighting fixture could be arranged with several sets of monochromatic LEDs, or even different sets of Correlated Color Temperature (CCT) white LEDs.

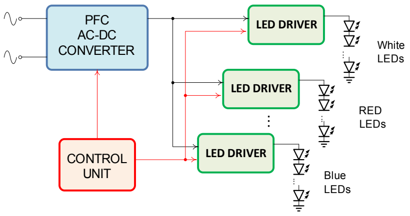

Fig. 2. Simplified schemtatic of the LED-based electronic system.

In all cases, the main issues with the LED driver is: 1) to ensure a well-regulated LED current; 2) to allow the control of the average current supplied to LEDs, i. e. dimming control; 3) to provide a square wave current, with constant peak and pulse-width modulation (PWM) of its average value for dimming purposes. This last procedure is intended to minimize color shifts, which is sometimes called chromaticity deviation [19]. Hence, the control unity should be also able to observe those requirements and should visually inform the luminaire user (either a biologist or a greenhouse operator) the amount of PAR condition being delivered to a given crop at a known distance between plant canopy and luminaire.

This paper will not deal with all the subsystem unities of the simplified system topology depicted in Fig. 2, being only focused on the LED module evaluation and on the design of the driver, which should be as simple, efficient and low-cost as possible.

A. LED Module Evaluation

In order to get a first experience with PAR radiation measurements concerning solid-state technology, several commercial LED models have been evaluated using a special experimental setup that could represent a simplified plant growth chamber. So, the measurement environment consists of a small "darkroom" with the dimensions presented in Fig. 3.

In this work, it was used a measurement system that included a spectroradiometer Labsphere CDS610 (350 – 1000 nm) in association with the SpectraSuite utility from Ocean Optics, which was equipped with its photosynthetically active radiation (PAR) plugin. An optical fiber and a CC-3-UV-S (200 – 2500 nm) cosine corrector have completed the apparatus, according to Fig. 4. After the initial tests with some LED modules alternatives, a luminaire composed by power LEDs has been chosen, due to its compact arrangement (see Fig. 5), simplified geometry, proper quantum radiation level and spectral distribution (see Fig. 6). The LED luminaire is composed of 28 high power, warm white HEXA LEDs. The total current delivered to the LED arrangement is 350mA.

The chosen LED luminaire has been evaluated inside a Labsphere LMS-400 40" integrating sphere and its main radiometric details are given in TABLE I.

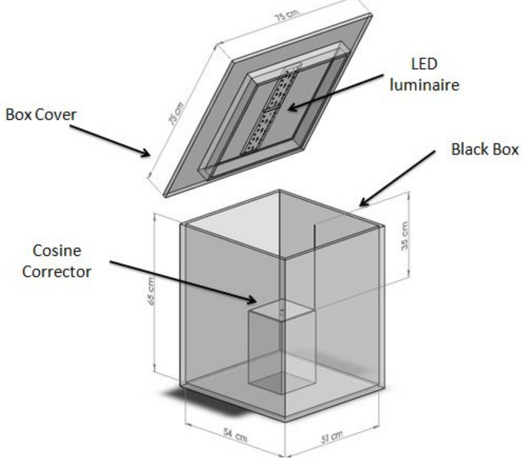

Fig. 3. Schematic representation of the "black box" setup.

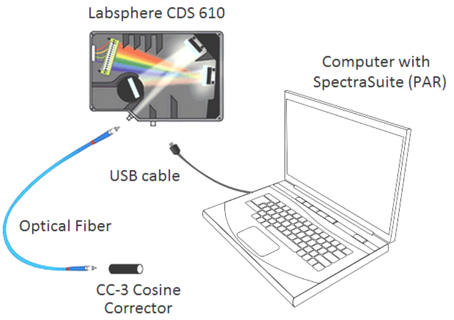

Fig. 4. Required equipments for PAR measurements.

Fig. 5. Commercial LED module.

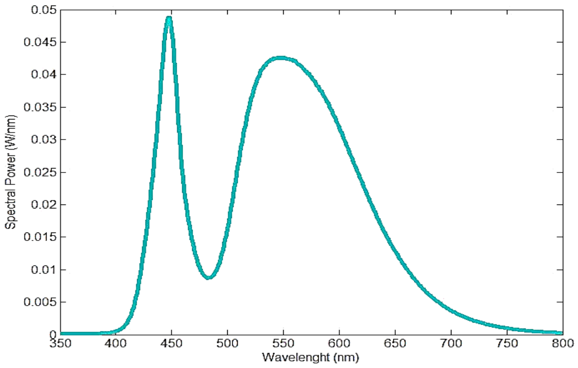

Fig. 6. Spectral power (radiometric) distribution of LED module.

TABLE I. MAIN PARAMETERS OF CHOSEN LUMINAIRE

Parameter	Value
Total photopic luminous flux	$2.491.10^{3}$ lm
Color correlated temperature	5319K
Color rendering index	67.2%
Equivalent resistance, r_d	50.1Ω
LED string threshold voltage, V_t	75.48 V
Module supply current	350 mA

The photosynthetic performance of the LED module has been also evaluated by means of the PAR measurement setup described before and shown in Fig. 3 and Fig. 4. Its radiometric data are given in TABLE II.

Table III presents some wavelength bands (bins) photosynthetic photon flux density (PPF) of the collected light as well as the total PPF measurement. Five distinct wavelength ranges have been measured by SpectraSuite utility. However, just bin 3 (500 nm to 600 nm) is given here.

As shown, the luminaire has provided a total PPF of about 100 μmol.m^{-2}.s^{-1} and the peak photosynthetic radiation has been observed between 600 nm to 700 nm, being around 37 μmol.m^{-2}.s^{-1}. Note that according to the spectral power distribution of the LED luminaire (Fig. 6) and the RQE curve of Fig. 1, linked by equation (3), this result was already expected.

Hence, it could be concluded that providing the chosen luminaire is driven by a proper and well-controlled supply current, its desired features should be preserved along the full dimming range allowing its use as a grow lamp.

TABLE II. LUMINAIRE RADIOMETRIC PARAMETERS

Attribute	Value
Measured radiant energy (joules)	$6.7215.10^{-5}$
Measured radiant power (watts)	$2.7058.10^{-4}$
Energy density (J/m^2)	5.62
Power density (Watt/m^2)	$2.265.10^{1}$

TABLE III. PHOTOSYNTHETICALLY ACTIVE RADIATION

Total PPF		$1.0066.10^{2}$ μmol.m^{-2}.s^{-1}
BIN 3		$3.689.10^{1}$ μmol.m^{-2}.s^{-1}
	From:	500nm
	To:	600nm
	Light:	36.65%

B. *PWM-dimmable LED Driver*

There are various topologies that could be used to supply and control LEDs light. Due to the characteristics of the LED luminaire and the practical application required by this study, it is desired that the driver be simple, inexpensive, efficient, and may keep LEDs current well regulated in spite of electrical perturbations and environmental changes. Moreover, it is very important that the PPF quantity can be adjusted by the driver control signal (which should be issued by the chamber or greenhouse operator or even a supervisory system), since each kind of crop has its ideal supplemental light level.

Hence, to integrate the electronic system depicted in Fig. 2 it could be adopted the LED driver of Fig. 7, which is based on a DC-DC buck converter [20]. As can be seen, it is supposed that a regulated bus voltage, V_B, is available but the driver control is devised to supply LEDs with a constant peak current. This strategy is employed to ensure minimum chromaticity deviation, what could interfere in PPF levels when dimming is required [19]. So, the inductor current should be continuously monitored by the control system, which employs a very simple hysteresis control action [21] that is able to keep this current at a fixed value, though allowing a certain current ripple around the desired peak current set point. Transistor Q_1 of buck converter is driven to ensure this desired condition. In order to provide a pulse width modulated (PWM) current through LEDs as required by dimming functionality, a second transistor (Q_2) is employed as also shown in Fig. 7.

The hysteresis control strategy is based on a comparator circuit, which compares the inductor current with two reference signals, lower and upper limits as seen in Fig. 8. Thereby, when the current through L reaches the positive reference, the first operational amplifier will goes high leading flip-flop to the reset state, while Q_1 transistor is switched OFF. A similar mechanism happens in the lower conduction limit. When the current reaches the lower reference value, the lower operational amplifier will set the flip-flop and Q_1 transistor is switched ON.

According to [22], the photometric performance of LEDs decreases with increasing amount of the ripple current percentage. However, it remains practically constant within the range of 0 to 30%. Thus, in this paper, the ripple factor will be chosen to be 10%. Therefore, REF+ and REF- in Fig. 8 are adjusted accordingly.

Providing Q_2 switch is open, the current through the LEDs is the same as the one through inductor, and the ripple factor is constant. Therefore, the inductance, L, of buck inductor can be designed by means of equation (5) [21].

$$L = \frac{V_0 \cdot (1 - D)}{\Delta I_0 \cdot f_S} \tag{5}$$

where V_o is the total voltage across LEDs module, D is the buck converter duty cycle, i. e. V_o/V_B, ΔI_o is the hysteresis band and f_S is the desired switching frequency.

It can be observed that higher values of f_S would result in lower values of L, what could be interesting in a practical implementation due to size and cost reductions of magnetic elements. However, excessively high values of f_S normally lead to unwanted switching losses, lowering the overall efficiency of the driver. Hence, a trade-off must be considered when designing the value of L, which should also take into consideration the switching parameters of the chosen Q_1 device.

The shunt resistor, R_{shunt} (see Fig. 8) is also an important element of the circuit. It must operate linearly, follow a fast response and should be as low as possible. Special chemical elements and careful geometrical arrangements would be required in a practical implementation.

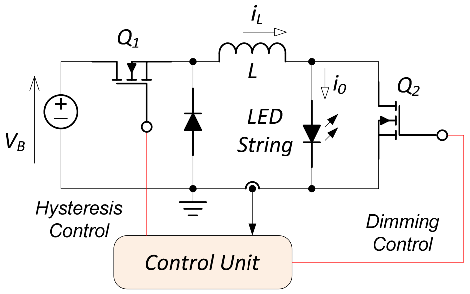

Fig. 7. Buck-based LED driver system with parallel dimming and current-mode control.

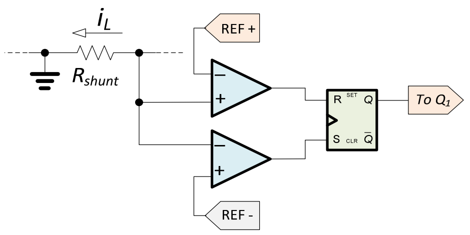

Fig. 8. Hysteresis control circuit.

Finally, the dimming switching frequency should be chosen with an order of magnitude lower than the buck switching frequency, f_S.

Next item of this Section presents some simulation results regarding the LED driver and control strategies described in this item.

C. LED Driver Simulation Results

Table IV shows the parameters that are going to be adopted in a PSIM simulation. They have been chosen according the design guidelines, hysteresis band, recommendations and equations as discussed in last item.

The main simulation results are shown in Fig. 9. Several dimming conditions (four steps of duty cycle, $D_{\_dim}$, representing the dimming levels) have been simulated along the total 1 ms simulation time. It can be noticed that the inductor current as well as the peak LEDs current remained stiff at the design average value of 350mA with a 10% hysteresis band.

TABLE IV. MAIN PARAMETERS OF BUCK-BASED LED DRIVER

Parameter	Value
Input dc voltage, V_B	175 V
Inductance, L	8.3 mH
Switching frequency, f_S	150 kHz
Dimming frequency, f_d	8 kHz
Inductor current, i_L	350 mA
Hysteresis band, Δi_O	10%

IV. CONCLUSIONS

This paper has presented a brief review concerning the interaction between light and photosynthesis of higher plants. Moreover, some aspects concerning the solid-state lighting use as an artificial supplement for plant growth have been also discussed.

Some commercial LED luminaires have been evaluated by means of a specialized set of radiometric instruments and the results regarding one of them have been reported here. The chosen LED module could provide a photosynthetic photon flux density of around 100 μmol.m^{-2}.s^{-1}, which is consistent with the expected level of certain crops. In the case a higher PPF levels are required, additional modules could be associated but the same controlled driver system would be adopted.

The paper has also proposed an electronic system intended to drive a typical LED luminaire, ensuring peak control of LED current, dimming capability, fast dynamics and high power factor (by means of the use of an AC-DC preregulator). In order to keep the LED current restricted to a fixed current band, a hysteresis control strategy has been suggested and verified by means of digital simulation.

The electronic system proposed in this work presents powerful features indicating proper operation and high efficiency capability, featuring low cost and simplicity. The use of a controlled peak current strategy has also the ability to minimize chromaticity deviation when dimming is required, ensuring better reproducibility in commercial activities as well as in plant physiology experiments.

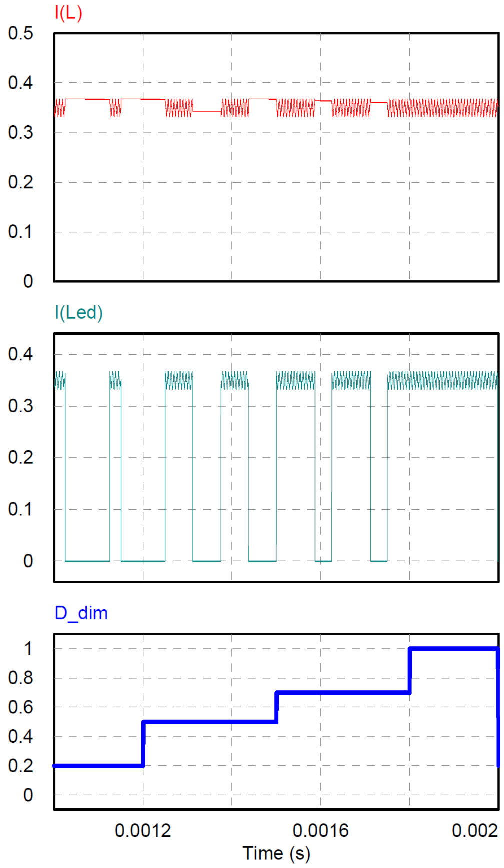

Fig. 9. Current provided by the driver through the LED string (PSIM simulation waveforms). From top to bottom, inductor current, LEDs current and dimming duty-cycle.

The present study is currently under development at NIMO/UFJF laboratory. Authors intend to publish the specific results in future publications, where they expect to verify the negligible LED color deviation concerning the proposed dimming approach.

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Sadly, one of the authors of this paper (Nicolas Monteiro) has died prematurely at age 21 in a car accident in last January. Authors would also like to dedicate this work in his memory.

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