# A Fast Dynamics and PWM-Dimmable LED Driver for Accurate Control of Illumination in Plants Physiology Experiments

Camila C. Almeida, Pedro S. Almeida, Milena F. Pinto, Rodolfo L. Valle, Carlos H.N.Martins and Henrique A. C. Braga.
Modern Lighting Research Group – NIMO
Federal University of Juiz de Fora – UFJF
Juiz de Fora, MG – Brazil
camila.almeida@engenharia.ufjf.br

***Abstract* - This work presents an electronic system in order to provide a simplified and efficient alternative for plants physiology experiment as well as for its utilization in greenhouses. Initially, it is shown a brief description regarding the artificial lighting and plants cultivation interaction, aiming the interpretation about plants behavior in botanic studies and to help the oriented and commercial crops purposes. Based on some previous work, it is proposed an autonomous system comprised of a white LEDs lighting fixture. Moreover, this paper includes an experimental prototype in order to evaluate converter efficiency and radiometric lamp behavior. Thus, the results have shown that the developed system is able to integrate flexibility, accurate control and relevant radiometric for some selected crops.**

**Keywords- Electronic system, vegetal physiology, artificial illumination, LEDs.**

## I. Introduction

Due to the advancement in science and research, LED technology has achieved a wide range of applications, such as residential, commercial and industrial lighting, traffic and medical markets, among others. Recently, it also has obtained attention for its usage in plants physiology applications.

According to [1], several studies were published regarding the effects of artificial light on plants cultivation. The LED characteristics, such as energy savings, long life-span, small size, consistent wavelength with the photosynthesis spectrum absorption of the of the plants its ability to produce high levels of illumination, and radiate less heat, makes it an adequate device for this purpose. Due to the growing interest and importance of the LEDs on plants development and agriculture, this paper proposes an electronic system based on LEDs to be used in studies of plants physiology and in greenhouse facilities as well.

The presented work is organized as follows. Section II shows a brief review of the environmental plants growth and relevant radiometric variables, highlighting the typical photosynthetic photon flux to obtain a good photosynthetic plants response. In the Section III is proposed an electronic system composed by white LEDs and also presents some experiments using commercial LEDs module in order to evaluate the main characteristics for a future experiments in artificial environment. The results and conclusion are shown in the Section IV and V, respectively.

## II. Suplementar illumination

One of the main concerns of researchers, producers and engineers, who are involved with agriculture, botanical studies and plants growth, is to know the quantity of artificial light to be used as a supplement for the day light in relation to various types of crops. In the last decade, several scientific studies concerning the effects of the artificial light sources for photosynthesis process during plants cultivations were published, showing the importance of this subject [2-5].

In this way, it is known that the most important quantity in the physiology of plants is the photosynthetic photon flux density (PPFD), which is represented by (1). Sometimes is called by Photosynthetically Active Radiation (PAR) or just by PPF. Usually, this quantity is expressed in terms of the moles of photons number (quanta of light) in the radiant energy between 400 nm and 700 nm square meters per second. In this case, a mole of photons is close to 6.022 x $10^{23}$ photons, which is the Avogadro constant, *NA*.

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

Where $E_{q,\,\lambda}$ is the spectral quantum irradiation of a given light source and it is represented in (μmol. $m^{-2}$. $s^{-1}$. $nm^{-1}$). The $\lambda$ is the radiation wavelength, given in(nm). Thus, $E_q$ is expressed in (μmol. $m^{-2}$. $s^{-1}$).

According to [6], typical levels of supplementary lighting in some plants physiology studies are among 30 and 600 (μmol. $m^{-2}$. $s^{-1}$). In this paper, it was obtained the amounts of PAR using the software SpectraSuite developed by Ocean Optics. A specific LED module was evaluated inside of a black box, using the optics measurement configuration,

978-1-4799-5551-0/14/$31.00 ©2014 IEEE

including an adaptor cosine corrector and the spectrometer CDS 610.

## III. ELECTRONIC PROPOSED SYSTEM

It is shown in Figure 10, a simplified schematic of the proposed electronic system. The system is composed by a high power factor (PFC) front-end AC-DC pre-regulator, which provides a regulated DC voltage to LED drivers. Besides, 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. Moreover, the luminaire can be combined with multiple sets of colored LEDs as well as with white LEDs, which has different colors temperature (CCT), ensuring greater functionality for growing plants. However, there are some problems concerning LED driver, such as how to ensure a well-regulated LED current, how to guarantee a control of the average current supplied to LEDs (i. e. dimming control) and finally, how to provide a square wave current. The last problem requires a constant peak and pulse-width modulation (PWM) of its average value for dimming in order to minimize color shifts, called by chromaticity deviation [7].

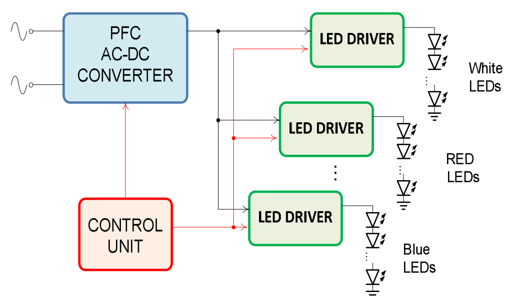


Figure 1: Simplified schematic of the LED-based electronic system [7].

In this work is not present all units represented in Figure 1. For this reason, it will be focus on the LED lamps evaluation and the practical construction of the driver.

### A. *Measurement environment.*

The system proposed in [7] for measurement of PAR used a commercial LED lamp to evaluate a special experimental apparatus that represents a "darkroom".

Thus, this measurement system includes a Labsphere spectroradiometer CDS610 (350-1000 nm) associated with the SpectraSuite Ocean Optics system, which is equipped with a Photosynthetically Active Radiation (PAR) plugin. An optical fiber and a DC-3-S-UV (200-2500 nm), connect with a cosine correction apparatus, as can be seen in Figure 2.

The LED lamp of Hexa contains twenty-eight warm white LEDs, with a current total of 350 (mA). In Table I is presented the main radiometric details given by the Labsphere LMS-400 40 integrating sphere of the mentioned lamp.

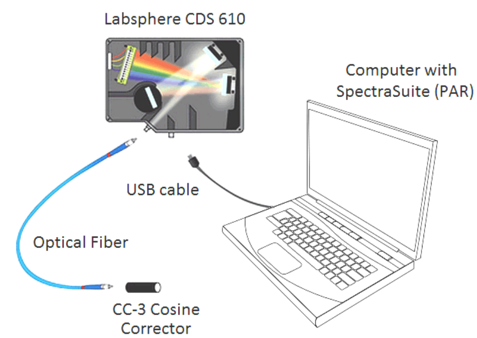


Figure 2: Required equipment for PAR measurements [7].

TABLE I. MAIN PARAMETERS OF CHOSEN LUMINAIRE

| **Parameter** | **Value** |
|---|---|
| Total photopic luminous flux | 2491 lm |
| Color correlated temperature | 5319K |
| Color rendering index | 67.2% |
| Equivalent resistance, $r_d$ | 50.1 Ω |
| LED string threshold voltage, $V_t$ | 75.48 V |
| Module supply current | 350 m A |

Table II presents some wavelength bands (bins) and its respective Photosynthetic Photon Flux Density (PPF) of the collected light. It is also shown the as the total PPF measurement. Note that, the luminaire has provided a total PPF of about 120 ($\mu$mol.m$^{-2}$.s$^{-1}$).

TABLE II. PHOTOSYNTHETICALLY ACTIVE RADIATION

| **Total PPF** | | $1.216.10^2$ µmol.m$^{-2}$.s$^{-1}$ |
|---|---|---|
| **BIN 2** | | $4.482.10^1$ µmol.m$^{-2}$.s$^{-1}$ |
| | ***From:*** | 400nm |
| | ***To:*** | 500nm |
| **BIN 3** | | $3.88210^1$ µmol.m$^{-2}$.s$^{-1}$ |
| | ***From:*** | 500nm |
| | ***To:*** | 600nm |
| **BIN 4** | | $3.831.10^1$ µmol.m$^{-2}$.s$^{-1}$ |
| | ***From:*** | 600nm |
| | ***To:*** | 700nm |

### B. *LED Driver*

Owing to LEDs characteristics and its practical application required by the presented study, it is desirable that the driver be simple, inexpensive efficient and has the ability to keep the LED's current well regulated, even in presence of electrical disturbances and environmental changes. Thereby, in order to integrate the electronic system represented by 0, it was used a DC-DC buck converter [9]. The proposed circuit has a hysteresis control; wich is shown in Figure 4.

The hysteresis control strategy is accomplished with a comparator circuit, which uses the comparison between inductor current and two reference signals, the upper and lower limits, as seen in Figure 4. Besides, to provide current signals to this strategy, it was used a commercial sensor current [10]. In addition to the hysteresis control developed for the buck converter switching, a PWM (Pulse-Width Modulation) controller was used to control the light intensity adjustment or LED dimming, Figure 5.

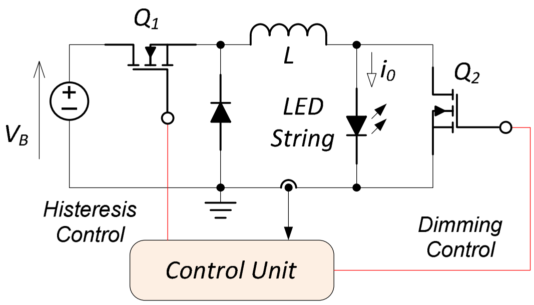


Figure 3: Buck-based LED driver system with parallel dimming and current-mode control [7].

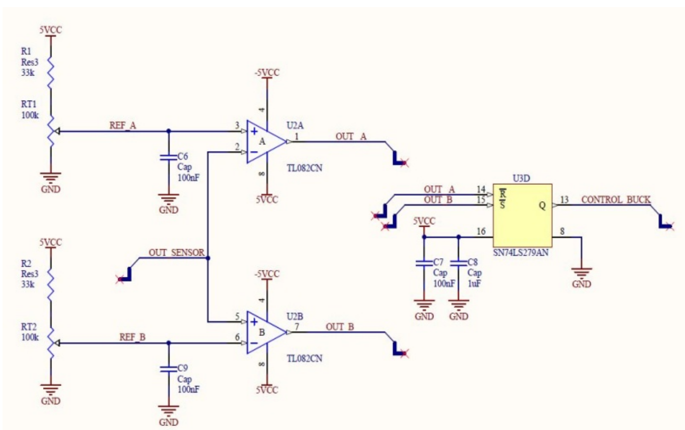


Figure 4: Hysteresis control circuit.

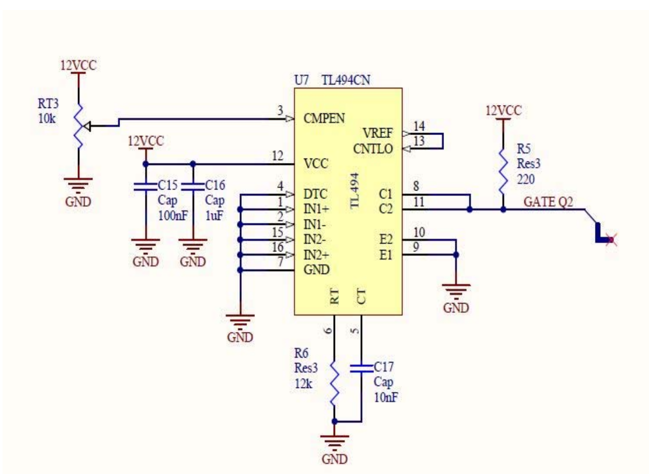


Figure 5: Circuit schematic of the dimming control.

According to [11], the photometric performance of LEDs decreases when the ripple current percentage is higher. However, it remains almost constant in the range of 0 to 30%. For this reason, in the present work, the ripple factor was chosen to be 20%. Therefore, the upper and lower references, in Figure 4, are adjusted accordingly. The value of the buck converter inductance is given by (2) [12].

$$L = \frac{V_0 \, . \, (1 - D)}{\Delta I_0 \, . \, f_S} \qquad (2)$$

Where $V_o$ is the total voltage of the lamp, D is the duty cycle of the Buck converter, i. e. $V_o/V_B$, $\Delta I_o$ is the hysteresis band and $f_S$ is the switching frequency. In the following item is discussed some results obtained from the simulation.

### C. Simulation Results

Table III shows the parameters used in circuit simulation. They were chosen according to the design guidelines, hysteresis band and equations discussed in the previous item. The main simulation results are shown in Figure 6. It can be noticed that the inductor current and the peak LEDs current remain fixed at the design average value of 350mA and with 20% hysteresis band, respectively.

TABLE III. MAIN PARAMETERS OF BUCK-BASED LED DRIVER

| Parameter | Value |
|---|---|
| **Input DC voltage, $V_B$** | 175 V |
| **Inductance, $L$** | 8.3mH |
| **Switching frequency, $f_S$** | 75 kHz |
| **Dimming frequency, $f_d$** | 10 kHz |
| **Inductor current, $i_L$** | 350 mA |
| **Hysteresis band, $\Delta i_O$** | 20% |

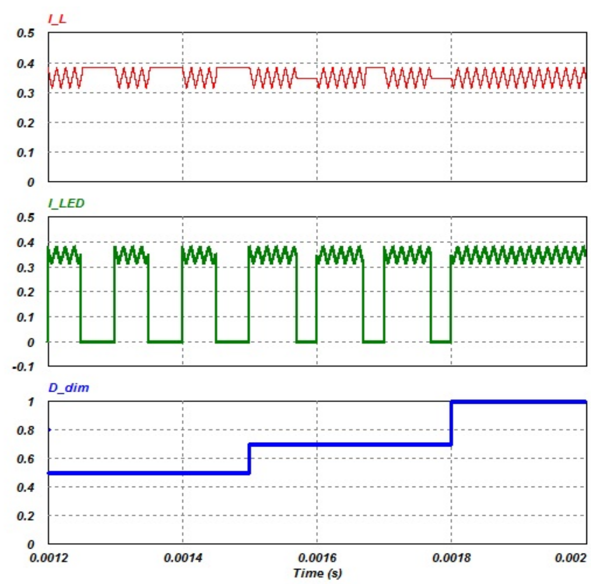


Figure 6: Current provided by the driver through the LED string (Simulation waveforms). From top to bottom, inductor current, LEDs current and dimming duty-cycle.

## IV. EXPERIMENTAL RESULTS

In this section, the experimental results of the developed prototype are given. The proposed system is shown in Figure 7.

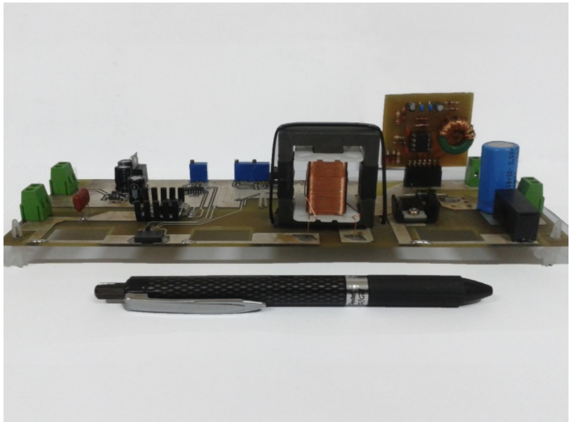

Figure 7: The proposed Buck Converter.

The voltage and current waveforms of the LED module using the hysteresis controller at full load (without dimming), are shown in Figure 8. It is observed that the current is in accordance with the designed hysteresis band of approximately 20% (i.e. 69 mA). Its average value was measured at 368 mA, thus within 5% of the design value (350 mA). The switching frequency is around 87 kHz.

In Figure 9 the waveforms at the output of the buck switching cell (i.e. voltage across the buck diode) are given along with the dimming signal for the gate of the parallel MOSFET and the inductor current for a dimming level of 50%. This shows the behavior of the converter plus hysteresis control loop when the parallel dimming switch is triggered (at 10 kHz with 50% of duty-cycle) for adjusting the light level the converter turns off and the current in the inductor freewheels.

In Figure 10 the waveforms presented are, once again, the voltage at the output of the buck switching cell and the gating signal of the dimming switch at 10 kHz with 50% of duty-cycle. Moreover, it also shows the current at the load, exhibiting that it is being diverted by the parallel switch to attain dimming of the light level (50% dimming).

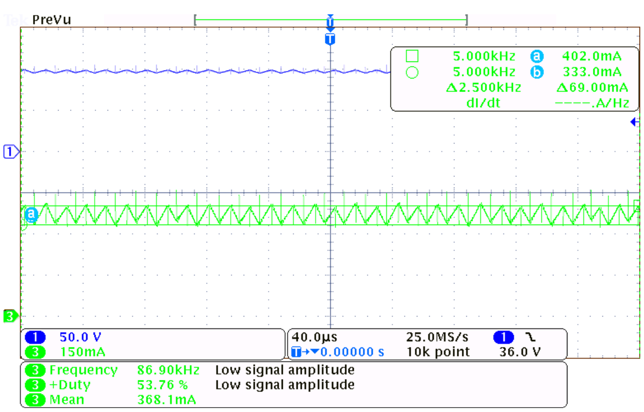


Figure 8: - Voltage (CHl- 50 V/div) and current of the LEDs (CH2- 150 mA/div).

The converter was analyzed for different dimming levels, ranging from 10% (lowest lighting level, highest dimming value – dimming switch at 90% duty-cycle) to 100% (no dimming, dimming switch is off).

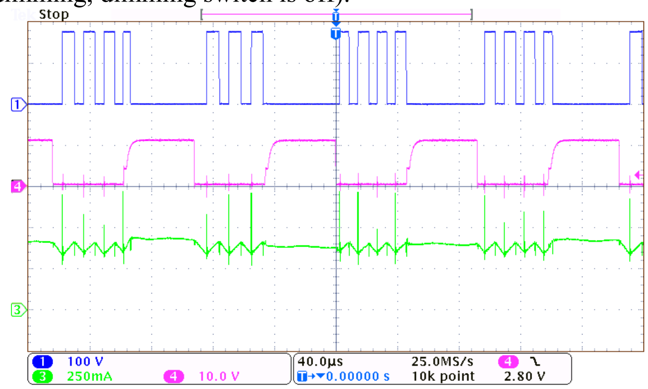


Figure 9: Voltage at output of the buck switching cell (CH1-100V/div), transistor Q2 voltage (CH2-10V/div) and inductor current (CH3-250 mA/div).

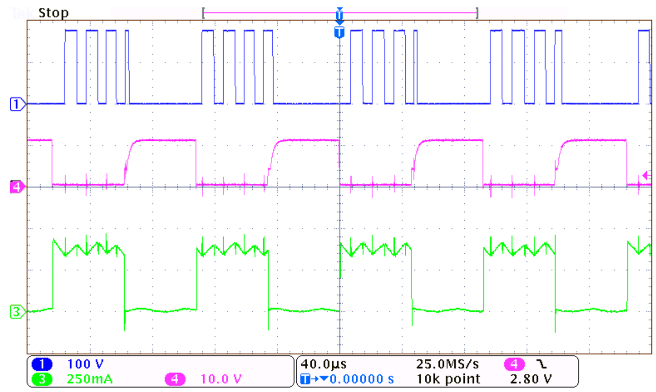


Figure 10: Voltage at output of the buck switching cell (CH1-100V/div), transistor Q2 voltage (CH2-10V/div), and LEDs' current (CH3-250mA/div).

The behavior of the normalized illuminance in front of the LED module (measured with a photodiode amplifier) is given in Figure 11, showing fair linearity according to what was expected. The converter also enabled an accurate control of the light level from very low values of average current (10% of rated, at 35 mA) up to the highest level (100%, at ca. 350 mA). This is mostly due to the use of PWM dimming scheme by means of a parallel switch, which is very compatible with the hysteresis current control employed.

Figure 12 shows the prototype efficiency curve for all the dimming range analyzed. The efficiency peaked at ca. 95%, at full load (no dimming). This figure naturally drops as the dimming control is triggered, because the converter losses (which are almost constant along the whole operating range) dominate over the load power. Thus, the lowest efficiency value was close to 57% at 10% light level (90% dimming). This is not an issue since converter efficiency was not the main focus of the prototype, but rather precise and linear lighting control.

A graph of variation of the lighting level versus the level of PPF detected by the cosine diffuser is shown in Figure 13. With this data, it is possible to observe that the behavior of the PPF level along the dimming range is not linear.

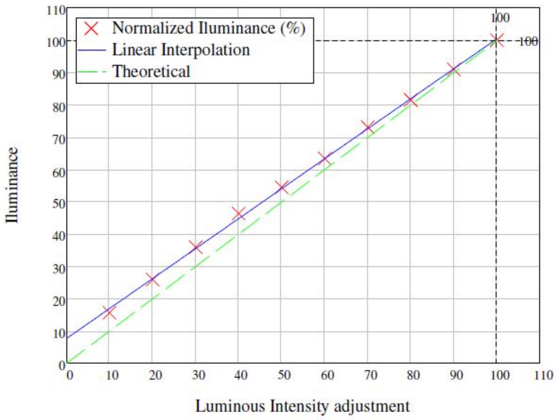


Figure 11: Illuminance vs. luminous Intensity adjustment.

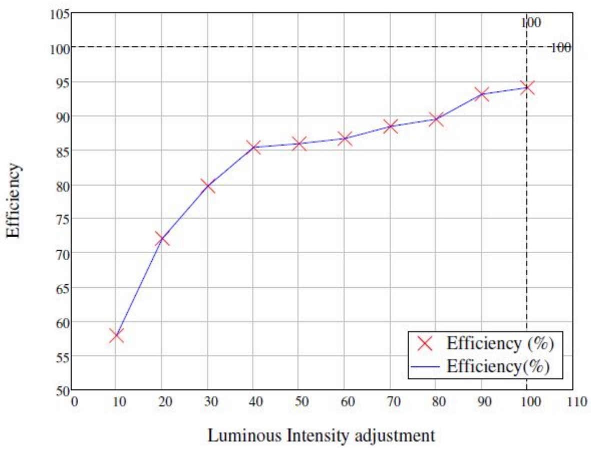


Figure 12: Prototype Efficiency vs. Luminous Intensity adjustment.

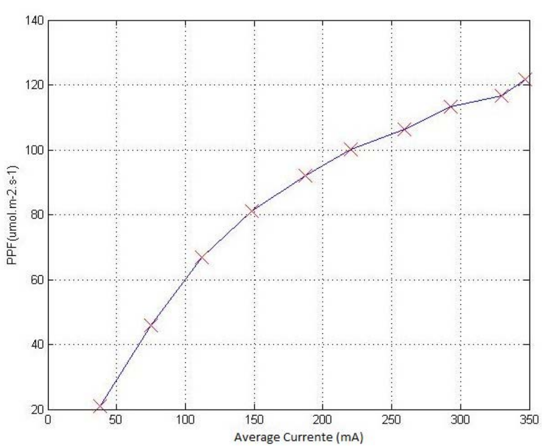


Figure 13: LEDs' average current vs. PPF.

## V. Conclusions

This paper has presented a brief review regarding plants physiology and its importance for vegetables crops applications. In addition, this study was able to provide an analysis of the quality of the studied luminaire, improving lighting products available to consumers and producers of vegetables.

The proposed electronic model developed in this work has shown excellent results, indicating a proper and efficient operation, which is explained by the correct selection of the project parameters.

Moreover, it is notice that the PWM-dimming controller is a good way to change linearly the average current applied to the LEDs and without the need of changing currents operation.

Finally, concerning the chromaticity results obtained in the laboratory, it was guaranteed a minimum deviation of chromaticity in the coordinates X and Y approximately of 0.06% and 0.12%, respectively, showing the efficiency of the PWM dimming .

## Acknowledgment

Authors would like to thank the Federal University of Juiz de Fora, CAPES, FAPEMIG, CNPq and the Brazilian Government for all financial, technical and scientific support on this work.

## References

[1] W. Grzesiak, et al., "Application of PV Powered High Intensity LEDs for Supplementary Irradiation of Horticultural Plants"□ In: IEEE. Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on. 2006. v. 2, p. 2400-2403.

[2] Y. Li , H. Chen, H. Ji , S. Wang and Z. Zhu, X. Wang , "Effect of LED Supplemental Illumination on the Growth of Strawberry Plants". Photonics and Optoelectronics (SOPO), pp. 1-4, Shanghai, 2012.

[3] A. Shimada and Y. Taniguchi, "Red and blue pulse timing control for pulse width modulation light dimming of light emitting diodes for plant cultivation", Journal of Photochemistry and Photobiology B: Biology 104 (2011) 399–404, 2011.

[4] N. C. Yorio, G. D. Goins, and H. R. Kagie ,"Improving Spinach, Radish, and Lettuce Growth under Red Light emitting Diodes (LEDs) with Blue Light Supplementation", *Hortscience* 36(2):380–383. 2001.

[5] C. S. Brown, A. C. Schuerger and J. C. Sager, "Growth and Photomorphogenesis of Pepper Plants under Red Light-emitting Diodes with Supplemental Blue or Far-red Lighting" *Hortscience* 120(5):808-813. 1995.

[6] P. Pinho, E. Tetri and L. Halonen, "Design and performance assessments of solid state light sources for plant growth," in Proceedings of the 10th European Lighting Conference Lux Europa 2005: Lighting for Humans, pp. 297-301, 2005.

[7] C. Almeida, et al., "LED-based Electronic Systems to support Plant physiology Experiments", Industrial Electronics (ISIE), IEEE 23rd International Symposium on, p. 531 – 536 , 2014.

[8] P. S. Almeida, F. J. Nogueira, L. F. A. Guedes and H. A. C. Braga "An experimental study on the photometrical impacts of several current waveforms on power white LEDs ", XI Brazilian Conference on Power Electronics, p. 728 - 733 , 2011.

[9] J. Garcia, A. J. Calleja, E. L. Corominas, D. Gacio, L. Campa, R. E. Díaz, "Integrated Driver for Power LEDs", IECON, pp.2578 – 2583, 2010.

[10] Texas Instruments Incorporated. INA193. Available at http://www.ti.com/lit/ds/symlink/ina193.pdf.

[11] P. S. Almeida, G. M. Soares, D. P. Pinto, H. A. C. Braga "Integrated SEPIC Buck-Boost Converter as an Off-line LED Driver without Electrolytic Capacitors" Conference on IEEE Industrial Electronics Society , pp. 4551 – 4556, 2012.

[12] I.H.Oh, "An Analysis of Current Accuracies in Peak and Hysteretic Current Controlled Power LED Drivers," Applied Power Electronics Conference and Exposition, 2008.