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On the use of the intrinsic ripple of a buck converter for Visible Light Communication in LED drivers

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***Abstract*—In this work, we present the analysis of a novel technique to implement Visible Light Communication (VLC) into LED drivers with minimum hardware requirements and efficacy degradation. It uses a synchronous buck converter as a circuit for a dual-purpose LED driver for illumination and VLC. The role of the converter is to regulate the average current via the duty cycle value for lighting purposes and to modulate digital data through the phase of its ripple waveform. In this technique, the phase of the Pulse Width Modulator (PWM) acts as an independent variable to modulate the ripple waveform for a binary phase-shift keying (BPSK) modulation and does not affect lighting regulation. Thus, transmission of wireless digital data uses the remaining AC content present in the waveform of the ripple. By detecting the phase of the ripple, a VLC receiver can decode the data sent by the transmitter. Finally, our experimental results show that the efficacy of the LED is not affected by the value of the ripple when operating outside its nonlinear region, along with minimum global efficacy degradation when compared to a standard synchronous buck converter with same parameters and no VLC capabilities.**

***Index Terms*—LED Lamps, Digital Communication, Power Electronics, Driver Circuits.**

I. Introduction

Visible Light Communication is becoming a hot topic for research in lighting engineering. It stands for the use of the visible light spectrum as a resource for wireless communications. In this scenario, allied to their great advantages as light sources compared to incandescent and fluorescent [1], Light Emitting Diodes (LEDs) are used as transmitters due to their capacity to respond to fast electrical stimuli at rates that are not perceived by the human eye. Therefore, the frequency response of the LED gives enough bandwidth for transmission of digital data at sufficient rates for many applications [2]. VLC can enable a new functionality to the regular lighting system, providing not only means for artificial lighting with greater quality, but also a wireless communication medium that does not interfere with common radiofrequency (RF) communications [3].

In addition, amongst other advantages, VLC can be deployed without the need of additional infrastructure in buildings, homes or offices. It can reuse the existing infrastructure of lighting systems by only changing its final device with a dual-purpose luminaire [4]. This aspect opens the door for many applications of a communication network of simple installation, such as sensor networks for monitoring and control [5], indoor positioning systems [6] and would also favor many Internet of Things (IoT) applications, another upcoming technology that is becoming already standardized [7].

Moreover, VLC systems offer an intrinsic security feature. The incapacity of light to penetrate through walls confines the network within one single room. Thus, such feature prevents external undesired malicious users to invade the network and also offers more spectrum spatial reuse with no interference, since several VLC networks can coexist close to each other confined into different rooms [4].

However, despite being more efficient than former light sources, LEDs may face implications regarding the overall system efficiency in virtue of the extra energy consumption of their driving circuitry for lighting regulation and control. In fact, literature presents extensive research efforts in terms of driver circuitry in order to increase not only the overall efficacy of the system but also match the lifespan of both LED and driver [8], [9], [10]. Furthermore, [11], [12], [13] show that adding VLC into lighting systems would also come with extra energy penalties due to the modulation of the current at the LEDs, mainly because of the physical limitations in the operation of the LED and the requirements of extra power components such as switches and gate drivers or power amplifiers. Hence, in a perspective of lighting engineering, a lighting system must provide VLC in a sense that does not compromise its efficiency and total manufacturing costs to the point of making such technology unreliable for use in day-to-day applications.

Given these reasons, we presented in [14] a simpler and novel way to implement a binary phase-shift keying (BPSK) modulation technique for VLC by taking advantage of the current ripple of a synchronous buck converter operating in Continuous Conduction Mode (CCM). Hence, our modulation strategy and converter topology is oriented to process the energy from an input DC bus employing a capacitance in the order of nanofarads in parallel with the LEDs. As the majority of dual-purpose LED drivers for VLC [15], [16], [17] and also several topologies of common drivers [18], the aims of application of this technique is to implement VLC into the power stage of two-staged power converters with Power Factor Correction (PFC) or any other future applications of DC-oriented grids [19], [20], [21]. In these terms, VLC function comes without adding any power components other than the ones used by the converter, which also acts as a

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regulator for the average value of current at the LED load. Thus, in this work, we explore and analyze this technique in terms of its changes in the overall efficacy of the system, along with its mathematical models for VLC and lighting purposes. Hence, this paper is organized as follows: Section II presents brief commentaries regarding VLC into LED and drivers circuits. Section III explains our modulation strategy and the mathematical models that describe it. Section IV presents our experimental setup and results and finally Section V closes this paper with our conclusions.

II. Merging VLC and Illumination Functions in One Device

LEDs are the most efficient source of artificial light used in illumination and a wide set of commercial options exist to any light application. Together with Laser Diodes (LDs) emitting in the blue spectrum [22], LEDs may be the basis for VLC infrastructure deployment in practical applications.

The LED electrical energy to light conversion is a main concern in general illumination. The overall light flux produced (lumens, lm) accordingly to the power spent (watts, W) defines how well a luminaire performs its main goal. This metric is given in the lm/W ratio, mainly known as efficacy. The Power Spectral Density (PSD) of light produced by the LED device is dependent on the semiconductor characteristic emission profile (color mixed, CM LEDs) and also on phosphor cover (phosphor coating, PC LEDs). CM LEDs contain different semiconductors (dies) to emit in each spectrum range of light, while PC LEDs have a single semiconductor emitting in short wavelengths ranges. Part of this light is transformed to longer wavelengths by the phosphor that covers the LED die or lens. Therefore Fig. 1 and Fig. 2 depict the PSD of CM and PC LEDs, respectively. The better matched to human eye sensitivity (wavelengths within the range of 380 nm to 750 nm), the greater is the light flux perceived by users.

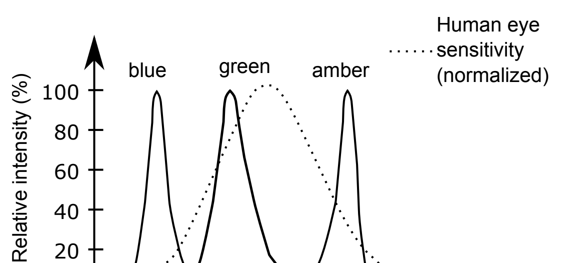

Fig. 1. Typical PSD for a CM commercial LED [23].

In addition, only part of the energy provided to the LED device is converted into light and emitted accordingly to its PSD profile. The efficacy of the device also depends on the semiconductor characteristics (those are affected by the material and building structure) and it is strongly dependent on the operating temperature and current level applied. These characteristics have been extensively explored in the scientific

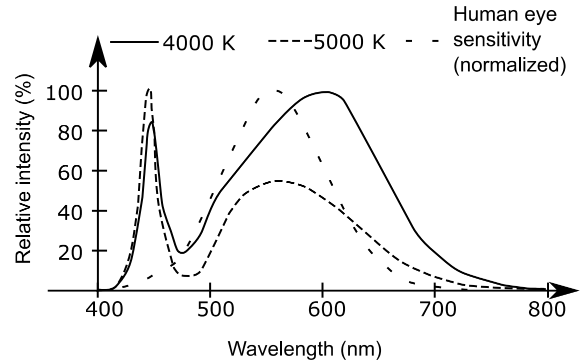

Fig. 2. Typical PSD for a commercial PC LED [24]. Two possible CCT via weighted phosphor coating are shown.

literature [25], [26] culminating into what is usually refereed as the Photo-Electro-Thermal theory (PET theory).

Furthermore, the temperature has a negative impact on the efficacy, thus the higher the temperature of the die, the lower is the overall light emission efficacy [25]. Moreover, the instantaneous current level applied to the device defines the total light flux obtained. However, the relationship between these two variables is nonlinear [27]. Thus, high instantaneous values of current reduce the efficacy of the LED (lm/W), a phenomenon called Droop Effect (DE), which it is also widely investigated in the literature [28], [23].

Henceforth, bringing together the illumination goal to VLC features, the Joint Illumination and Communication (JIC) concept was coined by [11], [12]. The authors proved that extra power is spent to modulate data over light given the reasons aforementioned. In addition, the analysis of modulation methods used in VLC signaling is pertinent in the power converter's efficiency performance as well as in the LED's efficacy [13], [29].

Moreover, the luminaire LED driver efficiency may also be a concern to the system designer, because such metric is affected by the electronic circuit topology being used, along with its parameters. LED driver circuits are usually classified in groups. Accordingly to common features or characteristics, different classifications can be proposed [29], [18], [30].

Finally, we focus this paper on the aspects that concern efficiency as a main performance metric with respect to the features needed for the active control of the instantaneous output current, in order to achieve VLC and lighting regulations. We begin our analysis by exploring two main types of converters regarding their potentials as VLC modulators, described as follows into two categories. Later, we will show our efforts to provide VLC in the sense of minimizing efficiency penalties by utilizing less active power components and other hardware requirements when compared to regular LED power sources usually employed in lighting engineering.

A. Linear Regulators

Linear regulator circuits operate with a dissipative principle. They are designed to maintain a linear stable gain in a given frequency bandwidth. In VLC, they are usually employed for

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high speed modulations, mainly Orthogonal Frequency Division Multiplexing (OFDM) [27]. They use power electronic devices that dissipate additional power (according to voltage or current available from the power source) in order to adjust these parameters to the LED load from an unregulated supply. This method of regulation describes a less energy efficient design approach, but those converters can reach very wide output signal modulation bandwidth. However, the excess of energy dissipation makes it an nonviable option for some scenarios where high efficiency conversion is required and high speed data rates are not necessary, such as IoT applications or sensor networks.

B. Switched Mode Power Converters

Switched mode power converters (SMPCs) have reactive elements such as capacitors, inductors and transformers, and are able to handle energy levels in a non-dissipative way. The power losses are associated only to parasitic elements and losses on active components during switching transitions, not to the operation principle itself such as the case in linear regulators.

These type of converters can reach very high efficiency levels, therefore being suitable to general illumination purposes. However, the dynamic behavior of the output signal is limited by reactive elements and their filtering characteristics. The last is a disadvantage in VLC, because the bandwidth of generated LED drive stimuli is important for the best use of the available light spectrum for wireless communications. Nevertheless, we will show later that we can achieve sufficient data-rates with suitable efficacy and efficiency values for lighting industry standards.

C. LED's bandwidth

The bandwidth of the current stimuli that can be generated by the power converter is also a limitation that must be faced in order to implement VLC in a practical system [29]. The bandwidth must be at least suitable for VLC applications and must be wide enough in order to avoid flicker patterns that may harm human health. This feature is affected by the bandwidth of the actual semiconductor elements that are used for current modulation. In this case, not only the power converter is the limitation of the system regarding efficiency, but it also can limit the overall bandwidth available for VLC. Nevertheless, with the advance of semiconductor technology, it is possible to overcome such limitation with the use of new materials that may reach greater frequency responses, such as GaN-based MOSFETs [28]. In this case, the main bandwidth concern lies on the LED's frequency response, which may represent the bottleneck of this particular characteristic in a near future. In conclusion, the LED's bandwidth can be explored into two dimensions in order to successfully take advantage of such available resource: on electrical domain or on its optical domain.

One of the electrical limitations on LEDs refers to resistances and capacitances that affect the speed that charge is applied in and removed from the semiconductor material. Also the lifetime of carriers inside the semiconductor die imposes attenuation to high frequency components of signal stimuli applied to its terminals [31], thus reducing the intensity of the light signal generated. [32], [33] refer on the frequency response of an LED to be dependent on the injected current, thus higher current levels in a same device lead to wider bandwidth. Hence, increasing current bias to increase bandwidth goes in the opposite direction than the illumination purpose, because high current levels reduce the efficacy of the LED.

Moreover, on the optical domain, the main limitation faced by PC LEDs is the slow speed that phosphor reacts to light. The bandwidth of light modulation in PC LEDs is around 3 MHz [32] and it is already a challenge to be faced. In conclusion, such limitations show that the physical properties of the LED will be the next bottleneck regarding bandwidth limitations for VLC applications.

Therefore, this work aims to present an efficient signal modulation strategy that is easy to be implemented in switched mode DC-DC power converters with little changes in design. Bandwidth limitations will be only dictated by the available technology present on the semiconductor switches, being used in the design of the driver considering the available bandwidth of PC-based white LEDs. In addition, our technique imposes a modulation to the LED's current that is useful for communication purposes and leads to insignificant reduction to the overall efficacy of the system in a practical design.

III. Modulation Strategy for VLC and Illumination

A synchronous buck converter is a step-down circuit that already contains a modulator built in it (see Fig. 3). Given this reason, we explored its Pulse Width Modulator (PWM) in order to regulate the output average current and send data via VLC. Potential applications of this particular topology and modulation strategy may include the deployment of VLC networks in smart buildings, offices, homes and other environments where VLC may be attractive such as airplanes, hospitals and power plants [3].

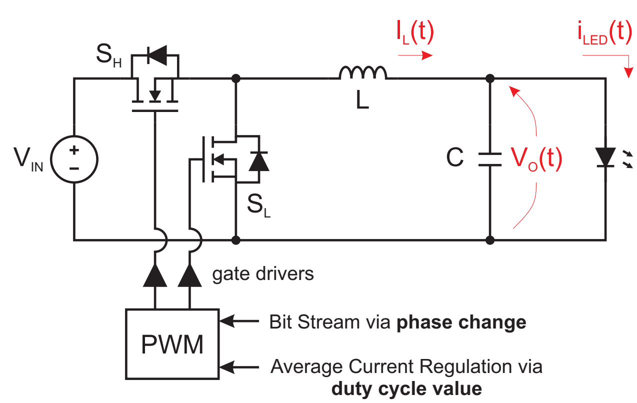

Fig. 3. Dual-purpose buck converter circuit.

To clarify our idea, we may see the converter as part of a communication system based on VLC. For instance, Fig. 4 shows the schematic of our communication system with the path of information in detail. The transmitter is composed by the LED and its driver circuit, while the receiver is composed

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by a photodiode (PD) with a filter and amplifier circuit, followed by a demodulation process, usually embedded as an algorithm in a digital processor. The channel represents the effects due to the propagation of the light signals in the environment [33]. Throughout this paper, we focused our efforts on the transmission and detection of our communication signals, as we will mention on our experimental results.

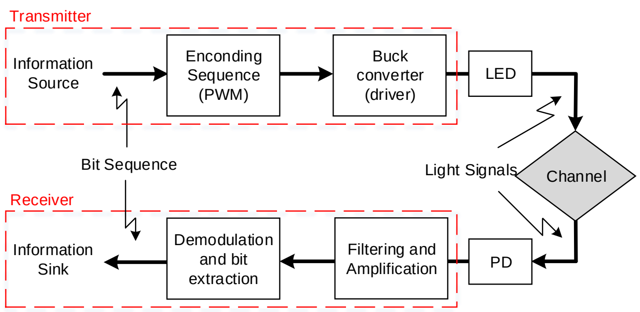

Fig. 4. Block diagram showing the proposed VLC system.

The driver sends the data by changing the phase of the PWM at each bit transition, thus encoding the bit sequence being transmitted into a periodic waveform based on the ripple of the converter. From the Communications perspective, such technique is also known in the literature as Binary Phase-Shift Keying Modulation (BPSK) [33], where an analog carrier exchanges its phase from 0 to π radians when a bit transition occurs. In this particular kind of modulation strategy, the carrier is maintained in a fixed frequency and fixed amplitude. In our scenario, the frequency is a multiple of the switching frequency of the converter, while the amplitude can be determined by the ripple percentage used to design the inductor of the converter and its peak value of current. The PWM phase change causes a phase change in the output current ripple, which acts as a periodic analog carrier waveform for the modulation aforementioned. Finally, Fig. 5 displays an example of simulated waveforms showing our modulation strategy for VLC when the converter is transmitting a bit sequence.

A. The Converter as Part of a VLC Transmitter

In our case, the carrier presents a triangular shape waveform due to the charge/discharge behavior of the inductor. This shape is given by the LC filter of the converter, and we will show later that its design plays an important factor for communication purposes. Thus, communication is possible without interfering the average current regulation because both duty cycle and the phase of the PWM carrier are independent from each other. In other words, we managed to use two independent input variables of the PWM, such as shown in the schematic of Fig. 6.

Moreover, the converter must be seen not only as a regulator of the output current average value, but also as part of a transmitter for VLC. We can directly relate the current at the LED to the luminous flux generated [34]. Thus, we separated both functionalities according to the frequency components of the output current, as we will show next.

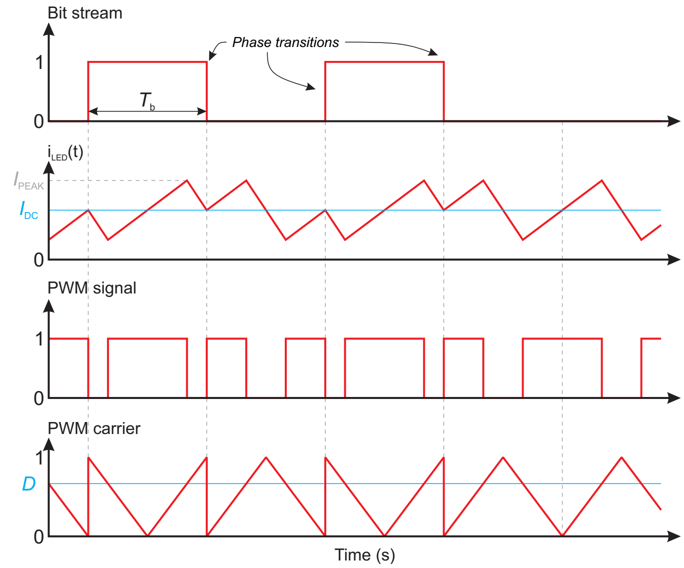

Fig. 5. Converter simulated waveforms while transmitting data.

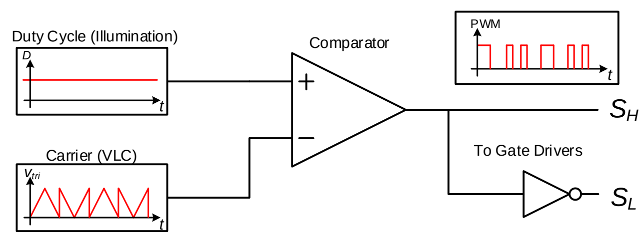

Fig. 6. Diagram of the PWM for both VLC and Illumination functions.

In fact, the output current $i_{LED}(t)$ delivered to the load shows two major components, displayed in (1).

$$i_{LED}(t) = I_{DC} + i_{AC}(t) \tag{1}$$

where I_{DC} is the output average value and $i_{AC}(t)$ is the AC component given by the remaining frequency content of the PWM. Hence, the energy contained in I_{DC} regulates the average luminous flux and thus the lighting level for illumination purposes [34]. Such statement is true if the fundamental frequency of $i_{AC}(t)$ is given in a value which is not perceivable by the human eye, according to standard regulations [35]. Finally, the energy remained in $i_{AC}(t)$ is responsible for transmitting digital information throughout the VLC channel.

In other words, we can relate one periodic waveform given by the triangular shape frequency content of the ripple as a carrier for digital communications. The bit sequence is encoded in the phase of the PWM carrier, and assume two different values (0 or π) according to the bit being transmitted (symbols “1” or “0”). Such transition is then translated to the ripple waveform. Hence, in Fig. 7 we show and example of the two possible modulated waveforms according to the bit being transmitted and the PWM phase change. The examples are related to the phase change of a sine wave for better clarification.

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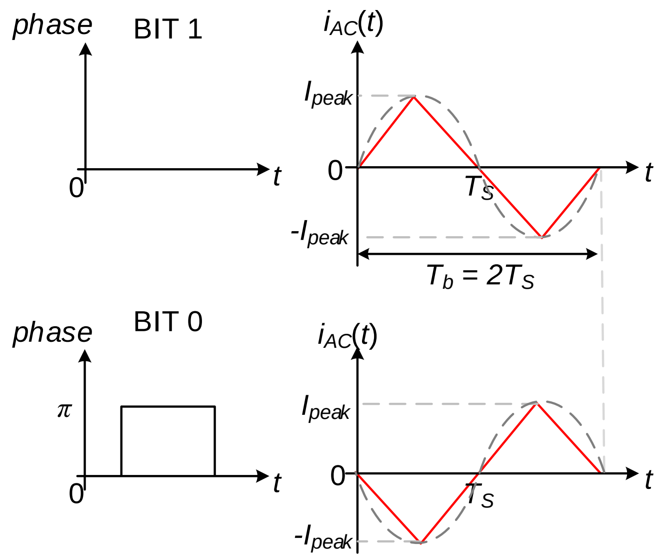

Fig. 7. Example of phase change according to the bit being transmitted.

In addition, in [11] the authors show the importance of the total amount of input power being used for VLC. Once transmitted, the signals that propagate through the channel are strongly dependent on the distance d between transmitter and receiver, with the emitted optical power being affected by the well-known factor of $1/d^2$ [11], [36].

To better understand this concept, in our modulation strategy, the transmitted optical power for communications and the design of the converter based on the output ripple are the link between a Communication perspective and the design of a power converter commonly used as an LED driver. In fact, the link in converter design for future VLC applications may include the amount of power available for data transmission. Since the average luminous flux is constant and does not carry any digital information, the AC signal that is left at the LED current is responsible for data transmission. Therefore, it is important to have a way to quantify the amount of energy processed by the converter circuit that effectively transmits information across the channel. For example, one way to obtain an effective measurement of the energy that is effectively being used for communications is through the RMS value of the transmitted signal. With the RMS value, several VLC features that are important for the system can be predetermined, for example maximum allowed distance between transmitters and receivers, minimum number of transmitters for a given network and the amount of power driven by the communication function in a dual-purposed LED driver.

In [12], the authors relate the transmitted optical power P_o as a function of the LED current, such as shown in (2).

$$P_o = \frac{I}{q}\xi \tag{2}$$

where I is the LED current, q the electron charge and ξ the energy of the photon. This relation represents the fundamental relation between the electrical energy to light conversion in an LED. Therefore, the optical power used for communication directly relates the AC component of the LED current that carries the information being transmitted. With the combination of (1) and (3), we can decompose the AC part of the optical power that transmits the digitally modulated signal, while its DC component is responsible for the average luminous flux perceived by the human eye.

Given these reasons, we quantified the effective power being processed for communication and the respective part for illumination in terms of the LED's current frequency components. Such analysis is an important feature because it relates the power being processed by the converter circuit with the effective power used for VLC. In [33], the authors show one way to determine the power used for transmission through the root mean square value (RMS) of the analog carrier waveform. In the converter's perspective, the RMS value of $i_{AC}(t)$ is a way to determine the power present in the AC components and therefore the amount of energy that transmits digital information [37]. In Fig. 8, we show a graph of the AC component of current in order to mathematically analyze the communication signal to obtain its RMS value. Here, $s_1(t)$ and $s_2(t)$ represent the straight line functions of the charge/discharge behavior of the inductor, which are modeled in order to calculate the integral of the RMS value. In our model, the influence of the output capacitor is considered very small. Hence, by analyzing the converter dynamics while transmitting data, we managed to determine the amount of power carried in our communication signal in function of the $i_{AC}(t)$ peak current I_p by subtracting the DC component from $i_{LED}(t)$. In essence, the components of $i_{LED}(t)$ are mainly determined by the value of the inductor and the switching frequency of the converter.

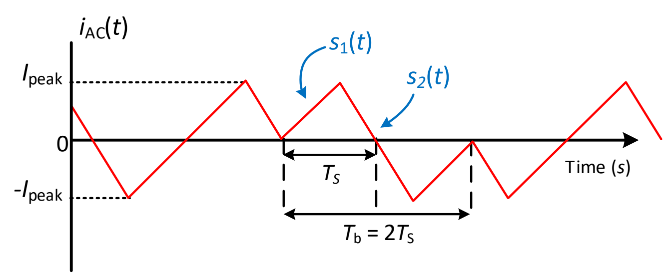

Fig. 8. AC component of the LED current used for transmission of data.

To calculate the RMS value of $i_{AC}(t)$, we took advantage of the symmetry imposed by the periodic ripple waveform, given by the charge and discharge behavior of the inductor (Switch ON State and Switch OFF State, respectively), as shown in (3). The analytical analysis of the RMS value of $i_{AC}(t)$ are shown in (4) and (5) and are based on the theory depicted in [37].

$$I_{AC}(RMS) = \left[\frac{1}{T_S}\left(\int_0^{DT_S} s_1(t)^2 dt + \int_{DT_S}^{T_S} s_2(t)^2 dt\right)\right]^{\frac{1}{2}} \tag{3}$$

$$I_{AC}(RMS) = \frac{\sqrt{3}}{3}\frac{V_{in}}{L}T_S D\left(1-D\right) = \frac{\sqrt{3}}{3}I_p \cong 0.58 I_p \tag{4}$$

$$I_p = \frac{V_{in}}{L}T_S D\left(1-D\right) \tag{5}$$

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where V_{in} is the input DC voltage, D is the duty cycle value, L the value of the inductor's inductance and T_S is half of the bit period T_b. In conclusion, in a similar way we see the effective value of a sine wave to be $1/\sqrt{2}$ (~ 0.707) of its peak value, the effective value of the energy that is being used for communication is about 58% of the AC component peak value designed for the converter.

In addition, the ripple's triangular shape waveform is a consequence of the presence of high amplitude harmonic content in the signal. This is achieved with a small output capacitor, in this case used only for high-frequency noise attenuation. The presence of high harmonic content is important for communication purposes because the triangular shaped waveform is the best periodic signal achievable by the converter in order to detect required phase changes for modulation of digital data. Hence, a receiver can easily extract the information sent by employing any phase detection technique (Phased-Locked Loop - PLL, Zero Crossing Rate and more sophisticated signal processing methods such as Matched Filtering [33]).

Furthermore, it is important to emphasize that the amplitude of the ripple does not impact on the LED lifetime while operating at nominal conditions. Several works in the literature have indicated that the LED lifespan is mainly driven by its thermal management in terms of heat sink design and/or active ventilation, as pointed in [1], [9], [27]. Therefore, communication capabilities using the inherent ripple of the converter do not impact on the LED operation lifetime.

B. The Converter as a Driver Circuit for Illumination

To compute the average value I_{DC} for illumination purposes, we take the well-known DC model of the converter as shown in [38] along with the linear model of the LED load as shown in [39].

$$I_{DC} = \frac{DV_{in} - V_t}{r_{LED}} \tag{6}$$

where r_{LED} is the LED's series resistance and V_t its threshold value, according to its linear model.

In addition, by taking a similar mathematical analysis shown in [37] and [40], it is possible to compute the RMS total value of $i_{LED}(t)$ in function of its DC and AC components as shown in (7). Such metric is a way to compute the amount of energy processed by the converter in terms of its output current [41].

$$I_{LED}(RMS) = \sqrt{I_{DC}^2 + I_{AC}(RMS)^2} \tag{7}$$

In this sense, the current effective value can be used to compute the amount of non-active power present in the load that does not contribute to the average luminous flux generated, but instead it is used to carry digital communication signals. In conclusion, with our modulation strategy, we take advantage of the AC amount of power being processed by the converter, separating it according to their frequency components and their respective functions.

C. Proof of Concept

In order to validate the mathematical models aforementioned, we performed a quick experimental test to check if our technique actually maintains the output average value of the current at a constant level when transmission is occurring. The main objective of this test was to confirm that I_{DC} does not depend on the transmitted bit sequence, and BPSK can be achieved without harming illumination constraints. We show in Fig. 9 the waveforms of a synchronous buck converter operating at 100 kHz while transmitting a giving bit sequence. Therefore, it is possible to see that the LED's current average value does not change when bit transitions occur.

Moreover, we also show that transmission data rate is a multiple of the switching frequency, thus making the switch's maximum operating frequency a limitation factor for maximum VLC data rate. Hence, in this case, we achieved a data rate of 50 kbps (half of the switching frequency).

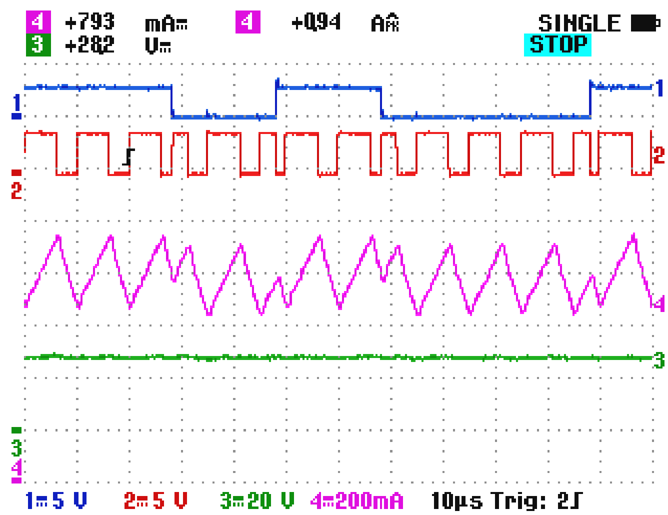

Fig. 9. Experimental converter waveforms while transmitting a given bit sequence. From top do bottom: CH1 - Bit sequence - 5 V/div; CH 2 - PWM Signal - 5 V/div; CH 4 - LED's Current - 200 mA/div; CH 3 - LED's voltage - 20 V/div; Horizontal 10 μs/div.

D. AC Power Ratio used for VLC

In a lighting engineering point of view, illumination must be the main system functionality, with VLC being a complementary function provided by the luminaire. Hence, with this line of thought, the value of D comes in function of the illumination level required and thus giving a value of I_{DC}. Later, we design the filter according to the desired ripple Δ_{i_L} value present in the output current. This design is directly related to the amount of AC energy that will be used for VLC. This is possible by using the well-known equation of the buck converter ripple factor [38] shown in (8) and (9).

$$L = \frac{(V_{in} - V_o)DT_S}{\Delta_{i_L}} \tag{8}$$

$$\Delta_{i_L} = \frac{I_{PkPk}}{I_{DC}} \tag{9}$$

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where V_o is the desired output voltage, I_{pkpk} is the peak-to-peak current value at the inductor and T_s is the switching period.

Furthermore, one way to analyze the amount of energy used for VLC is to plot $I_{AC}(RMS)$ as a ratio of the RMS value of $i_{LED}(t)$ as shown in (10).

$$\frac{P_{AC}}{S_{LED}} = \frac{I_{AC}(RMS)^2}{I_{DC}^2 + I_{AC}(RMS)^2} \tag{10}$$

where P_{AC} stands for the AC transmitted power and S_{LED} is the total power (AC and DC components) delivered to the load.

By combining (10) and (8), we show a parabolic behavior increase of P_{AC} in function of the ripple percentage, for a given LED load and a given average value of current at the output. With these parameters defined, we can calculate the amount of power supplied by the converter that it is being used for communication purposes. Such percentage can be used as a tool to design a dual-purpose buck converter driver. Therefore, we can define a link between communication parameters with lighting constraints. We see such scope of design a novelty feature to be further analyzed in VLC applied to solid-state lighting systems.

Thus, in order to verify the viability of our mathematical conclusions, we decided to perform a series of circuit simulations utilizing PSIM software. The simulations were performed by varying the ripple (and therefore the inductor) of a given buck converter in order to provide different values of ripple and P_{AC} such as shown in Fig. 10. This curve displays the ratio of the energy present in $i_{LED}(t)$ that is being used as a communication signal based on the converter's designed ripple. This metric gives a good procedure in order to provide not only information regarding the amount of energy processed aimed at communication features, but also to help in the design of a dual-purpose LED driver. Thus, the focus while designing a driver of such purpose must come with metrics that may help in the design of VLC system in general.

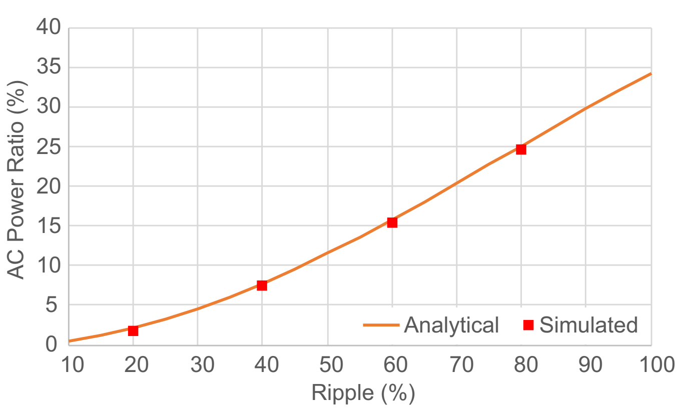

Fig. 10. P_{AC} over S_{LED} versus ripple value.

IV. Experimental Results

A. Capturing the Modulated Received Signals

In order to validate the possibility of capturing the modulated waveforms for communication, we designed a simple receiver circuit that consists of a trans-impedance amplifier (TIA) and a photodiode, such as shown in Fig. 11. The reference circuit was designed in order to regulate the frequency bandwidth of the amplifier.

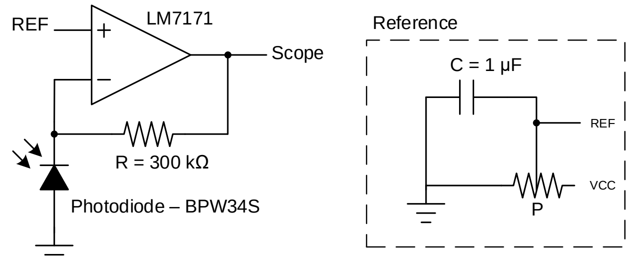

Fig. 11. Receiver circuit design.

In addition, we developed a test setup that consists of a line of sight (LOS) configuration. In this particular setup, both transmitter and receiver are aligned over a straight line and separated in a given distance [3]. Finally, Fig. 12 shows the setup schematic, while Fig. 13 presents the captured signals on an oscilloscope for a transmitter operating at a switching frequency of 100 kHz, a data-rate of 50 kpbs and a percentage ripple of 30%.

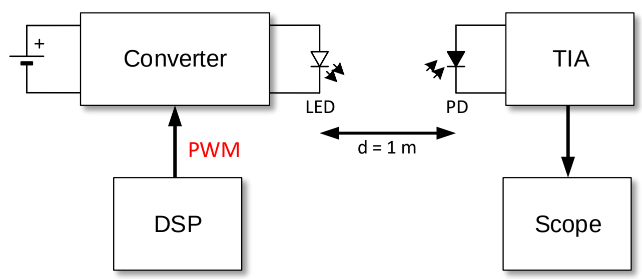

Fig. 12. Setup schematic for detection of the light signals.

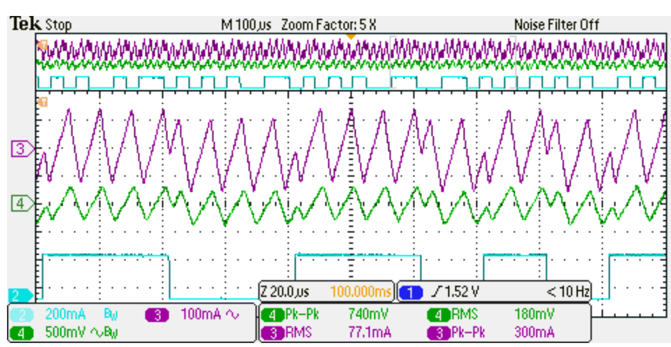

Fig. 13. AC Coupling of Converter waveforms of current and the received signals over 1 m. CH3 - Current at the LED; CH4 - Received Signal; CH2 - Transmitted bit sequence.

B. Efficacy of the System

According to the commentaries made during section II, we showed that the relations between the overall efficacy of an

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LED driver circuit is of complex nature and may involve many variables that are related to the physical constraints of the LED load and its nonlinear relations of its photo-electrical-thermal model. Moreover, global efficacy is also affected by the limitations on the driver circuitry. Therefore, the presence of extreme independence between the physical variables of the LED and the power converter being used result in very complexes calculations in order to model possible efficacy losses when adding VLC functionality. Given these reasons, we decided to evaluate our proposed modulation scheme and its impacts on the efficacy of the system by developing a series of experimental results. This experiment makes use of a Power Analyzer in order to measure the efficiency of the driver circuit along with an Integrating Sphere to measure the emitted luminous flux of the LED load during specific forms of driving conditions. With these types of measurements, we intend to calculate the overall system efficacy and the possible impacts that communication feature may imply on it when operating in a worst case scenario.

Therefore, we built three converter circuits with three different ripple specifications. All converters operate at a fixed 150 kHz switching frequency and with the same input and output parameters, as summarized in Table I. The main objective of these prototypes was to check possible global efficacy losses of the system for different values of inductors (and hence different values of transmitted power for communications) when driving the same LED load. For such frequency, we managed to provide sufficient data rates for the aforementioned applications without compromising EMI constraints and still managing to utilize commercially available inductors and capacitors with significant reduced volume.

TABLE I
SPECIFICATIONS OF THE PROTOTYPES

Converter	Parameter	Value
All	Nominal input voltage	48 V
	Nominal output voltage	28.3 V
	Nominal output current	800 mA
	Nominal output power	22.6 W
#1	Output current ripple	20%
	Inductor	470 μH
	Output capacitor	66 nF
#2	Output current ripple	44%
	Inductor	220 μH
	Output capacitor	66 nF
#3	Output current ripple	100%
	Inductor	100 μH
	Output capacitor	66 nF

As a load, we used a Bridgelux BXRC-50C4000-F-24 COB LED for all converters.

The PWM signals used to control the power MOSFETs were generated by a TMS320F28377S digital signal processor. We tested each converter with a fixed PWM pattern (without VLC - Fig. 14) and with an alternating bit pattern (Fig. 15). We used this sequence as a digital data to represent the worst-case scenario in terms of converter's efficiency as the switching frequency of the converter doubles during a sequence of bit transitions, hence increasing switching losses.

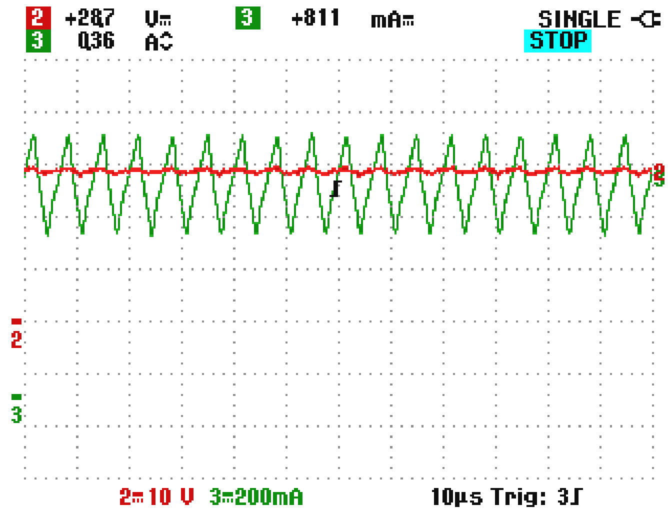

Fig. 14. LED waveforms with 44% ripple and no VLC. Channel 2 - LED voltage - 10 V/div; Channel 3 - LED current - 200 mA/div; Horizontal 10 μs/div.

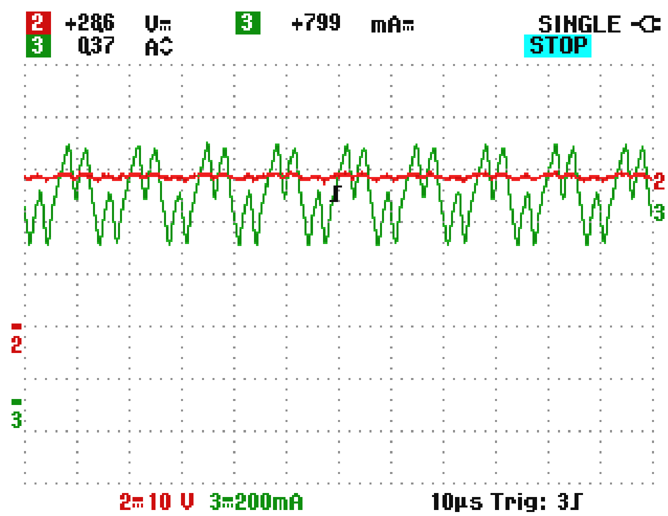

Fig. 15. LED waveforms with 44% ripple and VLC (alternating bit pattern). Channel 2 - LED voltage - 10 V/div; Channel 3 - LED current - 200 mA/div; Horizontal 10 μs/div.

In all tests with VLC, the bit period T_b is equal to two times the converter's switching period T_s ($T_b = 2T_s$), meaning a bit data-rate R_b of half its switching frequency ($R_b = F_S/2$). This measure was necessary in order to obtain a periodic waveform at the output current for phase change. Fig. 16 presents the system's efficacy with and without transmission of data. Thus, as can be seen, the global efficacy decreases when VLC is applied with an average reduction of 3%.

This degradation in the global efficacy of the system is caused by the increased losses in the power converter. As mentioned above, this modulation scheme increases the number of commutations in a switching period, thus increasing switching losses. We also have to highlight that our tests were driven based on a worst case scenario of consecutive

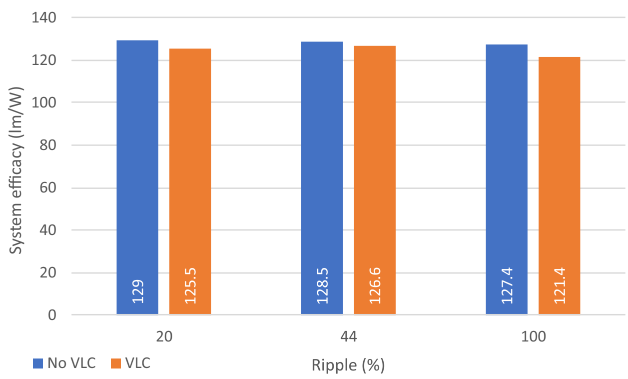

Fig. 16. System efficacy plot for different ripple values.

transitions of bits between 1 to 0. This realization is visible in Fig. 17 when we analyzed the same converter without and with VLC capabilities. Furthermore, it is important to notice that our LED's operating point of 800 mA is working below its nominal value (1050 mA). Hence, we did not observe any Droop Effect in our experiment, and the overall efficacy of the LED remained in 134.4 lm/W for all cases. Moreover, as the output ripple increases, conduction losses in the converter also increase due to the rise of the non-active power flowing through the circuit.

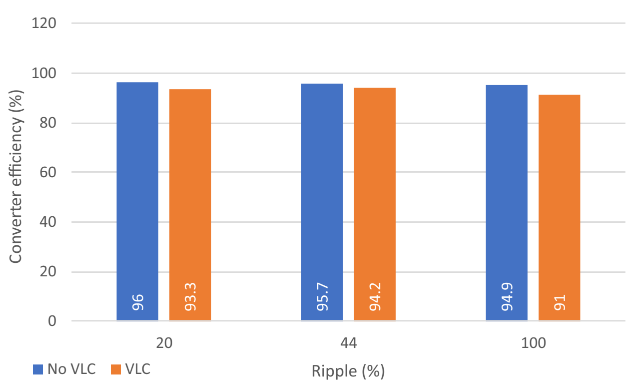

Fig. 17. Converter efficiency for different ripple values.

V. Conclusion

In this work, we analyzed a novel modulation technique presented in [14] that aims to integrate VLC and illumination in one single switched LED driver. In order to become a commercially available technology, VLC must come in a simpler and efficient way that does not compromise the quality standards already followed by the lighting industry. In other words, VLC must be treated as an additional functionality embedded into an LED luminaire, with low cost implementation and minimal degradation on the efficacy of the system. Literature already presented that the addition of VLC comes with intrinsic efficacy losses when compared to regular LED-based lighting systems [11], [12]. Therefore, our efforts in providing this novel modulation strategy are intended to mitigate these possible losses by exploring an existent converter topology to act as a transmitter for VLC. Given these reasons, we presented a set of possible applications where VLC may come with minimal design changes and energy penalties, such as IoT applications and other scenarios where light sources may be used as sensor networks for monitoring and control.

Moreover, based on the reasons aforementioned, we presented a technique that does not require the addition of extra power components in order to enable VLC into an LED driver. By using one single buck converter, an already consolidated LED driver for current regulation, we managed to provide a BPSK modulation that explores the driver's remaining AC components. From a constant input voltage source acting as a DC bus and with the ripple of the converter waveform acting as a carrier for digital communications, we successfully implemented means to modulate binary data via its phase change. The only requirements for one to properly make use of this modulation strategy is to guarantee a sufficient ripple amplitude at the output of the converter. Given this fact, the output capacitance must be sufficient small (in the order of nanofarads) to not attenuate the signal being used for communication purposes. Hence, we provided the required mathematical models in order to calculate the amount of energy processed for communications and illumination as well. We believe that the amount of power being used for communications in a dual-purpose LED driver is of great importance in order to dictate several communication constraints that might come along with the design of a power converter for both illumination and communication. Such constraints will have to count as future design variables in scenarios where the LED lights are intended not only to illuminate the environment but also to create a network of wireless communications.

Finally, we performed experimental results in three circuit prototypes in order to analyze the impacts on the system's efficacy over the insertion of VLC. The main purpose of this investigation was to see if energy penalties would come along with the increase on the communication signal energy. With the use of our measurement tools (a power analyzer and an integrating sphere), we managed to check any possible efficacy changes in the overall system. We designed our circuits based on the amount of power being used for communications through the design of the output current ripple value. Our test results showed that our technique can provide different levels of transmitted power for communications with minimal efficacy degradation (only 3%) in a worst case scenario, when compared to a regular buck converter without VLC functionality. Therefore, based on our results, we conclude that the technique here presented can be a good candidate to provide additional VLC functionality into well-known LED drivers without compromising quality and efficacy standards of the light industry.

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