
High Performance Series/Parallel Boost/Buck DC/DC Converter as a Visible Light Communication HB-LED Driver Based on Split Power

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Article

High Performance Series/Parallel Boost/Buck DC/DC Converter as a Visible Light Communication HB-LED Driver Based on Split Power

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Abstract: This work proposes a High-Brightness LED (HB-LED) driver for Visible Light Communication (VLC) based on two converters, a high frequency Buck DC/DC converter and a low frequency Boost DC/DC converter, connected in series with respect to the LED load and connected in parallel at the input. This topology is called a Series/Parallel Boost/Buck DC/DC Converter. A VLC system needs to do two different tasks: biasing the HB-LED and generating the communication signal. These typically have different power requirements, the bias power is 3/4, while the communication power is 1/4 of the total power. The requirements of each are also different: the communication signal requires a high frequency, fast output response, while the biasing control requires a converter with a slow output voltage response. The proposed architecture takes advantage of the differences between the two tasks and achieves high efficiency and high communication performance by means of splitting the power between the two DC/DC converters. A high frequency Buck DC/DC converter generates the communication signal, while the low frequency Boost DC/DC converter is responsible for biasing the LEDs. This technique allows most of the DC biasing power to be processed by the low frequency converter (achieving high efficiency), keeping the high frequency converter delivering the communication power (achieving high communication performance). To provide experimental results, the proposed VLC HB-LED driver was built and validated by reproducing a 64-QAM with a bit rate up to 1.5 Mbps, reaching 91.5% overall efficiency.

Keywords: Visible Light Communication (VLC); High-Brightness LED; Series/Parallel Boost/Buck DC/DC converter and split power

1. Introduction

Current wireless technologies are mostly based on the Radio Frequency (RF) spectrum, with ubiquitous technologies such as Wi-Fi, Bluetooth, and 5G. The current growth of new wirelessly connected devices is leading to stricter regulation and notable congestion of the RF spectrum [1]. To mitigate the congestion, or find alternatives to the RF spectrum, researchers and industry have been examining new technologies and solutions to substitute or supplement the RF spectrum.

One of the most promising solutions is Visible Light Communication (VLC) [2]. By taking advantage of widespread High-Brightness LED (HB-LED) based Solid-State Lighting (SSL), VLC uses HB-LED's inherent capability for fast changes in its emitted light, which makes it suitable as a wireless transmitter. VLC is proposed as an alternative to the RF spectrum where such lighting is already present or where RF is not a viable option due to strict regulations (such as hospitals or aircraft, etc.) [3–5].

Figure 1 depicts the behaviour of a string of HB-LEDs and its control in a VLC system. A VLC system needs to accomplish two tasks: the bias task and the communication task.

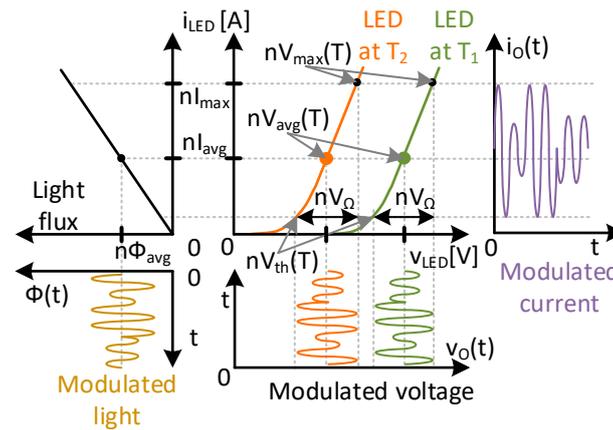


Figure 1. Temperature shift in HB-LED curves (string of n HB_LEDs).

The bias task generates a constant voltage across the HB-LED string, controlling the average current through the HB-LEDs, and then the light emitted by the HB-LEDs. As Figure 1 shows, for a specific emitted light flux $n\phi_{avg}$ and average current nI_{avg} , the voltage $nV_{avg}(T)$ depends on the temperature T of the HB-LEDs due to the temperature shift. $T_2 > T_1$ when the HB-LEDs go from a lower temperature T_1 to a higher temperature T_2 , the necessary $nV_{avg}(T)$ decreases for the same current nI_{avg} . This undesired effect leads to the need for a control system for the LEDs. Without proper control to counteract this effect, communication performance is affected [6]. In order to counteract the temperature shift, the driver has to control the average current in order to always be working in the middle of the LED's linear region, which also maximizes the range for the communication signal, nV_{Ω} . The working range nV_{Ω} is defined as the linear part of the voltage-current relation, between the threshold voltage $nV_{th}(T)$ and the maximum voltage $nV_{max}(T)$.

The communication task is responsible for generating the communication signal within the working range nV_{Ω} . As Figure 1 shows, the slope of the curve and the maximum HB-LED current are kept unmodified regardless of the temperature, meaning that the working range is also unchanged. Providing that the communication signal is lower than nV_{Ω} and the bias task works properly delivering nI_{avg} , distortion on the emitted light is minimized [6].

The most common VLC HB-LED transmitter topology is based on using a regular HB-LED driver for the bias task connected to an amplifier (i.e. class A or B) for the communication task [7–9], using a bias-T circuit. Even though they achieve high bit rates, the main drawback of this approach is power efficiency. For example, the maximum efficiency of class A and B amplifiers is 50% and 78% respectively (when a constant amplitude signal is delivered), but when a more complex amplitude modulated signal is used, the efficiency drops significantly [10].

Another way to implement a VLC transmitter is to modify the traditional HB-LED driving stage by integrating the communication task, producing a VLC HB-LED driver. High frequency and fast response DC-DC converters have been proposed as a very promising alternative to linear amplifiers, achieving higher efficiencies (around 90%) and providing high bit rate communication [11–13]. The main drawback of this approach is that the converter is processing both bias and communication power at high frequency, increasing total power losses. In a VLC system roughly 3/4 of the power comes from bias and 1/4 from communication. The bias task controls the current to adapt it according to the slow temperature effects over the HB-LEDs. This means that there is no need for the converter to have a fast response and therefore no need to have a high switching frequency. Thus, one way to further improve efficiency is by splitting the power in the converters depending on which part of the VLC HB-LED driver they are [14], [15]. The idea involves making two specialized converters working together: a low frequency converter and a high frequency, fast output voltage response converter. The low frequency converter is responsible for delivering the bias power (most of the power in the system) and then maintaining the illumination at the desired level. In the other part, the high

frequency, fast response converter is responsible for delivering a limited part of the power (mostly only the communication power). In [14] two Buck DC/DC converters were used with their outputs connected in series for the HB-LED load: one low frequency converter for the bias task and a high frequency converter for the communication signal. Although the solution achieved high efficiency and communication capability, the main drawbacks of this approach are the need for two different input voltages, one for each converter, and one higher than the threshold voltage of the HB-LED load. In [15] the need for two different input voltages was addressed by using two Buck DC/DC converters in a Two Input Buck (TIBuck) configuration, although the need for an input voltage higher than the HB-LED maximum voltage (due to the use of only Buck DC/DC converters) would not be suitable for battery powered VLC applications. Moreover, the TIBuck DC/DC converter suffers a reduction in its resolution for tracking the voltage across HB-LED load versus temperature changes.

This paper presents a VLC HB-LED driver based on a low frequency Boost DC/DC converter and a high frequency Buck DC/DC converter, called a Series/Parallel Boost/Buck DC/DC converter. Both DC/DC converters share the same input voltage and are connected in series for the HB-LED load. The proposed topology achieves high efficiency and high communication performance by splitting the power between them. The low frequency Boost DC/DC converter is responsible for controlling the bias of the HB-LEDs, while the high frequency Buck DC/DC converter generates the communication signal. This technique allows most of the bias power to be processed by the low frequency converter (achieving high efficiency) and keeping the high frequency converter delivering the communication power (achieving high communication performance). This configuration follows the same principle as other split power proposals for VLC but without the need for two input voltages [14], and without the inability to take advantage of the Buck DC/DC converter useful duty cycle range, which always provides the maximum resolution to the converter [15].

The paper is organized as follows. Section 2 reviews the analysis of the Series/Parallel Boost/Buck DC/DC converter, highlighting the main advantages over other topologies that use split power [14,15]. Section 3 describes the power flow between the two converters and an efficiency analysis. The experimental results are given in Section 4, and finally, the conclusions are described in Section 5.

2. Analysis of the Series/Parallel Boost/Buck DC/DC Converter as a VLC HB-LED Driver

2.1. Principle of Operation

The block diagram of the proposed topology is shown in Figure 2a and an example for the waveforms are shown in Figure 2b. Both converters are connected to the same input voltage V_1 and their outputs are connected in series with respect to the HB-LED string load. The HB-LED string load is comprised of n HB-LEDs. The Boost DC/DC converter is responsible for generating a DC voltage V_{bias} , while the Buck DC/DC converter generates the communication signal $v_{sig}(t)$, as shown in the block diagram in Figure 2(a).

In order to make the n HB-LED string work within the linear region (Figure 1), the HB-LED voltage $v_o(t)$ has to be between the threshold voltage $nV_{th}(T)$ and the maximum voltage $nV_{max}(T)$, where $V_{th}(T)$ and $V_{max}(T)$ are the threshold and maximum voltage of a single HB-LED, and $nV_{avg}(T)$ is the voltage in the middle of the linear region of the HB-LED string. For the sake of simplicity, the HB-LED string working range is defined according to the middle point of the linear region $nV_{avg}(T)$. It is important to highlight that dependency with temperature is noted as (T) .

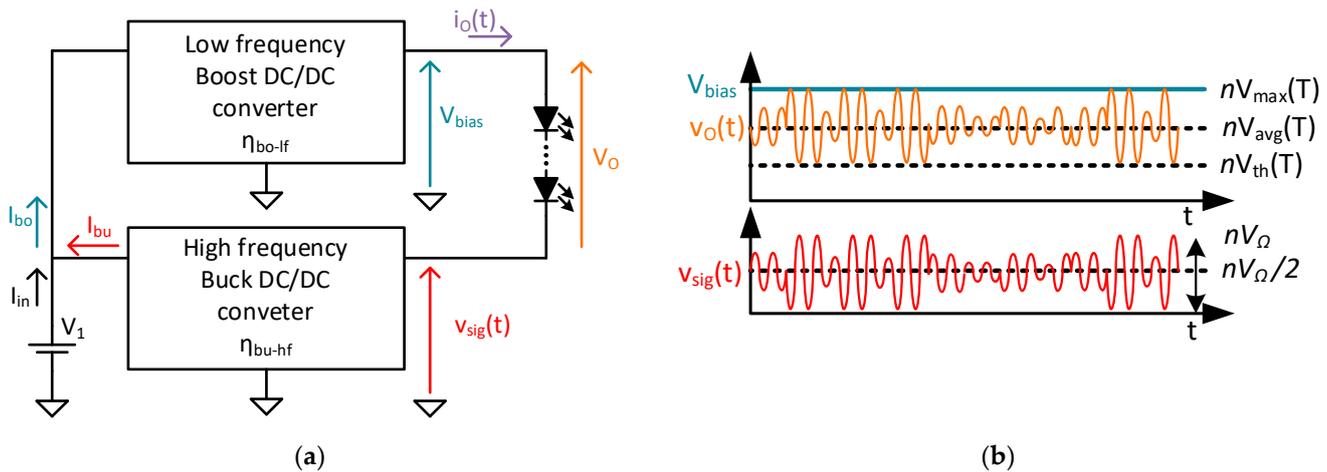


Figure 2. (a) Block diagram of the proposed Series/Parallel Boost/Buck DC/DC converter acting as a VLC HB-LED driver. (b) Main waveforms of the proposed Series/Parallel Boost/Buck DC/DC converter acting as a VLC HB-LED driver.

The useful voltage range of the HB-LED load for communication (i.e., the peak-to-peak maximum amplitude allowed for the communication signal due to its linearity) is nV_{Ω} , defined as follows

$$nV_{\Omega} = nV_{max}(T) - nV_{th}(T), \quad (1)$$

where nV_{Ω} has no dependency with temperature. For the sake of simplicity, the limits of the useful voltage range of the HB-LED can be obtained from the middle point of the linear region, $nV_{avg}(T)$.

$$nV_{max} = nV_{avg}(T) + \frac{nV_{\Omega}(T)}{2}, \quad (2)$$

$$nV_{th} = nV_{avg}(T) - \frac{nV_{\Omega}(T)}{2}. \quad (3)$$

Considering (2) and (3), we can conclude that controlling $nV_{avg}(T)$ when temperature varies, always allows the HB-LED string to work at the middle point of the linear region that defines the useful voltage range of the HB-LED load for communication, nV_{Ω} . From Figure 2(a) the expression of the voltage across the HB-LED string is

$$v_o(t) = V_{bias} - v_{sig}(t). \quad (4)$$

V_{bias} (voltage of the Boost DC/DC converter) only has a DC component (neglecting its ripple), while $v_{sig}(t)$ (voltage of the Buck DC/DC converter) can be represented by its average value (V_{sig}) plus the amplitude of the signal ($\Delta v_{sig}(t)$)

$$v_{sig}(t) = V_{sig} - \Delta v_{sig}(t). \quad (5)$$

2.2. Resolution of the Buck DC/DC for Tracking the Output Voltage

The target is to keep the average voltage of the string of HB-LEDs $V_o = \text{avg}(v_o(t))$ equal to $nV_{avg}(T)$ at any temperature. Moreover, it is important to note that V_o only depends on the average value of the output voltage of both converters, which is

$$V_o = nV_{avg}(T) = V_{bias} - V_{sig}. \quad (6)$$

Equation (6) shows that the biasing point can either be controlled by the average value of the Boost or the Buck DC/DC converters. If control of the temperature drift is implemented via the action of the Boost DC/DC converter, we can conclude that it is only the Boost DC/DC converter output voltage, V_{bias} , which compensates for temperature changes, making the average value of the Buck

DC/DC converter independent of temperature. This is very important because the Buck DC/DC converter always has the maximum resolution in its duty cycle (i.e., $d_{bu}(t)$) to track $v_o(t)$.

If $d_{bu}(t)$ is the duty cycle of the Buck DC/DC converter then $v_{sig}(t)$ can be expressed as a function of $d_{bu}(t)$ and V_1

$$v_{sig}(t) = V_1 d_{bu}(t). \quad (7)$$

Substituting (7) in (4), the value of $v_o(t)$ becomes

$$v_o(t) = V_{bias} - V_1 d_{bu}(t). \quad (8)$$

with $[0,1]$ being the range of $d_{bu}(t)$; the highest output voltage occurs for $d_{bu}(t)=0$ and the lowest output voltage occurs for $d_{bu}(t)=1$. Considering previous definitions, the range of output voltage is $[V_{bias}-V_1, V_{bias}]$. At this point, two design rules can be defined if we want the entire useful voltage range of the HB-LED load (i.e., nV_Ω) to be used for communication

$$nV_{max}(T) = V_{bias}, \quad (9)$$

$$nV_{th}(T) = V_{bias} - V_1. \quad (10)$$

Figure 3(a) shows that the full range of $d_{bu}(t)$ defines useful voltages in the linear region of the HB-LED load, maximizing the resolution of the Buck DC/DC converter for tracking the output voltage for communication tasks.

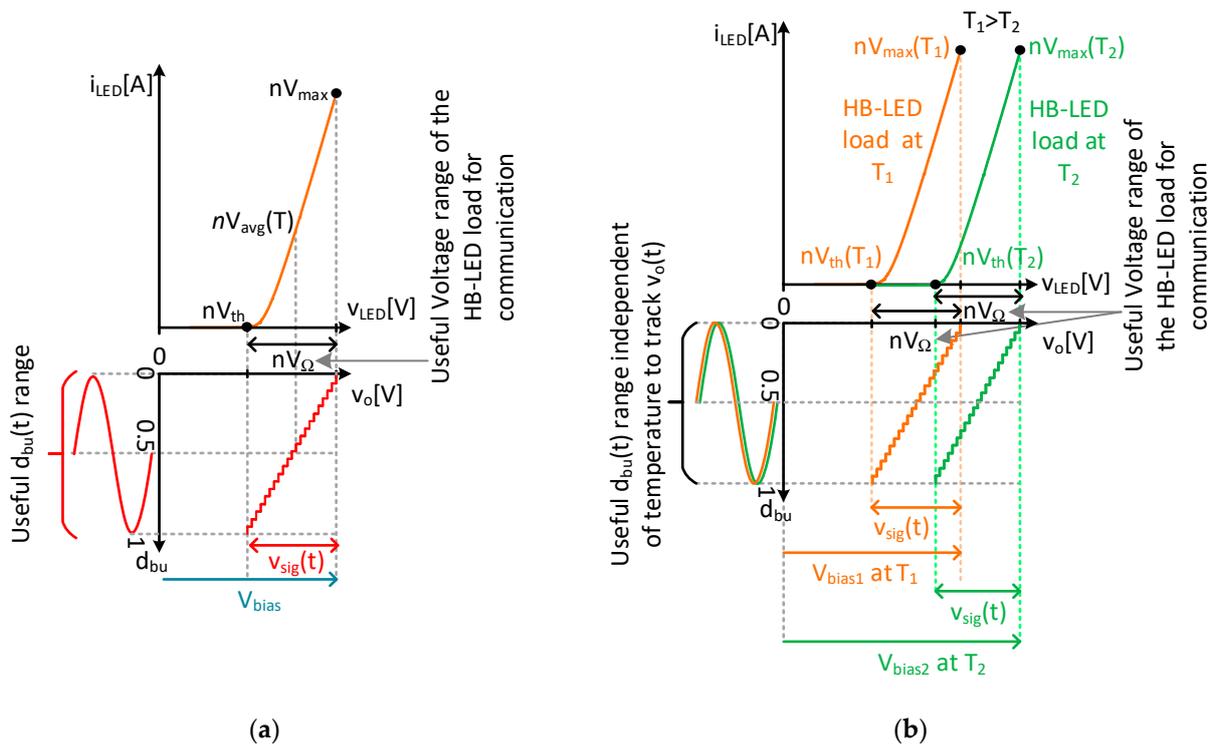


Figure 3. Representation of the output voltage range of the Buck DC/DC converter versus the useful voltage range of the HB-LED load and their impact on resolution for tracking the output voltage. (a) Without temperature change. (b) With an increase of temperature.

Considering (1), (9) and (10) the following expression is obtained

$$V_1 = nV_\Omega. \quad (11)$$

Therefore, V_1 determines the value of the voltage that maximizes the output voltage range of the Buck DC/DC to track it, which only depends on nV_Ω . As previously mentioned, nV_Ω does not depend on temperature. This is extremely important because maximization of the output voltage range of the

Buck DC/DC for tracking the communication signal $v_{sig}(t)$ is independent of temperature. Figure 3 shows the representation of the output voltage range of the Buck DC/DC converter (by means of the $d_{bu}(t)$ useful range) versus the useful voltage range of the HB-LED load and their impact on the resolution when temperature changes from T_2 to T_1 , with $T_1 > T_2$. If (9) and (10) are fulfilled by the Boost DC/DC converter, two conclusions can be drawn. First, the Boost DC/DC converter is responsible for temperature changes. Second, the Boost DC/DC converter provides the maximum resolution to the Buck DC/DC converter for tracking its output voltage (i.e., $v_{sig}(t)$) and therefore, the output voltage across the HB-LED load (i.e., $v_o(t)$) versus temperature changes. Thus, the Series/Parallel Boost/Buck DC/DC Converter improves on the performance reported in [14] and [15] because it uses only a single input voltage source (unlike [14], which uses two). Moreover, the proposed converter is better than [15] in terms of resolution versus temperature changes. However, both converters process all power and the main switches are rated to the input voltage. This is the price to pay to use only one voltage source and the improvement in terms of resolution temperature changes.

2.3. Controlling the Average Value of the Voltage Across the HB-LED Load

As previously mentioned, the Boost converter is responsible for controlling the average value of $v_o(t)$. With D_{bias} being the duty cycle of the Boost DC/DC converter, V_{bias} can be expressed as

$$V_{bias} = \frac{V_1}{1 - V_{bias}}. \quad (12)$$

By substituting (12) in (6), and assuming that the duty cycle of the buck converter is 0.5 to maximize useful $d_{bu}(t)$ range, the average value of output voltage can be rewritten as

$$V_o = nV_{avg}(T) = \frac{V_1}{1 - V_{bias}} - \frac{V_1}{2}. \quad (13)$$

3. Power Flow and Efficiency Analysis

An important consideration to study is the power flow between the two converters to achieve the power balance and efficiency of the Series/Parallel Boost/Buck DC/DC Converter. Note that the Boost DC/DC converter injects power to the HB_LED load, but the Buck DC/DC converter drains power from the HB_LED load.

3.1. Power Flow Analysis

As Figure 2(a) shows, I_{bo} is demanded by the Boost DC/DC converter from the voltage source V_1 . In contrast, the Buck DC/DC converter injects I_{bu} to V_1 . Therefore, I_{in} can be written as

$$I_{in} = I_{bo} - I_{bu}. \quad (14)$$

The Boost converter injects an average power to the HB-LED load, generating the voltage V_{bias} and the I_o current. In this case the power of the Boost DC/DC converter is

$$P_{bo-out} = I_o \cdot V_{bias}. \quad (15)$$

One part of the power is processed by the HB-LED load, P_{LED} . By using (4), P_{LED} can be expressed as

$$P_{LED} = I_o \cdot V_o = I_o \cdot (V_{bias} - V_{sig}), \quad (16)$$

where V_o is the average value of $v_o(t)$ and V_{sig} is the average value of $v_{sig}(t)$. The other part of the power is processed by the Buck DC/DC and drained from HB-LED load by injecting I_{bu} to V_1 . Thus, the Buck DC/DC converter drains P_{bu-in} , which can be written as

$$P_{bu-in} = I_o \cdot V_{sig}. \quad (17)$$

3.2. Simplification of Series/Parallel Boost/Buck DC/DC

This converter's way processing power allows it to be simplified. A Buck DC/DC converter that drains rather than supplies current can be analysed as a Boost DC/DC converter. Due to this, one possible Series/Parallel Boost/Buck DC/DC Converter implementation is that shown in Figure 5.

If the switching of both converters is asynchronous, it is possible to connect both MOSFET to ground, making implementation easier because an isolator is not needed to control the floating MOSFET in the Buck DC/DC converter.

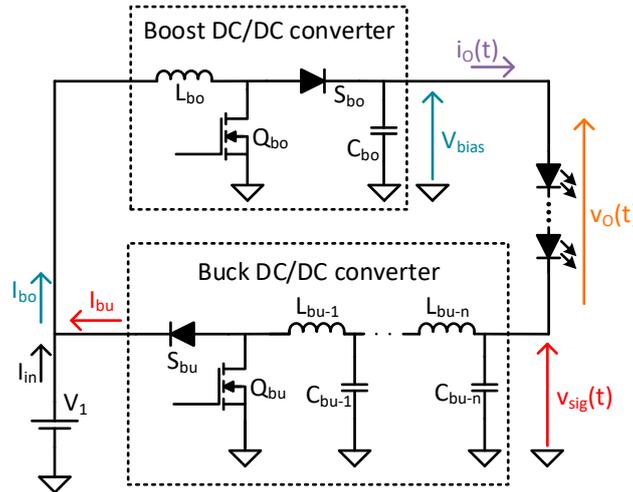


Figure 4. Representation of the simplification of the Series/Parallel Boost/Buck DC/DC Converter, where the switching of the two converters is asynchronous. This allows the control signals of both MOSFETs to be linked to ground.

3.3. Efficiency Analysis

Efficiency analysis is done by examining the efficiency of each converter in the Series/Parallel Boost/Buck DC/DC Converter. Figure 2(a) defines the efficiency of the Boost DC/DC converter as η_{bo} and the efficiency of the Buck DC/DC converter as η_{bu} . Moreover Figure 2(a) defines the input power as

$$P_{in} = I_{in} \cdot V_1 = V_1 \cdot (I_{bo} - I_{bu}). \quad (18)$$

The output power is defined in (16). Thus, the efficiency of the Series/Parallel Boost/Buck DC/DC Converter (i.e., η_t) can be easily defined by the output power divided by the input power

$$\eta_t = \frac{P_{LED}}{P_{in}} = \frac{I_o \cdot (V_{bias} - V_{sig})}{V_1 \cdot (I_{bo} - I_{bu})} = \frac{I_o \cdot V_{bias} - I_o \cdot V_{sig}}{V_1 \cdot I_{bo} - V_1 \cdot I_{bu}}. \quad (19)$$

The input power of the Boost DC/DC converter can be expressed as a function of the input voltage and the input current

$$P_{bo-in} = I_{bo} \cdot V_1. \quad (20)$$

The output power of the Buck DC/DC converter can be expressed as a function of the input voltage and its output current.

$$P_{bu-out} = I_{bu} \cdot V_1. \quad (21)$$

By substituting (15), (17), (20) and (21) in (19), the efficiency η_t can be rewritten as

$$\eta_t = \frac{P_{bo-out} - P_{bu-in}}{P_{bo-in} - P_{bu-out}}. \quad (22)$$

Input power of the Boost DC/DC converter (i.e., P_{bo-in}) can be rewritten as a function of its output power and its efficiency (i.e., η_{bo-lf})

$$P_{bo-in} = \frac{P_{bo-out}}{\eta_{bo-lf}} \quad (23)$$

Following the same procedure the output power of the Buck DC/DC converter can be expressed as a function of its input power (i.e., P_{bu-in}) and its efficiency (i.e., η_{bu-hf})

$$P_{bu-out} = P_{bu-in} \cdot \eta_{bu-hf} \quad (24)$$

Taking into account (23) and (24), (22) can be rewritten as

$$\eta_t = \eta_{bo-lf} \cdot \frac{1 - \frac{P_{bu-in}}{P_{bo-out}}}{1 - \eta_{bo-lf} \cdot \eta_{bu-hf} \cdot \frac{P_{bu-in}}{P_{bo-out}}} \quad (25)$$

In order to simplify the analysis of (25), a new parameter will be defined. This parameter is α , defined as

$$\alpha = \frac{P_{bu-in}}{P_{bo-out}} = \frac{V_{sig} \cdot I_o}{V_{bias} \cdot I_o} = \frac{V_{sig}}{V_{bias}}, \quad (26)$$

where α depends on the amplitude of the communication signal (i.e., V_{sig}) and the output voltage of the Boost DC/DC converter that defines the bias of the HB-LED load (i.e., V_{bias})

Now, putting (26) into (25), the overall efficiency of the Series/Parallel Boost/Buck DC/DC Converter is

$$\eta_t = \eta_{bo-lf} \cdot \frac{1 - \alpha}{1 - \eta_{bo-lf} \cdot \eta_{bu-hf} \cdot \alpha} \quad (27)$$

(27) shows the dependency of η_t on the efficiency of each converter in the Series/Parallel Boost/Buck DC/DC Converter architecture. For example, an edge case: When there is no signal, V_{sig} equals zero and therefore the overall efficiency is the efficiency of the Boost DC/DC converter.

It is important to note that the Series/Parallel Boost/Buck DC/DC Converter supplies an HB-LED load for communication. As explained in section 2.2, the idea is to take advantage of all useful voltages in the linear region of the HB-LED load. This means that V_{sig} value must be $0.5V_{\Omega}$. By using (7), (9), (11) and (26), the α parameter can be expressed as a function of the HB-LED characteristics

$$\alpha = \frac{V_{\Omega}}{2V_{max}} \quad (26)$$

Taking typical values of commercial HB-LEDs [16], $V_{\Omega}=1$ and $V_{max}=4$. These values define an α parameter of 0.125. Taking advantage of this calculation, it is very interesting to evaluate how each converter's efficiency (i.e., Buck DC/DC converter and Boost DC/DC converter) influences the overall efficiency of the Series/Parallel Boost/Buck DC/DC converter. Figure 5, makes this analysis, evaluating η_t in two cases. First, keeping the efficiency of the Boost converter constant at 0.95 (i.e., $\eta_{bo-lf}=0.95$) and varying the efficiency of the Buck DC/DC converter between 0.8 and 1 (solid line in Figure 5). Second, keeping the efficiency of the Buck DC/DC converter constant at 0.95 and varying the efficiency of the Boost DC/DC converter between 0.8 and 1 (dotted line in Figure 5). As Figure 5 shows, the range of variation of η_t is lower when the efficiency of the Buck DC/DC converter varies and the efficiency of the Boost DC/DC converter is kept constant. It is clear that the efficiency of the proposed Series/Parallel Boost/Buck DC/DC converter depends more on the efficiency of the Boost DC/DC converter (i.e., η_{bo-lf}). This is because the Boost DC/DC converter processes higher power levels, making its efficiency much more important. This is a notable benefit because the Boost DC/DC converter operates at a lower switching frequency and it is easier to achieve higher efficiency here than in the Buck DC/DC converter, which operates at a higher frequency.

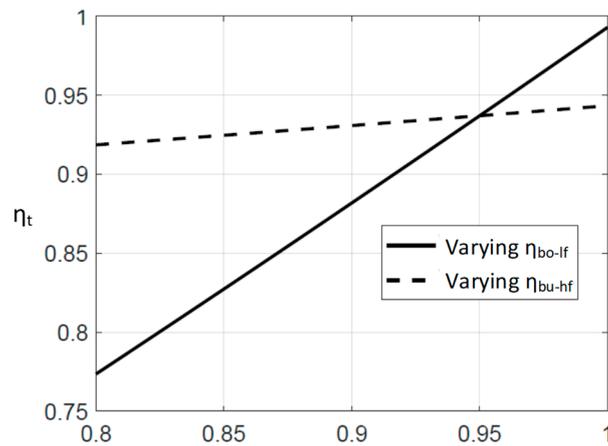


Figure 5. Effect of varying the efficiency of each individual DC/DC converter in η_t .

4. Experimental Results

To provide experimental results, the proposed VLC HB-LED driver was built. The proposed converter is based on a low frequency Boost DC/DC converter and a high frequency Buck DC/DC converter sharing the same input voltage and connected in series in relation to the HB-LED load (Figure 6).

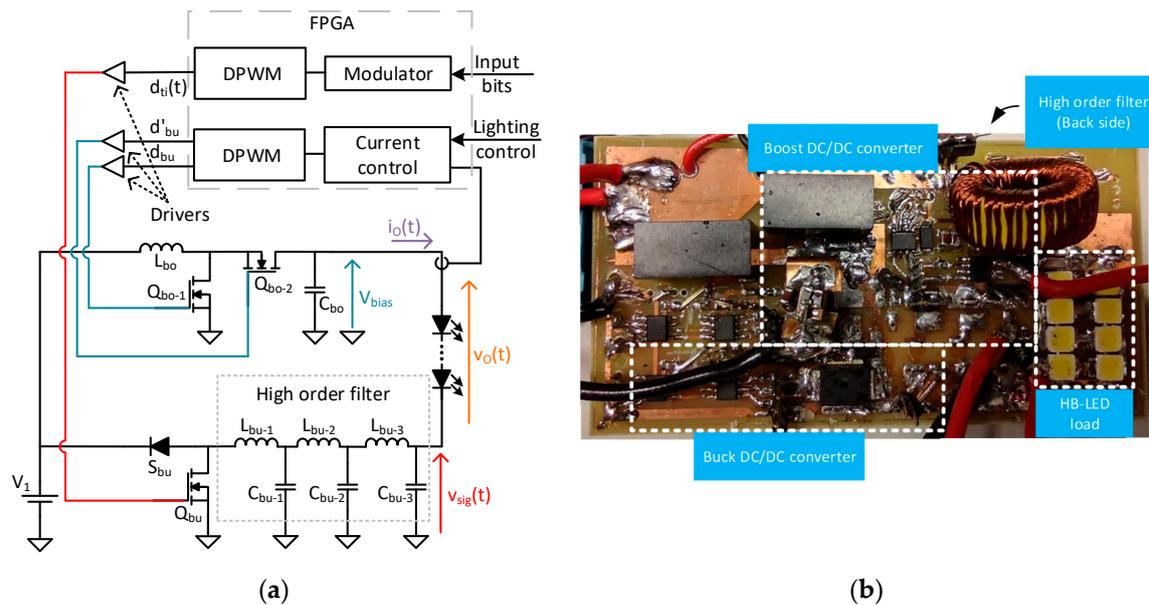


Figure 6. (a) Schematic and control for the Series/Parallel Boost/Buck DC/DC Converter. (b) Photograph of the prototype.

The HB-LED load is a string of 8 XLamp MX-3 HB-LEDs, with an output power around 8 W. The current and voltage necessary for the HB-load can be obtained from the datasheet of the XLamp MX-3 LED used [16]. A string of 8 XLamp MX-3 HB-LEDs has a maximum voltage of 32 V (4 V for a single LED) and a current of 0.25 A in the middle of the linear region. The working range is $nV_{\Omega} = 8$ V (1 V for a single LED). The input voltage used was $V_1 = n nV_{\Omega} = 8$ V. As previously explained, this value of input voltage maximizes the resolution for tracking the output voltage for communication tasks.

The average current through the HB-LEDs was kept at 0.25 A (in the middle of the linear region) and the overall efficiency achieved was 91.5%. Efficiency was measured by comparing the DC input power to the RMS output power (taking into account biasing and communication power) on the HB-LED load.

A Field Programmable Gate Array (FPGA) (Nexys A7) was used both to control the Buck DC/DC converter and the Boost DC/DC converter using a Digital Pulse Width Modulator (DPWM). The FPGA controls the Boost DC/DC converter in order to control the average value of the current through the HB-LED load (i.e., controlling V_{bias} value using a control loop). The FPGA also controls the Buck DC/DC converter operating at high frequency in order to send information (i.e., reproducing the input bits at its output).

4.1. Efficiency Analysis

The low frequency boost DC/DC converter is designed to work as a traditional HB-LED driver with a switching frequency of 100 kHz, working in a closed loop. It is responsible for increasing the dc output voltage up to the maximum voltage allowed across the LED. It also implements the bias current loop control of the LED string. Due to the low dynamic behaviour of the temperature shift in the LEDs, there is no need for the converter to have a fast output dynamic response. There needs to be a trade-off with regard to the switching frequency: increasing the switching frequency allows the reactive elements of the converter to be reduced (especially interesting in small applications), but it increases power losses and the effect of switching noise on communication (if this noise is within the communication band). The noise is produced by the output voltage ripple on the output boost capacitor C_{bo} . Using (10), the boost output ripple is limited to a maximum of 2% of the output boost voltage. The final values of the reactive elements of this converter are shown in Table 1.

$$C_{bo} = \frac{\Delta Q}{\Delta 2V_{\text{bias}}} = \frac{I_o D_{bo} T_{bo}}{\Delta 2V_{\text{bias}}} \quad (27)$$

In this equation, ΔQ is the total charge of the capacitor and D_{bo} and T_{bo} are the duty cycle and the time period of the boost DC/DC converter. A current control was implemented so that the boost DC/DC converter could control the I_o current. The current was measured by means of an isolated current shunt, connected in series to the LED string. The current control included a low pass filter which eliminates the communication components in the HB-LED current and a PI controller. No new considerations are needed with regard to the PI controller in this implementation, and a standard current controller for HB-LED can be used. Both the PWM modulation and the current control were implemented in a FPGA Nexys A7, as noted previously. The remaining component selection was as follows: the dual CSD88539 MOSFET was used for Q_{1bo} and Q_{2bo} ; an ISL6700 half bridge driver was used for the driving stage. The complete list of components are summarized in Table 2.

Table 1. Circuit components of the VLC HB-LED driver.

Q_{1bo} and Q_{2bo}	Boost driver	L_{bo}	C_{bo}	Q_{1bu} and Q_{2bu}	D_{1bu} and D_{2bu}	Buck drivers	HB-LEDs
CSD88539	ISL6700	71 μ H	9 μ F	PD84010-E	UPS115UE3	EL7155CSZ	XLamp MX-3

Table 2. Circuit components of the VLC HB-LED driver.

L_{bu1}	C_{bu1}	L_{bu2}	C_{bu2}	L_{bu3}	C_{bu3}
1.7 μ H	9.9nF	2.2 μ H	9.9nF	1.9 μ H	5.72nF

4.2. Efficiency Analysis

The converter reproduces a 64-QAM modulation, with a carrier frequency f_{sig} of 1 MHz. The symbol period is equal to four signal periods, achieving a maximum bit rate of 1.5 Mbps. In order to avoid any switching noise coming from the Boost DC/DC converter, the signal frequency was selected a decade higher than the Boost DC/DC converter switching frequency.

4.3. High Frequency and Fast Response Buck DC/DC Converter Design

The high frequency Buck DC/DC converter is responsible for generating the communication signal as mentioned previously. This converter works in an open loop and includes a high order output filter to achieve high bandwidth and a fast response. To properly reproduce a communication signal by means of a Buck DC/DC converter, the inequation

$$f_{sig} < f_{cut} < f_{bu} \quad (28)$$

relating to the carrier frequency f_{sig} , the cut-off frequency of the filter f_{cut} , and the Buck DC/DC converter switching frequency f_{bu} , must be applied. The exact relation between the frequencies and the order and attenuation of the filter was analysed in [17]. Based on this analysis, the output filter used a 6th low-pass filter with a cutoff frequency f_{cut} of 2.5 MHz. The reactive components of the filter are shown in Table 2. The switching frequency f_{bu} used was 10 MHz

Due to the high switching frequency of the Buck DC/DC converter, two RF high frequency PD84010-E MOSFETs were used for Q_{1bu} and Q_{2bu} in parallel with two high speed Schottky UPS115UE3 diodes. For the driving stage two high speed EL7155CSZ drivers were used.

4.4. Experimental Results for Communication

Figure 7 shows some of the most representative waveforms of the DC/DC converters. The signals v_{gs-bot} and v_{gs-bu} are the gate-to-source signals of the Boost and Buck DC/DC converters respectively. The difference in frequency between these two signals is notable, v_{gs-bot} is a 100 kHz PWM signal, while v_{gs-bu} is a 10 MHz PWM signal. The signals V_{bias} and $v_{sig}(t)$ are the output voltage of the Boost and Buck DC/DC converters respectively. As shown, the output voltage of the Boost DC/DC converter is kept constant (and with low ripple) and the current loop control varies the duty cycle of the signal v_{gs-bot} in order to keep the average output current constant through the HB-LEDs, at the design level of 0.25 A. Without considering any temperature shift over the HB-LED, the input voltage of the Boost DC/DC converter should be 32 V, which is the maximum HB-LED voltage of the 8 LED string used. After a few minutes, when the LED temperature is stabilized, the current control loop of the boost dc-dc converter reduces V_{bias} by 21% to 25 V.

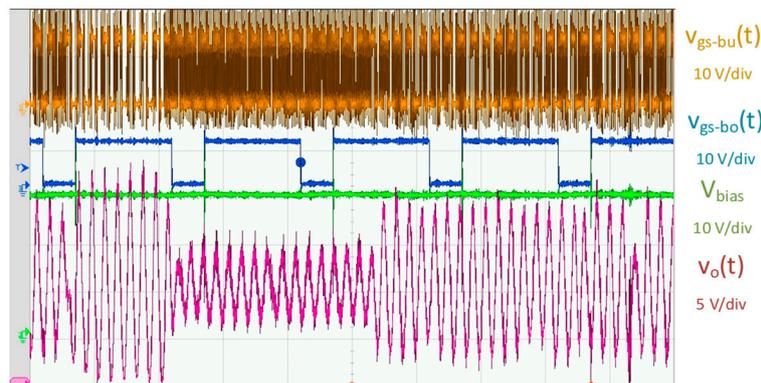


Figure 7. Gate signal of the Buck and Boost DC/DC converters v_{gsbuck} (orange) and $v_{gsboost}$ (blue), output voltage of the Boost DC/DC converter (green) and output voltage of the signal (magenta).

The Buck DC/DC converter works in an open loop reproducing the communication signal. The variation of the duty cycle in v_{gs-bu} can be seen, along with the effect over the output voltage $v_o(t)$. The peak to peak voltage of the Buck DC/DC converter is 7.5 V, closer to the maximum working range of the 8 HB-LED string, which is 8 V. The output Buck DC/DC converter filter is able to filter the high switching frequency of the converter and allows the communication signal to pass through. The correct design of this filter must take into account the correct reproduction of the sine carrier frequency of the modulation and the correct change in phase and amplitude between symbols.

In order to focus the analysis on the converter's communication task, a longer period of time is shown in Figure 8. Thus to test the communication performance, the communication signal generated by the Buck DC/DC converter $v_{sig}(t)$ and the light emitted by the HB-LEDs were measured during

transmission of 12 different symbols. To properly measure the light, a Thorlabs PDA10A-EC [18] high bandwidth optical receiver was used, placed in front of the HB-LED string, giving an output voltage $v_{rx}(t)$ proportional to the light. Comparing the two signals $v_o(t)$ and $v_{rx}(t)$ shows that the converter was able to properly reproduce the communication signal without distortion. Distortion could occur due to temperature shifts in the HB-LEDs by making the HB_LED work outside its linear region. Comparing the $v_o(t)$ and its received light signal $v_{rx}(t)$ indicates that this undesired effect was avoided due to proper current loop control.

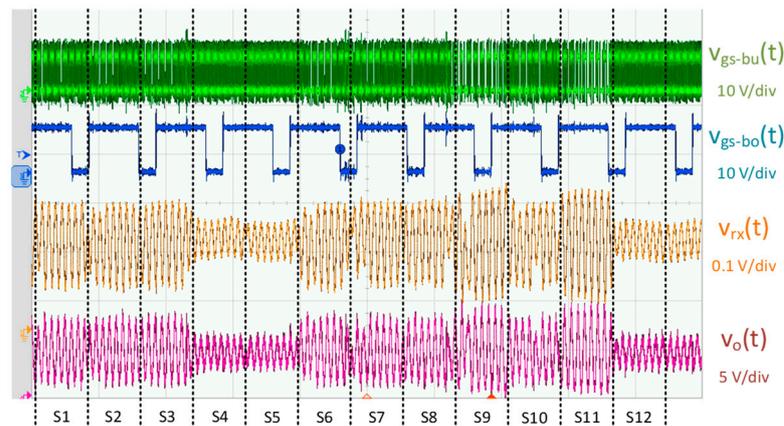


Figure 8. Gate signals of the Buck and Boost DC/DC converters v_{gs-bu} and v_{gs-bo} , output voltage of the buck converter $v_o(t)$ and the voltage of the optical receiver v_{rx} during a transmission.

In terms of efficiency, the experimental results were gathered using 34461A Digital Multimeters and indicated an efficiency of 91.5% reproducing a 64-QAM digital modulation, with a bit rate of 1.5 Mbps

5. Conclusions

The proposed HB-LED driver for VLC can achieve high efficiency and high communication performance by means of splitting the power between two different converters. The design is based on two converters connected to the same input voltage, with their outputs connected in series in relation to the HB-LED load. A low frequency Boost DC/DC converter working in a closed loop is responsible for delivering most of the power and controlling the bias of the HB-LEDs. In contrast, an open loop, fast response Buck DC/DC converter is responsible for generating the communication signal. Advantages of this approach include high efficiency, high communication capability, input voltage flexibility, and improved duty resolution. The overall power efficiency is improved by means of splitting the power between two converters where the communication signal is delivered by the high frequency converter and the bias power is processed by the low frequency boost. Another advantage is the flexibility in terms of input voltage. In contrast to other topologies based only on buck converters, the input voltage can be lower than the threshold voltage of the LED string. An additional effect of lower input voltages is increased resolution of the duty cycle for tracking the output voltage in the high frequency Buck DC/DC converter. The experimental results demonstrated an efficiency of 91.5% reproducing a 64-QAM digital modulation, with a bit rate of 1.5 Mbps.

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