Converter with Wide Input Voltage Range Applied to Solid State Lighting Based on HV9930

R. A. Lodo, E. A. A. Coelho, F. V. R. Da Silva, A. W. F. V. Silveira, L. C. G. Freitas, J. B. Vieira Jr.

Universidade Federal de Uberlândia (UFU)
Faculdade de Engenharia Elétrica (FEELT)
Núcleo de Pesquisa em Eletrônica de Potência (NUPEP)
Uberlândia-MG, Brasil 38400-902
e-mail: rafaellodo@hotmail.com, batista@ufu.br

Abstract. Currently research has pointed to LEDs as the technology more efficient and durable to be used in lighting, however, it requires a static converter in order to control the electrical current flowing through the LED lamp. In this context, this paper describes the implementation of a DC/DC converter with wide input voltage range called Boost-Buck Quadratic, with simple control strategy, driving a LED lamp. The converter can be powered from 12 V_{DC} (battery voltage) to the universal AC input voltage (90 to 240 V_{AC}). Theoretical analysis, design guidelines and experimental results from a prototype of the proposed Boost-Buck Quadratic converter driving a 12 W LED lamp are shown in this paper.

Key words

Wide input voltage range, DC/DC converter, LED lamp.

1. Introduction

Nowadays, there is a great concern about the technologies used in lighting, among them one can outline: efficiency, durability, robustness, free from heavy metals in manufacturing, and others. On the contrary to other lamps, LEDs (Light Emitting Diodes) provide all these characteristics and are the most viable alternative existing on the market. The following topics describe some advantages of LEDs [1]:

- Extremely long lifetime, approximately 50,000 hours.
- Extremely robust, because there are no filaments or glass components, then it becomes insensitive to movements and vibrations.
- It does not emit UV or IR.
- It can be dimmed smoothly from full load to no-load.

Apart from the advantages described previously, in [3] it is presented a comparative study of public system lighting between high-pressure sodium vapor lamps and solid-state lighting (LEDs), demonstrating the advantages of LED in relation to average illuminance, CRI (Color Rendering Index), energy consumption, long lifetime, and it shows that the human eye is more sensitized to some light wavelengths, depending on the photometric condition. Then, a light source with a lower luminous efficiency (lm/W), which is the case of LEDs, can be more sensitizing to the human eye compared to a light source with a great luminous efficiency, which is the case of the high-pressure sodium vapor lamps, when they focus on the same surface.

Thus, knowing that LEDs are more efficient and the global energy consumption with lighting is estimated in about 19% of the total amount of energy consumed in the world [2], it is possible to estimate that this percentage can be reduced by its half using the solid-state lighting, representing about 10% of the total energy consumption [3].

Although LEDs lighting provides a significant reduction of energy consumption, its implementation cost still being high, and there are high-pressure sodium vapor lamps which have higher luminous efficiency than LEDs. However, according to [4], there is a theory for lighting LEDs that mentions that LED brightness increases in thirty times every ten years and it costs decreases ten times in the same period. Then, it is expected that in next years, there will be more efficient LEDs offered for a more accessible price.

Concerning the development of LED drivers, previous works had presented proposals of cascade converters providing a wide input voltage range [5]-[8]. However, depending on the application, converters are designed to increase or decrease the input voltage, according to the rated voltage of the LED lamp to be driven. Therefore,

LED drivers with a wide input voltage range are very attractive, because it could operate the same LED lamp for emergency (powered at 12 V_{DC}) or conventional lighting (90-240 V_{AC}).

Based in this context, this paper presents the implementation and the experimental analysis of a Boost-Buck Quadratic converter, also known Boost-Buck2, designed to drive power LEDs using a single active switch. The converter can operate with an input voltage varying from 12 V_{DC} (battery voltage) to the universal AC input voltage (90-240 V_{AC}). Despite of this wide input voltage range, the control technique and its implementation is quite simple. In order to verify the effectiveness of the proposed converter driving a LED lamp, detailed theoretical and experimental analyses are presented in this paper.

2. Boost-Buck2 Converter

The Boost-Buck2 converter is equivalent to the conventional Boost cascaded with two Buck converters and, consequently, it can operate as step-up or as step-down converter. When it operates as step-up its gain depends directly on the duty cycle and while it operates as step-down its gain has a quadratic relationship with the duty cycle. Moreover, the converter has current source characteristic as much input as output, and with the advantages of using an active single switch. The schematic of the converter is showed in Fig. 1.

Fig. 1. Schematic of converter Boost-Buck2.

Converter operating at steady state, with the current through the inductors in continuous conduction mode (CCM), presents two operation stages.

First stage: This stage starts when switch S is turned-on. During this stage diodes D₁ and D₄ are forward-biased, and diodes D₂, D₃ and D₅ are reverse-biased, inductor L₁ is charged linearly by source V_i and inductors L₂ and L₃ are charged linearly by capacitors C₃, C₄ and C₅. Fig. 2 illustrates the first stage of operation.

Fig. 2. First stage of operation of Boost-Buck2 converter.

Second stage: This stage starts when switch S is turned-off and finishes when switch S is turned-on. During this stage diodes D₂, D₃ and D₅ are forward-biased and diodes D₁ and D₄ are reverse-biased. Current through the inductors

decrease linearly, and in that way, inductor L₁ supplies capacitor C₃, inductor L₂ supplies capacitor C₄ and inductor L₃ and capacitor C₅ supplies LED lamp. Fig. 3 illustrates the second stage of operation.

Fig. 3. Second stage of operation of Boost-Buck2 converter.

Fig. 4, 5, 6 and 7 show the main theoretical waveforms of Boost-Buck2 converter.

Fig. 4. Voltage waveform on gate of switch S.

Fig. 5. (a) Current and (b) voltage waveforms of inductors L₁, L₂ and L₃.

Fig. 6. (a) Current and (b) voltage waveforms of switch S.

Fig. 7. (a) Current and (b) voltage waveforms of capacitors C₃ and C₅.

3. Basic Equations

Knowing that integral of voltage across the inductors for one switching period is zero, yields:

For inductor L_1 .

$$V_i DT - (V_i - V_{C_3})(1-D)T = 0 \quad (1)$$

Solving (1) for V_{C_3} , yields:

$$V_{C_3} = \frac{V_i}{(1-D)} \quad (2)$$

For inductor L_2 .

$$(V_{C_3} - V_{C_4})DT - V_{C_4}(1-D)T = 0 \quad (3)$$

Solving (3) for V_{C_4} , yields:

$$V_{C_4} = V_{C_3} \cdot D \quad (4)$$

For inductor L_3 .

$$(V_{C_4} - V_o)DT - V_o(1-D)T = 0 \quad (5)$$

Solving (5) for V_o , yields:

$$V_o = V_{C_5} = V_{C_4} \cdot D \quad (6)$$

Replacing (2) and (4) in (6), yields:

$$V_o = V_{C_5} = \frac{D^2}{(1-D)} \cdot V_i \quad (7)$$

From (7) it is found the equation of static gain of Boost-Buck2 converter.

$$G = \frac{V_o}{V_i} = \frac{D^2}{(1-D)} \quad (8)$$

Knowing that the integral of current through the inductors for one switching period is zero, yields:

For capacitor C_3 .

$$I_{L_2}DT - I_{L_1}(1-D)T = 0 \quad (9)$$

Solving (9) for I_{L_2} , yields:

$$I_{L_1} = I_{L_2} \frac{D}{(1-D)} \quad (10)$$

For capacitor C_4 .

$$(I_{L_3} - I_{L_2})DT - I_{L_2}(1-D)T = 0 \quad (11)$$

Solving (11) for I_{L_2} , yields:

$$I_{L_2} = I_{L_3} \cdot D \quad (12)$$

For capacitor C_5 .

$$(I_o - I_{L_3})DT - (I_{L_3} - I_o)(1-D)T = 0 \quad (13)$$

Solving (13) for I_o , yields:

$$I_{L_3} = I_o \quad (14)$$

From (12) and (14), yields:

$$I_{L_2} = I_o \cdot D \quad (15)$$

From (10), (12) and (14), yields:

$$I_{L_1} = \frac{D^2}{(1-D)} I_o \quad (16)$$

Fig. 8 shows the static gain of converter.

Fig. 8. Static gain of Boost-Buck converter

4. Control with HV9930

HV9930 is a control integrated circuit for variable frequency PWM, manufactured by Supertex®, applicable to converters with the Boost-Buck topology driving LEDs. Its great advantage is its quite simple implementation, because it has an internal linear regulator, allowing it to be powered directly from 8.0 to 200 V_{DC}, maintaining the voltage VDD at 7.5 V (see Fig. 9). Moreover, the GATE pin can be connected directly to the MOSFET, and there's no need of isolation circuit and pulse amplification. However, it is recommended that the MOSFET input capacitance (Ciss) not exceed 1000 pF.

The load current control is realized by two identical comparators, of which its inverting input is connected to a built-in 100 mV. In this manner, when the gate is high, the inverting input is connected to GND, and when the gate is

low it is connected to 100 mV. The input comparator acts in the control during an overload or in the start-up condition, limiting the converter input current. The output comparator controls the converter output current, which it's maintained between a lower and an upper limit (hysteresis) [9], [10].

Fig. 9 shows block diagram of IC HV9930.

Fig. 9. Block Diagram of IC HV9930.

Fig. 10 shows the schematic of Boost-Buck2 converter based on the HV9930. It's possible to observe that components R, T and Z₁, make up the start-up circuit. Components L_{1f}, L_{2f}, D_f and C_f, make up an auxiliary power supply that powers the IC in steady state and, this way, continuing the steady state mode, diode D₆ is reverse-biased minimizing the energy dissipation in transistor T. Resistors R_{cs1}, R_{s1} and R_{ref1}, makes up input current sensor and R_{cs2}, R_{sa}, R_{sb} and R_{ref2}, make up output current sensor.

Fig. 10. Schematic of Boost-Buck2 converter based on the HV9930

5. Design of Boost-Buck2 Converter

The design parameters of the Boost-Buck2 converter are shown in Table I

For the inductors design L₁, L₂ and L₃ of Boost-Buck2 converter, it will be considered maximum input voltage, V_{imax} = 340 V_{DC}, which is the critical case for inductors, and from (8) it is found that D_{min} = 0.2.

From first stage of operation, yields:

$$V_i = V_{L_1} = L_1 \frac{di_{L_1}}{dt_1} \quad (17)$$

Table I. - Design parameters of the Boost-Buck2 converter

PARAMETERS	VALUE
Output power	P ₀ = 12 W
Output current	I ₀ = 700 mA
Output voltage	V ₀ = 16 V
Minimum input voltage	V _{imin} = 12 V _{DC}
Maximum input voltage	V _{imax} = 340 V _{DC}
Current ripple in L ₁	ΔI _{L1} = 0.9 · I _{L1}
Current ripple in L ₂	ΔI _{L2} = 0.9 · I _{L2}
Current ripple in L ₃	ΔI _{L3} = 0.2 · I _{L3}
Voltage ripple in C ₃	ΔV _{C3} = 0.2 · V _{C3}
Voltage ripple in C ₄	ΔV _{C4} = 0.2 · V _{C4}
Voltage ripple in C ₅	ΔV _{C5} = 2 V
Minimum switching frequency	f _{smin} = 80 kHz
Predicted efficiency	η = 0.8

Solving (17) for L₁ and from (16), yields:

$$L_1 = \frac{V_i}{\Delta I_{L_1}} D_{\min} \cdot T_{s_{\min}} \Rightarrow L_1 \cong 27 \text{ mH} \quad (18)$$

From the second stage of operation, yields:

$$V_{C_4} = -V_{L_2} = -L_2 \frac{di_{L_2}}{dt_2} \quad (19)$$

Solving (19) for L₂, and from (6), yields:

$$L_2 = \frac{V_0 (1 - D_{\min})}{D \cdot \Delta I_{L_2}} T_{s_{\min}} \Rightarrow L_2 \cong 6.7 \text{ mH} \quad (20)$$

From the second stage of operation, yields:

$$V_o = -V_{L_3} \Rightarrow V_o = -L_3 \frac{di_{L_3}}{dt_2} \quad (21)$$

The negative sign in (21), indicates that the output voltage polarity is reversed with respect to the input voltage.

Solving (21) for L₃, and from (14), yields:

$$L_3 = \frac{V_o (1 - D_{\min})}{\Delta I_{L_3}} T_{s_{\min}} \Rightarrow L_3 \cong 1.1 \text{ mH} \quad (22)$$

For the capacitors design C₃, C₄ e C₅ of Boost-Buck2 converter, it will be considered the minimum input voltage, V_{imin} = 12 V_{DC}, which is the critical case to the capacitors, and from (8) it is found that D_{max} = 0,67.

Filter capacitor of the rectifier can be calculated by [11]:

$$C_1 = \frac{P_i}{f_{\text{ret}} \left(V_{i \text{ pk}}^2 - (0,9 \cdot V_{i \text{ pk}})^2 \right)} \Rightarrow C_1 \cong 41 \mu\text{F} \quad (23)$$

Capacitor C2 was placed in parallel with capacitor C1 and it has a purpose of improving the response at high

frequencies. C2 was empirically defined, and was chosen polyester capacitor 560 nF.

From the first stage of operation, yields:

$$I_{L_2} = -I_{C_3} = -C_3 \frac{dV_{C_3}}{dt_1} \quad (24)$$

Solving (24) for C₃, and from (2) and (15), yields:

$$C_3 = \frac{I_{L_2} D_{\max}}{\Delta V_{C_3}} \cdot T_{S_{\min}} \Rightarrow C_3 \cong 540 \text{ nF} \quad (25)$$

From the second stage of operation, yields:

$$I_{L_2} = I_{C_4} = C_4 \frac{dV_{C_4}}{dt_2} \quad (26)$$

Solving (26) for C₄, and from (6) and (15), yields:

$$C_4 = \frac{I_{L_2} (1 - D_{\max})}{\Delta V_{C_4}} \cdot T_{S_{\min}} \Rightarrow C_4 \cong 405 \text{ nF} \quad (27)$$

If disregarded current ripple in the load, then $\Delta I_{L_3} = \Delta I_{C_5}$. Thus, capacitor average current charge in time T/2 is $I_{C_5} = \Delta I_{L_3}/4$, then the voltage ripple on capacitor C₅ [12], is:

$$\Delta V_{C_5} = \frac{1}{C_5} \int_0^{\frac{T}{2}} \frac{\Delta I_{C_5}}{4} dt = \frac{\Delta I_{C_5}}{8 C_5 f} \quad (28)$$

Hence as $\Delta I_{L_3} = \Delta I_{C_5}$, and from (22) and (28) it is obtained:

$$C_5 = \frac{V_o (1 - D_{\max})}{8 L_3 f^2 \Delta V_{C_5}} \cong 47 \text{ nF} \quad (29)$$

6. Experimental Results

The experimental results were achieved with a converter prototype, which was consisted of components described in Table II.

Table II. - Components Used In Prototype

COMPONENTS	VALUES
Inductor L ₁	27 mH
Inductor L ₂	6.7 mH
Inductor L ₃	1.1 mH
Electrolytic capacitor C ₁	47 μF
Polyester capacitor C ₂ e C ₃	560 nF
Polyester capacitor C ₄	390 nF
Polyester capacitor C ₅	47 nF
Mosfet S	STD8NM60N-1
Diodes D ₁ , D ₂ , D ₃ , D ₄ e D ₅	HFA30TA60C
LED ₁ , LED ₂ , LED ₃ , e LED ₄	EDSW-KLC8-B3/700 mA

Fig. 11 shows the prototype with LED lamp, and Fig. 12 shows current waveform in LED to the V_i=12 V_{DC}.

Fig. 11. Prototype of Boost-Buck2 converter

Fig. 12. Waveform to V_i = 12 V_{DC}. (current in LED lamp - 200mA/Div).

As it can be noticed in Fig. 12, for minimum input voltage, V_i = 12 V_{DC}, the current through LED lamp is pulsed. This is an intrinsic characteristic of the control strategy of IC HV9930 applied to converters with wide input voltage range.

Knowing that the minimum voltage supply is only for operation in emergency lighting, it was looked into Standard NBR 10898:1999 [14]. Then, it was verified in laboratory that the illuminance which the LED lamp produces with the converter powered in V_i = 12 V_{DC}, meets the requirements of the standard previously mentioned. Even the current being pulsed, it's observed only the decrease on the brightness of the LEDs, but there's no occurrence of flicker.

Fig. 13 shows the current waveform in the LED lamp and the voltage waveform on switch S, to input voltage from V_i = 127 VRMS. Thus, it was verified, for highest input voltage, the LED lamp current wasn't pulsed. Fig. 14 and Fig. 15 show the current waveforms in the LED lamp and voltage waveforms on switch S, to input voltage from V_i = 220 Vrms and V_i = 240 Vrms, respectively.

7. Conclusion

This paper had purpose of analyzing and designing the Boost-Buck2 converter and to evaluate its functionality using IC HV9930 for control of switch S. Thus, this topology brings great operational flexibility, because the converter was designed to operate from the battery voltage

Fig. 13. Waveforms to $V_i = 127 \text{ V}_{\text{RMS}}$. (CH1 – current in LED lamp – 200mA/Div, CH2 – voltage on switch S – 100V/Div).

Fig. 14. Waveforms to $V_i = 220 \text{ V}_{\text{RMS}}$. (CH1 – current in LED lamp – 200mA/Div, CH2 – voltage on switch S – 100V/Div).

Fig. 15. Waveforms to $V_i = 240 \text{ V}_{\text{RMS}}$. (CH1 – current in LED lamp – 200mA/Div, CH2 – voltage on switch S – 100V/Div).

(12 V_{DC}) to the universal AC input voltage (90 to 240 V_{RMS}), moreover, the control technique and its implementation is quite simple with the IC HV9930.

Therefore, a single device can be used for emergency and conventional lighting. Thus, the converter turns it very attractive from the technical and economical standpoint for industrial and commercial applications.

Through computer simulations results and subsequent

experimental verification on a prototype (shown in Fig. 11), it was verified that for minimum input voltage the current in the LED lamp was pulsed. Nevertheless, the results meet the standard NBR 10898:99. In the other hand, current in LED lamp to be pulsed, allows its junction to work at a lower temperature, increasing its lifetime.

For the universal AC input voltage (90 to 240 V_{RMS}), as shown in experimental results, the current in the LED lamp wasn't pulsed, proving the functionality of Boost-Buck2 converter and of CI HV9930.

Acknowledgment

The authors gratefully acknowledge the financial support of Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPQ - Brazil.

References

- [1] de Britto, J.R.; de Freitas, L.C.; Farias, V.J.; Coelho, E. Vieira, J.B., "LED Lamp Driver Using a Converter with Wide Range Conversion Microcontroller-Based", Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, pp: 1988 – 1993, 10-13 Nov. 2008.
- [2] http://www.metodoeventos.com.br/6eficienciaenergetica/palestras/22_07_workshop2/eduardo_polidoro.pdf, "Iluminação Eficiente com LEDs", Eduardo Polidoro, Philips, accessed 04/29/2011.
- [3] Rodrigues, C.R.B.S.; Almeida, P.S.; Soares, G.M.; Jorge, J.M.; Pinto, D.P.; Braga, H.A.C., "Um Estudo Comparativo de Sistemas de Iluminação Pública: Estado Sólido e Lâmpadas de Vapor de Sódio em Alta Pressão", Industry Applications (INDUSCON), 2010 9th IEEE/IAS International Conference on, pp: 1-6, 8-10 Nov. 2010.
- [4] Liu YU, Jinming YANG, "The Topologies of White LED Lamp's Power Drivers", Power Electronics Systems and Applications, 2009. PESA 2009. 3rd International Conference on, pp: 1-6, 20-22 May 2009.
- [5] Demian, A.E., Reginaldo de Britto, J., de Freitas, L.C., Farias, V.J., Coelho, E.A.A., Vieira, J.B., "Microcontroller-Based Quadratic Buck Converter Used as LED Lamp Driver", Power Electronics And Application, 2007 European Conference on, pp: 1-6, Sept. 2007.
- [6] Bassan, S., Moschopoulos, G., "Properties and Applications of Quadratic Converters", IEEE Canada Electrical Power Conference, pp: 123-127, Oct. 2007.
- [7] Alonso, J.M., Viña, J., Gacio, D., Campa, L., Martínez, G., Osorio, R., "Analysis and Design of the Quadratic Buck-Boost Converter as a High-Power-Factor Driver for Power-LED Lamps", IECON 2010 – 36th Annual Conference on IEEE Industrial Electronics Society, pp: 2541-2546, Nov. 2010.
- [8] Silva, W.G., Rodovalho, D.S., da Silva, F.V.R., de Moraes, J.S., de Freitas, L.C., Coelho, E.A.A., Vieira Junior, J.B., "Conversor Boost Quadrático-Buck Utilizado no Acionamento de um Vetor de LED Empregado no Tratamento de Disfunções Celulares", Eletrônica de Potência, vol. 16, N° 3, Jun./Aug. 2011.
- [9] Supertex inc., "Hysteretic Boost-Buck (Cuk) Led Driver IC – HV9930", 2008 Supertex inc.
- [10] Steve Winder, "Power Supplies for LED Drives", Newnes, 2008.
- [11] Barbi, I., "Projetos de Fontes Chaveadas", Edition of the author, Florianópolis, 2001.
- [12] Rashid, Muhammad H., "Eletrônica de Potência: Circuitos, Dispositivos e Aplicações", Makronn Books, São Paulo, 1999.
- [13] http://www.edison-opto.com.tw/Datasheet/Edixeon/Edison%20Opto_Edixeon%C2%AE%20K%20Series_Eng_v4.pdf, accessed 06/28/2011.
- [14] NBR 10898:1999 – "Emergency Lighting System"