

Simulation of a Two Stage High Power Factor Driver for White Power Led

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ABSTRACT : In this paper, an integrated double buck–boost (IDBB) converter is proposed as a high-power-factor offline power supply for power-LED lamps. The IDBB converter features just one controlled switch and two inductors and is able to supply a solid-state lamp from the mains, providing high power factor and good efficiency. In this paper, the IDBB converter is analyzed, and a design methodology is proposed. It is demonstrated that, with a careful design of the converter, the filter capacitances can be made small enough so that film capacitors may be used. In this way, the converter mean time between failures can be made as high as that of the solid-state lamp. A design example for a 70-W converter supplied from a 230 V/50 Hz mains for street lighting applications is shown. MATLAB is applied to execute the whole circuit simulations. Finally, simulation results demonstrate that the power factor of the closed-loop IDBB converter is 0.993 and the output voltage of the designed controller can be stably maintained at 200V.

Keywords : Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM), Duty cycle (D), Integrated double Buck–boost (IDBB), white power LED

I. INTRODUCTION

Energy prices have skyrocketed in recent years owing to depleting renewable resources. In addition to seeking other energy sources, countries worldwide are also initiating energy-saving and carbon reduction programs. Due to the small size and high efficiency, semiconductor lighting has attracted researchers and manufacturers to develop new products using this technology. Nowadays the energy-inefficient incandescent lamps and mercury-based tubular and compact fluorescent lamps are replacing LED lamps. Although HB white LEDs are not the most efficient lighting systems in terms of lumens per watt for streetlight applications (indeed, they achieve a lower efficiency than low-pressure sodium vapor lamps), they are quite interesting compared to traditional solutions due to their longer operating life and their more pleasant light spectrum (sodium lights emit only in yellow color, thus providing a very poor Color Rendering Index, CRI). High Brightness-LEDs do not need neither warm up nor restart period, which do imply the use of specific circuitry.

Due to the high efficiency of the LEDs with maximum illumination, the utilization is 85%-90% of the input power into light energy, whereas the fluorescent lamps will produce only 77%. On the other hand global warming and increasing power demand etc. may be fulfilled by LEDs by implementing enhanced control technique (light dimming and preheating of filaments if possible). The recombination of electrons and holes can cause either photons (light) or phonons (heat). So the junction temperature of the LEDs increasing leads to the degradation of the luminous flux of LEDs [11]. The high efficacy of power LEDs is only maintained under strict operating conditions, which include low direct current and low junction temperature (Fig 1). All these mean that the development of power supplies that achieve correct driving of the LED-based lamp is an important topic of research [16]–[20].

White power LEDs are becoming an attractive light source, owing to their high reliability, long life, high color rendering index, and small size [1]. In addition, there are commercially available units that can reach light efficacies as high as 100 lm/W. All these features make white LEDs a good candidate to override fluorescent and other discharge lamps.

The main drawback of these LEDs is they need constant voltage as input and they need current limiter before the input of the LED. Therefore, some kind of current-limiting device must be used, similarly to the ballast used to limit the current through a discharge lamp. On the other hand, the high efficacy of power LEDs is only maintained under strict operating conditions, which include low direct current and low junction temperature.

A review of literature shows that a variety of LED power supplies and driver solutions, which can accurately control the current of the LED while achieving a near-unity input power factor, have been proposed

[8]–[10]. This drive is currently implemented with power electronic stages based on switch mode power supplies (SMPS). However, an electrolytic capacitor is required in these applications. Unfortunately, the operating life of such capacitors is by far shorter than the life of the HB LEDs, and usually are the shortest of all the devices in the power supply. Thus, removing the electrolytic capacitor would imply a remarkable increase in the operating life and reliability of the system [3],[4].

PFC converters can be classified into two types: two-stage and single-stage. Two-stage PFC converters consist of a PFC stage and a dc/dc stage. Single-stage PFC converters integrate the PFC stage and the dc/dc stage, leading to simple topology and low cost. They are suitable for low-power applications [7]. The simplest active PFC circuits are implemented with a single-stage that makes the power factor correction. The most common single-stage topology used is the flyback converter [5], [6] working in Discontinuous Conduction Mode (DCM), being called DCM flyback PFC converter. The main drawbacks of these pre-regulators are, by one hand, the high peak current stresses caused by the DCM and serious EMI problem [3] and, by the other, the poor dynamics that these converters perform due to the low-pass filter (10 Hz-20 Hz) needed to reduce the input line current total harmonic distortion (THD). Therefore, if dimming operation is required, which must be done at frequencies above 200 Hz, these single stage solutions are not feasible. Attending to the reasons exposed above, a two-stage is needed so the Power Factor Correction can be done properly and a fast enough output dynamics is obtained.

The numerous types of switching converter include boost, buck, buck-boost, and Cuk converters. Here an integrated double buck-boost converter is proposed to supply power-LED lamps from the line, providing high power factor, low LED current ripple, and high efficiency. The operation of the converter is equivalent to two buck-boost converters in cascade, in which the controlled switch is shared by the two stages. Thus, the proposed converter includes two inductors, two capacitors, three diodes, and one ground-referenced controlled switch, featuring affordable low cost and good reliability for this kind of applications.

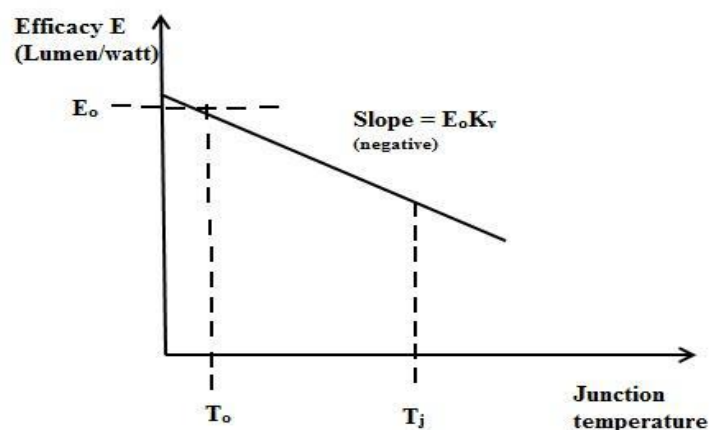


Figure 1.1: Efficacy versus junction temperature of LED.

II. White Power Led

LEDs can be divided into three categories: indicative LEDs, high-brightness LEDs, and power LEDs. White power LEDs are becoming an attractive light source, owing to their high reliability, long life, high color rendering index, and small size [1]. In addition, there are commercially available units that can reach light efficacies as high as 100 lm/W. All these features make white LEDs a good candidate to override fluorescent and other discharge lamps in many applications, including street lighting, automotive lighting, and decorative applications.

There are two primary ways of producing white light-emitting diodes (WLEDs), LEDs that generate high-intensity white light. One is to use individual LEDs that emit three primary colors—red, green, and blue—and then mix all the colors to form white light. The other is to use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, much in the same way a fluorescent light bulb works.

There are three main methods of mixing colors to produce white light from an LED:

- [1] blue LED + green LED + red LED (color mixing; can be used as backlighting for displays)
- [2] near-UV or UV LED + RGB phosphor (an LED producing light with a wavelength shorter than blue's is used to excite an RGB phosphor)

- [3] blue LED + yellow phosphor (two complementary colors combine to form white light; more efficient than first two methods and more commonly used)^[79]

2.1 LED efficiency and efficacy:

In lighting design, "efficacy" refers to the amount of light (luminous flux) produced by a lamp (a lamp or other light source), usually measured in lumens, as a ratio of the amount of power consumed to produce it, usually measured in watts. This is not to be confused with efficiency which is always a dimensionless ratio of output divided by input which for lighting relates to the watts of visible power as a fraction of the power consumed in watts. The visible power can be approximated by the area under the Planck curve between 300 nm and 700 nm for a blackbody at the temperature of the filament as a ratio of the total power under the blackbody curve. Efficiency values for light from a heat source are typically less than two percent.

2.2 Advantages of LED over incandescent and fluorescent lamps

- a. Efficiency: LEDs emit more lumens per watt than incandescent light bulbs.^[115] The efficiency of LED lighting fixtures is not affected by shape and size, unlike fluorescent light bulbs or tubes.
- b. Color: LEDs can emit light of an intended color without using any color filters as traditional lighting methods need. This is more efficient and can lower initial costs.
- c. Size: LEDs can be very small (smaller than 2 mm) and are easily attached to printed circuit boards.
- d. On/Off time: LEDs light up very quickly. A typical red indicator LED will achieve full brightness in under a microsecond.
- e. Cycling: LEDs are ideal for uses subject to frequent on-off cycling, unlike fluorescent lamps that fail faster when cycled often, or HID lamps that require a long time before restarting.
- f. Dimming: LEDs can very easily be dimmed either by pulse-width modulation or lowering the forward current.
- g. Cool light: In contrast to most light sources, LEDs radiate very little heat in the form of IR that can cause damage to sensitive objects or fabrics. Wasted energy is dispersed as heat through the base of the LED.
- h. Slow failure: LEDs mostly fail by dimming over time, rather than the abrupt failure of incandescent bulbs.
- i. Lifetime: LEDs can have a relatively long useful life. One report estimates 35,000 to 50,000 hours of useful life, though time to complete failure may be longer. Fluorescent tubes typically are rated at about 10,000 to 15,000 hours, depending partly on the conditions of use, and incandescent light bulbs at 1,000 to 2,000 hours.
- j. Shock resistance: LEDs, being solid-state components, are difficult to damage with external shock, unlike fluorescent and incandescent bulbs, which are fragile.
- k. Focus: The solid package of the LED can be designed to focus its light. Incandescent and fluorescent sources often require an external reflector to collect light and direct it in a usable manner. For larger LED packages total internal reflection (TIR) lenses are often used to the same effect.

2.3 Disadvantages of LED

- a. High initial price: LEDs are currently more expensive, price per lumen, on an initial capital cost basis, than most conventional lighting technologies. As of 2010, the cost per thousand lumens (kilolumen) was about \$18. The price is expected to reach \$2/kilolumen by 2015. The additional expense partially stems from the relatively low lumen output and the drive circuitry and power supplies needed.
- b. Temperature dependence: LED performance largely depends on the ambient temperature of the operating environment – or "thermal management" properties. Over-driving an LED in high ambient temperatures may result in overheating the LED package, eventually leading to device failure. An adequate heat sink is needed to maintain long life. Toshiba has produced LEDs with an operating temperature range of -40 to 100°C, which suits the LEDs for both indoor and outdoor use in applications such as lamps, ceiling lighting, street lights, and floodlights.
- c. Voltage sensitivity: LEDs must be supplied with the voltage above the threshold and a current below the rating. This can involve series resistors or current-regulated power supplies.
- d. Light quality: Most cool-white LEDs have spectra that differ significantly from a black body radiator like the sun or an incandescent light. The spike at 460 nm and dip at 500 nm can cause the color of objects to be perceived differently under cool-white LED illumination than sunlight or incandescent sources, due to metamerism, red surfaces being rendered particularly badly by typical phosphor-based cool-white LEDs. However, the color rendering properties of common fluorescent lamps are often inferior to what is now available in state-of-art white LEDs.

- e. Area light source: Single LEDs do not approximate a point source of light giving a spherical light distribution, but rather a lambertian distribution. So LEDs are difficult to apply to uses needing a spherical light field, however different fields of light can be manipulated by the application of different optics or "lenses".
- f. Electrical polarity: Unlike incandescent light bulbs, which illuminate regardless of the electrical polarity, LEDs will only light with correct electrical polarity. To automatically match source polarity to LED devices, rectifiers can be used.
- g. Electric shock hazard: There have been LED recalls because faulty wiring that can cause electric shock, fire or burns.
- h. Blue hazard: There is a concern that blue LEDs and cool-white LEDs are now capable of exceeding safe limits of the so-called blue-light hazard as defined in eye safety specifications such as ANSI/IESNA RP-27.1-05: Recommended Practice for Photo biological Safety for Lamp and Lamp Systems.
- i. Blue pollution: Because cool-white LEDs with high color temperature emit proportionally more blue light than conventional outdoor light sources such as high-pressure sodium vapor lamps, the strong wavelength dependence of Rayleigh scattering means that cool-white LEDs can cause more light pollution than other light sources. The International Dark-Sky Association discourages using white light sources with correlated color temperature above 3,000 K.
- j. Efficiency droop: The luminous efficacy of LEDs decreases as the electrical current increases above tens of milliamps.

III. Modeling Of Led

HB-LEDs are usually low power devices, ranging from 1 W to 5 W at currents from 350 mA up to 2000 mA in the latest devices, while performing luminous efficiencies around 100 lm/W at 350 mA [8], [9]. The fact that they are low power devices means that many of them will be necessary for wide area lighting applications such as streetlights. The devices chosen for the first prototypes were the DragonTape from Osram [10], composed of six Golden Dragon LEDs in series attached to a flexible self-adhesive tape, achieving a luminous efficiency of 21 lm/W at 350 mA . Since as forward current rises the luminous flux decreases, and lifetime decreases too, the design is focused on providing the nominal current of 350 mA. The nominal power requirement for most LED streetlights ranges from 60 W to 150 W [1]. The load finally chosen is made of 10 DragonTapes run at 350 mA, composing a 60LEDs load emitting 1500 lumens at a nominal power of 72 W.

The second step in the load design consists of its modeling. In a first step, the data obtained from the datasheet [11] are used. The simplest linear model takes in account only the equivalent resistance of the device at the nominal operating point. This is a valid method only if the load is going to work in a narrow range around the nominal point. Otherwise, this approximation yields to unacceptable errors due to the great difference between the equivalent resistance at the operating point and the dynamic resistance, much higher the former than the latter. Therefore, the most accurate approximation is the one consisting of a threshold voltage and a dynamic resistance in series, as shown in Fig 3. 1.

Then, the LED load I-V model would be the following:

$$V_d = R_d * I_d + V_\gamma$$

Where V_d is the forward voltage drop of the LED, R_d is the dynamic resistance, I_d is the LED current and V_γ is the threshold voltage.

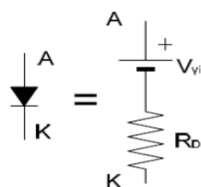


Figure 3.1: Equivalent circuit of diode: linear model

The LED modeling process done in the lab consisted in obtaining the forward voltage for several current values, taking steps of approximately 50 mA during few seconds and letting the devices to cool down again, so the heating effects on the threshold voltage were negligible. The results extracted from the test, as well as the load threshold voltage and dynamic resistance obtained from a linear interpolation, are shown in Table 3.1, as well as in Fig 3.2.

TABLE 3.1: TEST FORWARD CURRENT AND VOLTAGE VALUES

$I_D(A)$	$V_O(V)$	$R_D(\Omega)$	$V_f(V)$
0.102	177.2	87.2	170.1
0.150	182.9		
0.208	189.0		
0.249	192.9		
0.301	197.4		
0.352	201.6		
0.403	205.4		
0.453	208.9		
0.492	211.8		

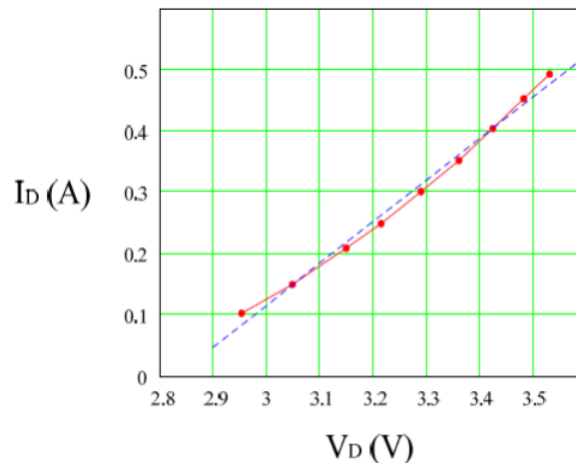


Figure 3.2: Forward current i_d and forward voltage v_d values obtained from the led lamp built and tested in laboratory (dotted line) and linear model (dashed line)

IV. Modified Idbb Converter

This IDBB converter acts as two buck-boost converter in series. The input of the buck-boost converter is made by L_1, D_1, C_1 , and S_1 . Similarly the output is L_2, D_2, D_3, C_2 , and S_2 . The reversing polarity produced by the first converter in the capacitor C_1 is corrected by the second converter, given a positive output voltage with respect to ground. It will make the circuit simple for the measurement of the load current in the closed loop operation and it leads to reducing sensing circuit and cost.

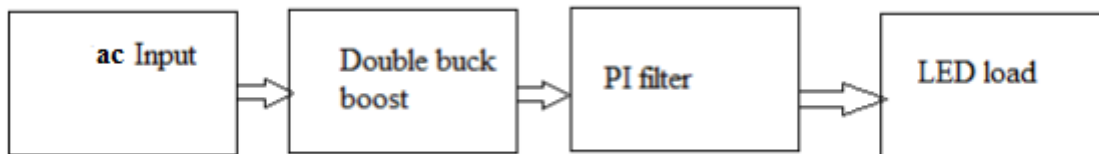


Figure 4.1: Block Diagram of Circuit Diagram

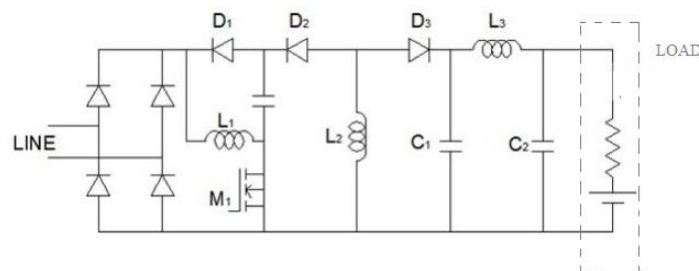


Figure 4.2: Modified IDBB converter

By operating the input inductor L_i in discontinuous conduction mode (DCM), the average current through the line will be proportional to the line voltage, therefore providing a near unity PF. On the other hand, the output inductance L_o can be operated either in continuous conduction mode (CCM) or DCM. The operation in DCM has the advantage of providing a bus voltage across C_B independent of the duty cycle and output power. However, it presents the disadvantage of requiring a higher value of the output capacitance to achieve low current ripple through the load. In order to have a reduced value for the output capacitance, the output inductance is operated in CCM, because the current ripple is lower in this operation mode. In addition, the operations of the second stage in CCM with a duty cycle lower than 0.5 reduces the low-frequency ripple voltage since it is multiplied by the buck–boost converter voltage ratio. In this way, it will be possible to use a film capacitor to implement the output capacitance, thus having a higher life rating and better efficiency than using electrolytic capacitors.

Moreover, with a careful design of the converter, the bus capacitor can also be made low enough to be implemented with film technology, thus avoiding the low-life-rating electrolytic capacitors in the whole converter. This implies the design of the converter so that it operates with a duty cycle lower than 0.5. In this manner, the output converter voltage ratio will be lower than one, thus reducing the low-frequency voltage ripple in the same amount. Under the exposed operation conditions, the equivalent circuits for the operation of the IDBB converter within a switching period are shown in Fig. 4.3. The main waveforms are shown in Fig. 4.4.

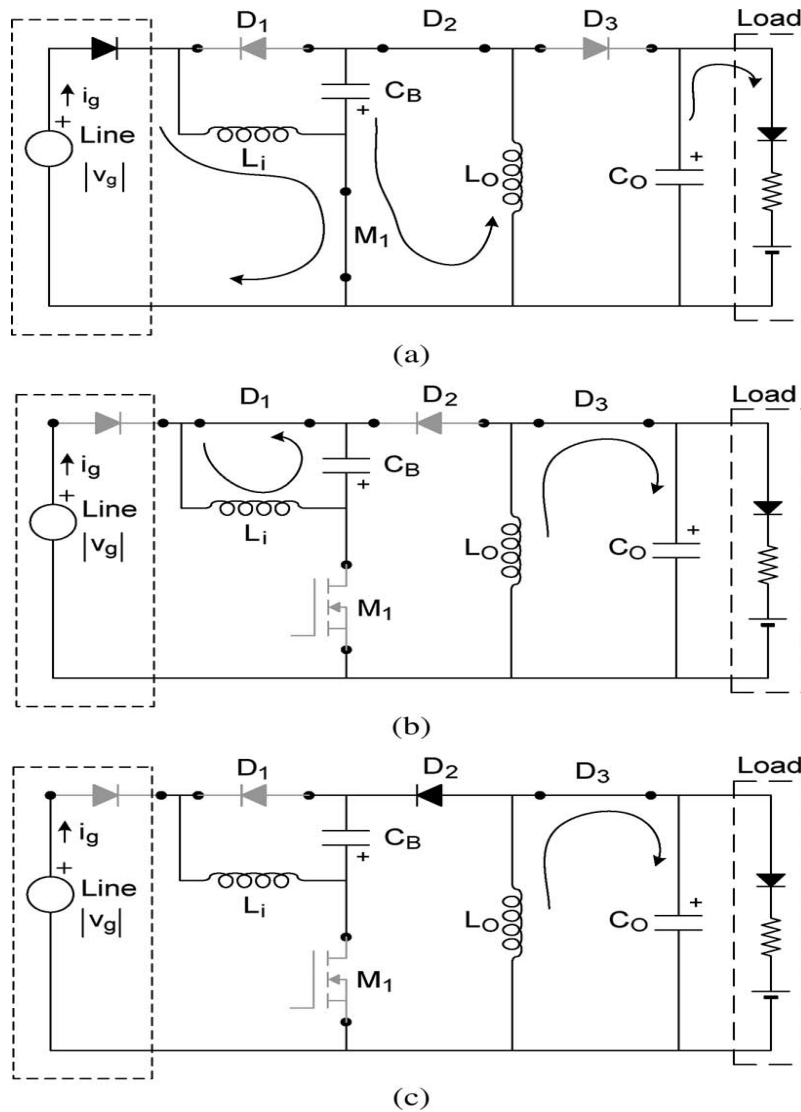


Figure 4.3: Equivalent circuits for the operation of the IDBB converter. (a) Interval I: $0 < t < DTS$. (b) Interval II: $DTS < t < DTS + t_1$. (c) Interval III: $DTS + t_1 < t < TS$.

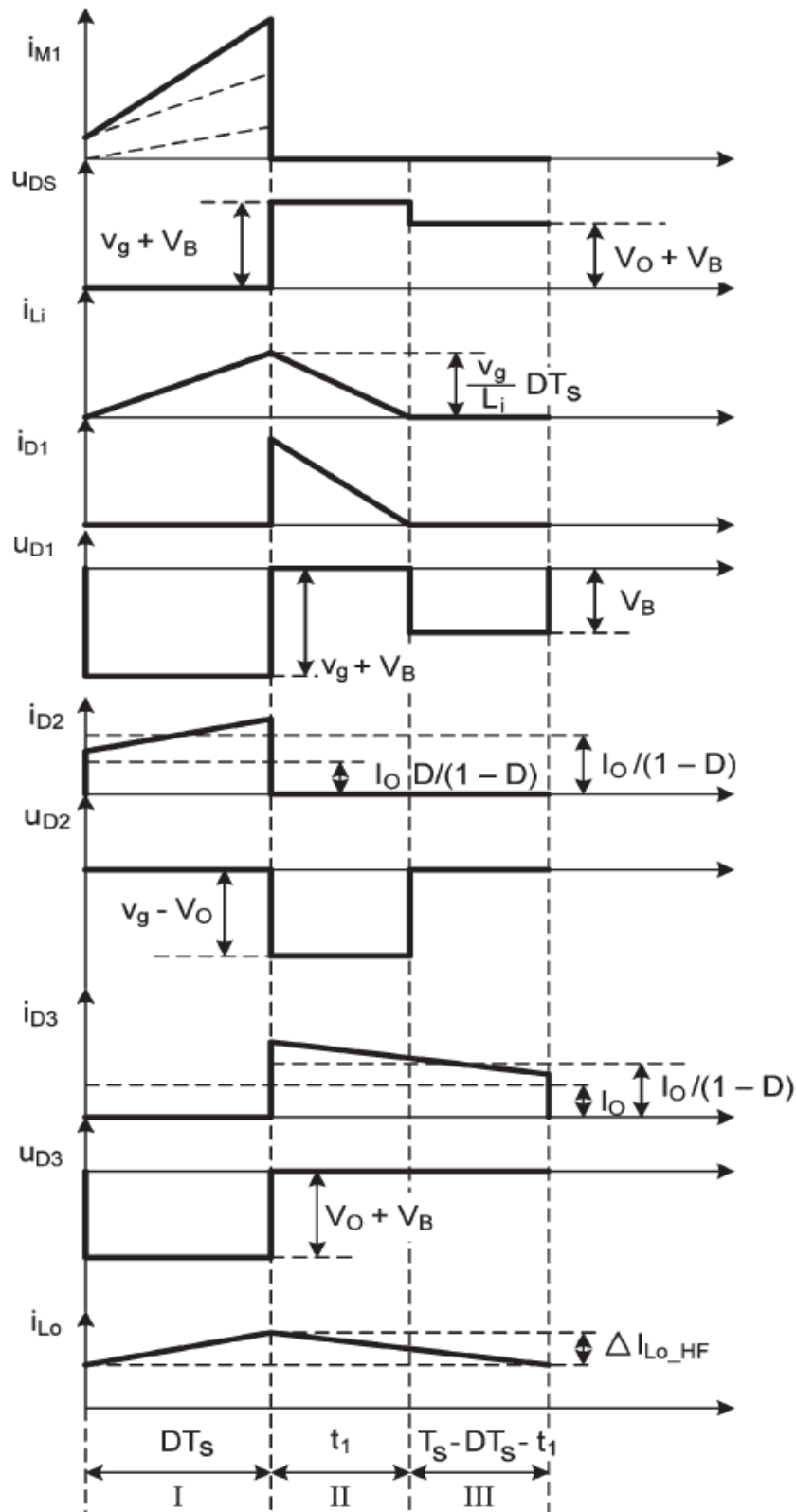


Figure 4.4: Main waveforms of IDBB converter with a high frequency switching period around peak line voltage

V. Analysis of the Offline Idbb Converter

In this section, the IDBB converter is analyzed when operated from the main voltage, achieving a near-unity input PF and a low-ripple current through the power-LED load. It is assumed that the line voltage is a sinusoidal waveform given as

$$v_g = V_g \sin \omega t \tag{1}$$

5.1 Line current and input power

The input current i_g corresponds to the current through the inductance L_i during the time interval $0 - DT_s$, where D is the transistor duty cycle and T_s is the transistor switching period. Thus, the value of the input current averaged at line frequency can be calculated as follows

$$i_g = \frac{1}{T_s} \int_0^{DT_s} i_{g_peak} DT_s = \frac{D^2 V_g}{2L_i f_s} \sin \omega L t \tag{2}$$

where i_{g_peak} is the instantaneous peak current in each switching period, f_s is the switching frequency, V_g is the peak line voltage, and ωL is the line angular frequency. As can be seen in figure 6.1, the averaged input current is a sinusoidal waveform that will provide an input PF close to unity once filtered by the input electromagnetic interference (EMI) filter. The mean input power P_g can now be calculated, taking into account that both input waveforms will be sinusoidal

$$P_g = \frac{1}{2} V_g \langle i_g \rangle_{peak} = \frac{D^2 V_g^2}{4L_i f_s} \tag{3}$$

where $\langle i_g \rangle_{peak}$ is the peak value of the averaged input current.

Since the output stage corresponds to a buck–boost converter operating in CCM, the bus voltage V_B can be calculated by using the voltage conversion ratio for this converter.

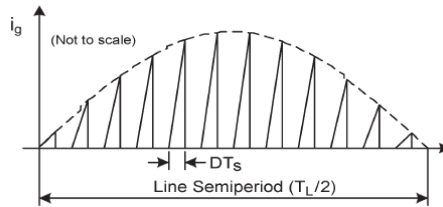


Figure 5.1: Input current waveform.

5.2 Output and Bus Voltages

The output voltage V_O for the ideal converter can be obtained by equaling input and output powers. The output power is obtained as follows

$$P_O = \frac{V_O^2}{R} \tag{4}$$

With R being the static equivalent resistance of the LED load, which can be obtained by the ratio between the dc values of LED voltage (V_{LED}) and current (I_{LED}) at each operating point.

$$R = \frac{V_{LED}}{I_{LED}} = \frac{(V_\gamma + R_\gamma I_{LED})}{I_{LED}} = \frac{V_\gamma}{I_{LED}} + R_\gamma \tag{5}$$

where V_γ and R_γ are the voltage and resistance parameters of the LED lamp equivalent circuit[29].

Then, assuming 100% efficiency, by equating equations (6.3) and (6.4), the output voltage is finally obtained

$$V_O = \frac{D V_g}{2\sqrt{K}} \tag{6}$$

where K is a non dimensional factor given by

$$K = \frac{f_s L_i}{R} \tag{7}$$

Since the output stage corresponds to a buck–boost converter operating in CCM, the bus voltage V_B can be calculated by using the voltage conversion ratio for this converter [29]

$$V_B = \frac{1-D}{D} V_O = \frac{(1-D)V_g}{2\sqrt{K}} \tag{8}$$

When operating the input stage in DCM and the output stage in CCM, the bus and output voltages are reversely dependent on the duty cycle. For example, if the duty cycle increases, the output voltage increases, and the bus voltage decreases in the same amount.

It must be noted that the input stage must be operated in DCM under any load and input voltage conditions to assure high input PF. The limit duty cycle D_{limit} can be obtained from the voltage conversion ratio in the DCM–CCM boundary

$$D_{limit} = \frac{1}{1 + \frac{V_g}{V_B}} \tag{9}$$

As long as the actual duty cycle is lower than the limit value the input stage will operate in DCM.

5.3 Reactive Components

The input inductance L_i can be calculated for a given output power using equation (6.6) and assuming 100% efficiency

$$L_i = \frac{D^2 V_g^2}{4 P_o f_s} \tag{10}$$

The bus capacitor C_B is calculated to limit the low-frequency ripple of the bus voltage, which is the voltage applied to the second stage. The current through this capacitor is given by the currents through diodes $D1$ and $D2$. In these diodes, only the current through $D1$ is modulated by a rectified line frequency, as shown in Figure. 6.2. In order to calculate the bus ripple, the low-frequency component of the current through $D1$ must be obtained. Referring to Figure.6.2, the average current through $D1$ can be calculated as follows:

$$\langle i_{D1} \rangle = \frac{1}{T_s} \int_0^{t_1} i_{D1_peak} dt \tag{11}$$

where i_{D1_peak} is the peak current through $D1$ in each switching period and t_1 is the time needed by this current to reach zero. Both values are changing after double the line frequency and have the following values:

$$i_{D1_peak} = \frac{v_g}{L_i} D T_s \tag{12}$$

$$t_1 = \frac{L_i v_g T_s}{V_B} \tag{13}$$

Using equations (11) and (12) in equation (10), the $D1$ average current is calculated as

$$\langle i_{D1} \rangle = \frac{D^2 V_g^2}{4 V_B f_s L_i} v_g^2 = \frac{D^2 V_g^2}{4 V_B f_s L_i} V_g^2 \sin^2 \omega t \tag{14}$$

$$\langle i_{D1} \rangle = \frac{D^2 V_g^2}{2 V_B f_s L_i} \left(\frac{1}{2} - \frac{1}{2} \cos 2\omega t \right) \tag{15}$$

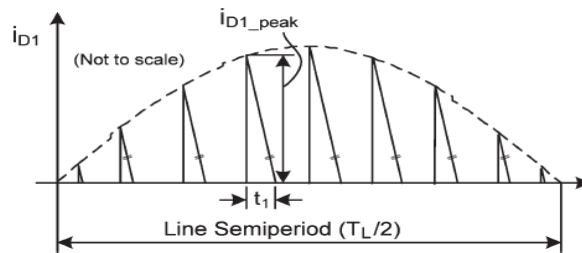


Figure. 5.2: Current waveform through diode $D1$.

Then, the low-frequency ac component circulating through $D1$ and C_B is given by

$$\langle i_{D1} \rangle_{ac} = \frac{D^2 V_g^2}{4 V_B f_s L_i} \cos 2\omega t \tag{16}$$

Now, the low-frequency peak-to-peak ripple voltage across capacitor $C_B, \Delta V_{B_LF}$ can be obtained as

$$\begin{aligned} \Delta V_{B_LF} &= 2 \langle i_{D1} \rangle_{ac_peak} X_{C_B} \tag{17} \\ &= \frac{2 D^2 V_g^2}{4 V_B L_i f_s 2\pi (2f_L) C_B} \\ &= \frac{D^2 V_g^2}{8\pi V_B L_i f_s C_B f_L} \end{aligned}$$

where $\langle i_{D1} \rangle_{ac_peak}$ is the peak value of the low-frequency current through diode $D1$, obtained from equation (16), and f_L is the line frequency. The necessary bus capacitance for a given peak-to-peak ripple in the bus voltage is then calculated from equation (17) as follows:

$$C_B = \frac{D^2 V_g^2}{8\pi V_B L_i \Delta V_{B_LF} f_s f_L} \tag{18}$$

Since the output buck–boost converter operates in CCM, the low-frequency voltage ripple at the output will be given by

$$V_{o_LF} = \frac{D}{1-D} \Delta V_{B_LF} \tag{19}$$

This ripple voltage will produce a low-frequency ripple current through the LED load that can be determined by the following:

$$\Delta I_{LED_LF} = \frac{\Delta V_{o_LF}}{R_Y} \tag{20}$$

As long as the output buck–boost converter operates in CCM, the LED current ripple at low frequency depends only on the bus voltage ripple and, thus, on the bus capacitance C_B . The output capacitance C_O has no effect on this low frequency ripple.

Finally, the output inductance and capacitance L_o and C_o are obtained using the well-known expressions for a buck–boost converter operating in CCM [29]

Output voltage ripple,

$$\Delta V_{o_{HF}} = \frac{\Delta Q}{C_o} \tag{21}$$

$$\begin{aligned} \Delta Q &= I * t \\ &= I_o D T_s \end{aligned}$$

$$C_o = \frac{I_o D}{\Delta V_{o_{HF}} f_s} \tag{22}$$

Average current through L_o ,

$$\begin{aligned} I_{L_o} &= I_{D_2} + I_{D_3} \\ &= \frac{I_o D}{1-D} + I_o = \frac{I_o}{1-D} \end{aligned} \tag{23}$$

Taking average voltage across $L_o=0$

$$\begin{aligned} \frac{L_o \Delta I_{D_2}}{D T_s} &= V_B \\ \frac{L_o \Delta I_{D_3}}{t_{off}} &= V_o \\ \Delta I_{L_o_{HF}} &= \Delta I_{D_2} + \Delta I_{D_3} \\ &= \frac{2 D V_B}{L_o f_s} \end{aligned} \tag{24}$$

Output inductance,
$$L_o = \frac{2 D V_B}{\Delta I_{L_o_{HF}} f_s} \tag{25}$$

where $\Delta I_{L_o_{HF}}$ is the L_o high-frequency peak-to-peak current ripple, $\Delta V_{o_{HF}}$ is the high-frequency peak-to-peak output voltage ripple, and I_o is the dc current through the LED load.

VI. Design of the Simulation Prototype

A simulation prototype for a street lighting application has been developed using MATLAB/SIMULINK. The lamp is formed by 60 LW W5SG power LEDs by Osram in a series array. The load rating current is 350 mA, with an output power of 70W and a total luminous flux of 1500 lm. The load was tested at the laboratory, obtaining the following model parameters: $V_\gamma = 170$ V and $R_\gamma = 87\Omega$. The equivalent load resistance at nominal power is $R = 570 \Omega$. The selected switching frequency is 50 kHz. The line voltage is 230 Vrms with a 50-Hz line frequency. The converter must admit at least • 10% line voltage variation, assuring constant current through the load.

Using equation (10) and selecting a 45% duty cycle for the nominal operating point, a value $L_i = 1.7$ mH is calculated. Now, the operation of the L_i in DCM for the whole line voltage range must be checked. Therefore L_i is selected to be 0.5mH. The limit duty cycle for the DCM–CCM boundary is obtained from equation (9). As can be seen, DCM operation is maintained in the range 208–253 Vrms line voltage. For voltages lower than 202 Vrms, the required duty cycle will be higher than the limit duty, and the input stage will enter in CCM mode. The bus voltage varies from 240 to 366 V for DCM operation. This must be taken into consideration in selecting the bus capacitor C_B . The bus capacitance has been calculated using equation (18). The maximum bus ripple voltage appears at the lower value of the line voltage. The maximum bus peak-to-peak ripple voltage has been selected to be 5%; this is 15 Vpp approximately. Using equation (18), a value $C_B = 68 \mu F$ is obtained. The low-frequency ripple voltage transferred to the LED load is obtained from equation (19).

In this case, giving a maximum ripple voltage of 4.2%, this is around 10 Vpp. The output inductance L_o is calculated for a 50% current ripple. Using equation (25), a value $L_o = 13.5$ mH is obtained. Finally, the output capacitance C_o is designed to achieve a 0.2% high frequency current ripple through the LED load. It must be noted that the voltage and current ripples in the LED load ΔV_{LED} and ΔI_{LED} , respectively, are related by the dynamic resistance as follows:

$$\Delta V_{LED} = \Delta I_{LED} R_\gamma \tag{26}$$

Then, by using equation (26) in (22), $C_o = 52 \mu F$ is obtained for a .2% current ripple at high frequency. However, the low-frequency current ripple is much higher. It can be calculated from (20), giving a value of 33%. This means a peak-to-peak current ripple of 110 mA p-p approximately for nominal operation, which is a current crest factor of only 1.16. In addition, both capacitances C_B and C_o can be implemented using long-life film capacitors without excessive volume penalty.

VII. Simulation Results

Simulation is done on MATLAB/Simulink background

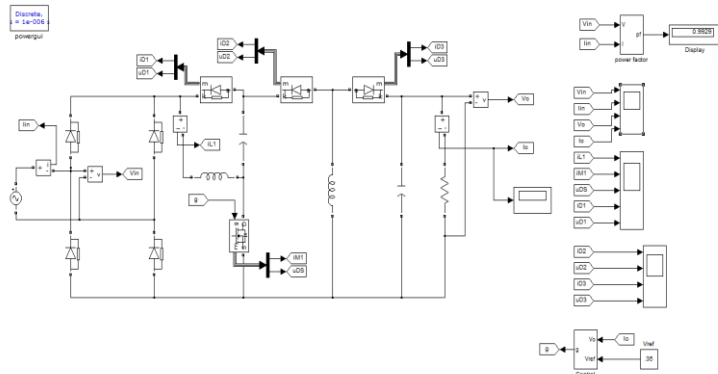


Figure 7.1: Simulated IDBB

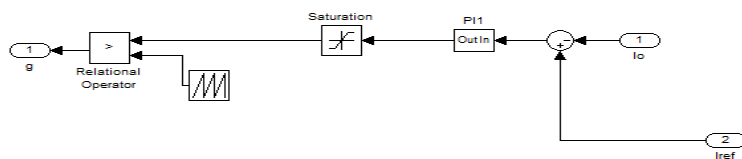


Figure 7.2: PWM signal generation subsystem

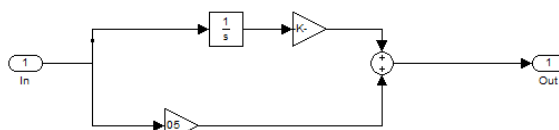


Figure 7.3: PI controller subsystem

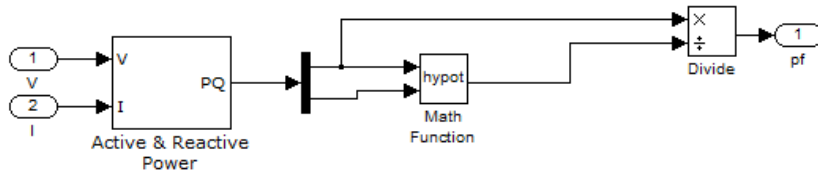


Figure 7.4: Power factor subsystem

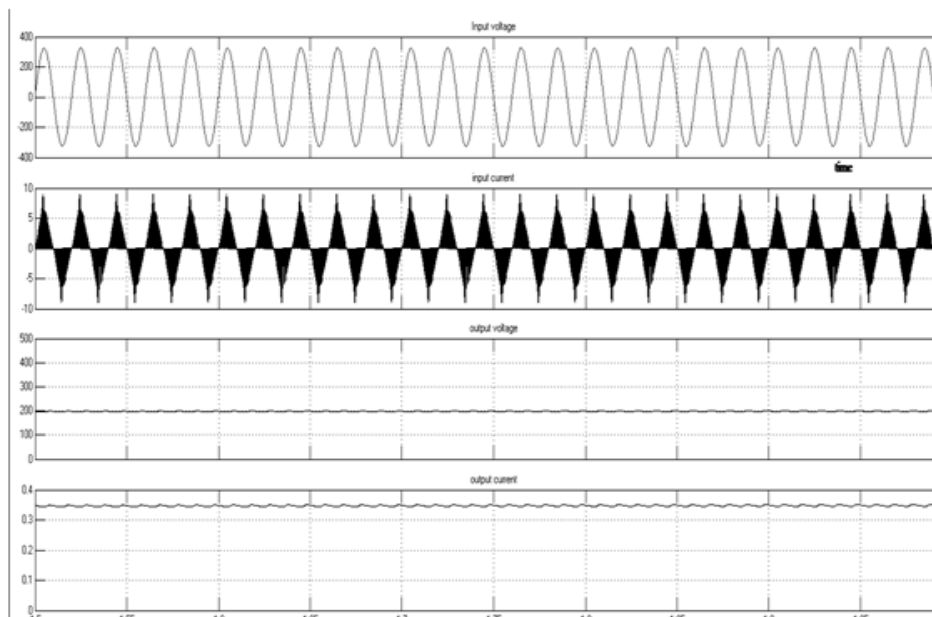


Figure 7.5: (a) input voltage (b) input current (c) output voltage (d) output current

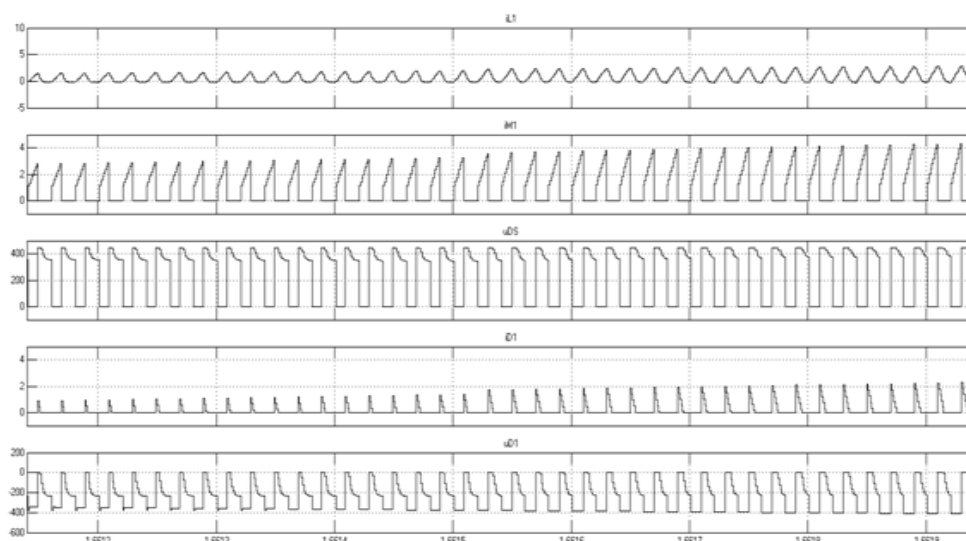


Figure 7.6: (a) current through inductor L_i (b) current through switch (c) voltage through switch (d) current through diode D1 (e) voltage through diode D1

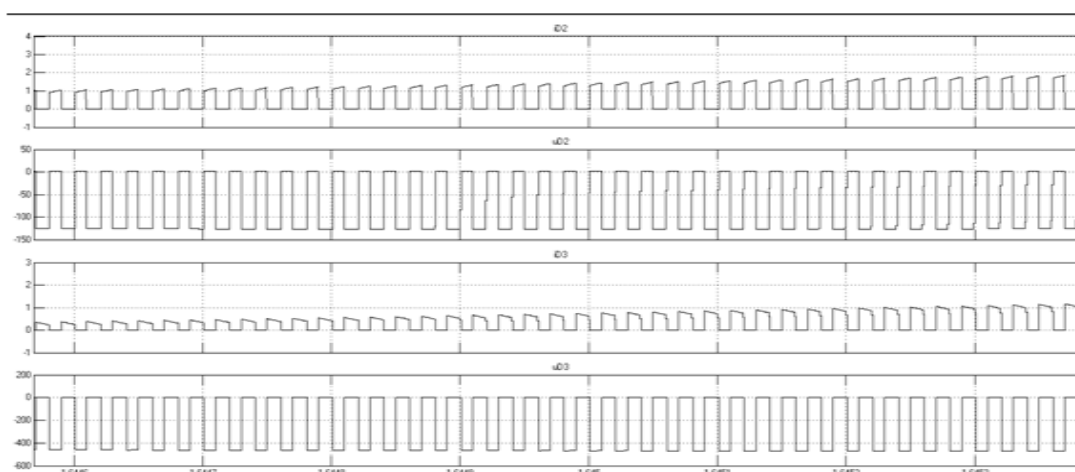


Figure 7.7:(a) current through diode D2 (b) voltage through diode D2 (c)current through diode D3 (d) voltage through diode D3

VIII. Conclusion

An IDBB converter has been investigated in this paper as a solution to implement a high-power-factor offline power supply for LED lighting applications. The topology features two buck–boost converters in cascade but using only one controlled switch. By operating the input converter in DCM, a high input PF can be obtained. On the other hand, the operation of the second stage in CCM assures a low-ripple current through the LED load without using a very high output capacitance. In this way, the converter can be implemented using only film capacitors, avoiding the use of electrolytic capacitors and increasing the converter mean time between failures.

A laboratory prototype for a 70-W solid-state lamp supplied from a 230-Vrms line voltage has been developed. Simulation results have shown that the proposed converter can provide high PF, good efficiency, and low cost.

8.1 Scope for Future Work

As a future scope, the low dimming level can be implemented by reducing the mean current through the LED lamp. It is proven that this method is more efficient compared with the PWM solution, because the LED efficiency increases for lower current values. Nevertheless, since the converter is formed by two stages integrated in a single one, its dynamics response can be made quite fast. Therefore, it is expected that a PWM dimming feature could be added for dimming frequencies up to 200–500 Hz. Also an EMI filter can be used to avoid high-frequency current circulating through the line.

In regard to galvanic isolation, the idea in this converter was to maintain it as simple as possible in order to reduce cost and achieve high efficiency. For these reasons, and taking into account that, at this moment, galvanic isolation is not required by the standards, the converter was designed without isolation. Nevertheless, it can be achieved very easily by simply including a secondary winding coupled to the output inductor. In this manner, the second stage will behave as a flyback converter instead of a buck–boost converter. The operation of the converter will be exactly the same, having just an extra design parameter given by the winding turn ratio.

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