LED Driver Circuit with Inherent PFC

D. Aguilar  
University of Minnesota  
Department of Electrical and Computer Engineering  
Minneapolis, MN 55455  
aguilarda@msn.com

C. P. Henze  
Analog Power Design, Inc.  
16220 Hudson Ave.  
Lakeville, MN 55044  
chrisapdi@charter.net

Abstract—A buck-boost topology operating in discontinuous conduction mode (DCM) is used as an off line LED driver for lighting applications. Operating from a full wave rectified ac-voltage with minimum input capacitance, with a constant switching frequency and constant on-time, the utility current has near unity power factor. This LED driver is suitable for cost sensitive applications because this circuit has a minimal parts count and a very simple control circuit. Disadvantages are that the LED drive current is modulated at twice the utility frequency and DCM operation increases component stress levels.

I. INTRODUCTION

In today's world of lighting applications everyone is striving to make a more energy efficient and cost effective way of driving a light source. One type of light source that is growing in popularity these days is the LED because of its ability to deliver a high quantity of lumens with relatively low power consumption. This interest in LEDs has prompted many power electronic designers to come up with different ways to drive these devices. If such a lighting application is going to use the standard home utility voltage as the source then the challenge the designer faces is making sure that the driving circuit is low cost, robust, and does not adversely interact with the power grid by generating non-unity power factor and harmonic distortion currents.

LED drive circuits are typically designed to control the current running through a string of LEDs independent of the voltage drop across the LED string [1-4]. This study here presents a non-conventional method for achieving the same goal of lighting a string of LEDs by using alternating current voltage source where the circuit appears as a resistive load to the utility and the LEDs are operated with a controlled current and limited current without having to use any complex feedback control loops and a minimizing the number of components that are required. An additional benefit is that the LED light output, when driven with the proposed circuit, can be dimmed using conventional phase controlled lamp dimmers which are widely used with incandescent lamps.

II. CIRCUIT CONCEPT

The simplified circuit and how it operates is shown in Figure 1. The utility voltage is full wave rectified to create the familiar pulsating dc-waveform which for a typical 120 Vrms utility would have a peak of 167 V and a frequency of 120 Hz. This fully rectified waveform does not get filtered with a large capacitor as only a small capacitor C1 of 1.0uF is placed across the output of the rectifying bridge. The sizing of this capacitor is important. The capacitor needs to be large enough to carry the switching ripple and thereby avoid putting a high frequency disturbance current back into the utility grid. The capacitor needs to be small enough to present a relatively high impedance at the utility frequency to avoid creating a leading power factor or creating harmonic distortion in the utility current in response to any harmonics that may be present in the utility voltages.

A switching frequency of 37 kHz was selected because it is well above the utility frequency, above the audio band and well below the onset of conducted emission requirements.

For the converter stage a single inductor L1 is used – this converter is similar to the conventional non-isolated buck-boost topology. The converter operates in the discontinuous conduction mode (DCM). This is because in DCM the average of the input current (switching waveform) ends up being in-phase with the input voltage. We will see this is true when the equations that govern the converter are explained. A single series-string of LEDs is present at the output - it operates at (approximately) a constant voltage when forward biased. A high-speed silicon rectifier D1 is also included as the first diode in the series string. This diode disconnects the LED from the inductor when being charged by the power switch. In practice a resistor on the order of tens of thousands of Ohms may be required in parallel with the LED string to force the reverse voltage to appear across the high-speed silicon diode D1.

Power converters typically have relatively large capacitors at the output to minimize the output ripple, however in this application an output filter capacitor is not used. This is because it is not necessary to filter the alternating current dumped by the inductor into the LEDs. The LEDs run in a switched-mode with pulsating current and therefore pulsating light output. The switching frequency (37 KHz) is far too fast for a human to see the blinking. In addition, the ripple current at the output will be varying with the 120 Hz cycle of the full rectified wave but is also too fast for the human eye to notice
the variation. The light output is proportional to the current delivered to the LED averaged over the utility period.

The inductor is sized so at the maximum allowed duty ratio and with the maximum input voltage and minimum LED voltage, the inductor current is discontinuous. For these conditions, during a portion of the switching cycle, the inductor current will be zero. The duty ratio is fixed (or slowly varying) compared to the utility period. The basic operation of this power stage portion of the circuit is that the inductor $L_1$ is charged when the switch $Q_1$ is on (just like a conventional buck-boost circuit). When the switch $Q_1$ is turned off, the inductor will discharge back to zero through the LEDs. Because the input voltage (full rectified wave) varies with time so does the peak ripple current (see Figure 2). So over one cycle the peak ripple current in the inductor will be maximum when the input voltage is maximum and likewise for the minimum peak ripple current (when the input voltage is minimum). Because the ripple current magnitude follows the input voltage and the period is not varying over the utility cycle, the instantaneous average input current is proportional to the instantaneous input voltage (shown in Figure 3). In this fashion, power factor correction is inherent in the circuit.

Figure 2 shows the details of the inductor waveforms for several different instantaneous input voltages. In Figure 2, notice the discharge rate is constant for each voltage. This is due to the simplifying assumption that the forward voltage drop of the LED string is constant and independent of the forward current. Because the discharge rate is constant the discharge time period will vary with the input voltage.

This discharge period does need to be limited in order for the inductor to discharge completely. So the duty ratio needs to be small (about 0.25 or less) in order to operate in this mode. It is also necessary that the total conduction period of the inductor, $T_{\text{L,zero}}$, be less than the switching period, $T_s$ (which is 27 micro-seconds in this case). Figure 4 illustrates this point – it is a graph of the time period $T_{\text{L,zero}}$ vs. $V_{\text{in}}$. The second portion of the switching cycle needs to be long enough so that there is enough time to discharge the inductor current completely otherwise there will be a build up of charge over the utility cycle and the waveform will not be consistent.
The instantaneous average input current is proportional to the input voltage.

The time interval in which the inductor is active and returns to zero current, \( T_{i,\text{zero}} \), is defined as a time that is equal to the sum of the charge and discharge periods of the inductor current. This time interval, \( T_{i,\text{zero}} \), also varies with input voltage over the utility cycle. See the bottom of Figure 2 for an illustration of the time interval \( T_{i,\text{zero}} \).

III. CIRCUIT ANALYSIS

Analyzing the circuit similar to the way we would analyze a standard non-isolated buck-boost converter we can derive a relationship between the input voltage \( V_{IN} \) and the peak inductor current \( i_{L,\text{peak}} \). This is done by starting with the definition of the current and voltage relationship of an inductor. In DCM the ripple current is equal to the peak ripple current of the inductor. So through derivations (not shown) the peak ripple current is equal to the following:

\[
i_{L,\text{peak}} = \frac{V_{IN} DT_s}{L}
\]

where \( D \) is the duty ratio, \( T_s \) is the switching period and \( L \) is the inductance value.

For off line applications, the input voltage will be a sinusoidal voltage with a peak value \( V_{pk} \) at a frequency \( f \). In an ideal circuit, the input current will consist of a series of triangular pulses of current of a fixed width for each switching cycle determined by the duty cycle \( D \). Averaging the input current over a number of high frequency switching cycles, the instantaneous average input current \( i_{IN(avg)} \) is given by:

\[
i_{IN(avg)} = \frac{V_{IN} \sin(2\pi f) D^2 T_s}{2L}
\]

The (average) input current is proportional to the input voltage; therefore this circuit presents a resistive load to the utility.

IV. CONTROL CIRCUIT

In a switch mode converter a gate driver circuit is needed to switch the power MOSFET Q1 on and off. This is accomplished with an oscillator that generates a saw tooth like waveform. The minimum and maximum values of this saw tooth can be set by using appropriate resistor values in the oscillator. The bias supply voltage used for these circuits is 12 volts and so the maximum value for this waveform is set to 8 volts and a minimum is set to 4 volts. The waveform’s frequency can be set by using specific resistor and capacitor values. The converter is operating at a frequency of 37 kHz. The block diagram of the control circuit shown in Figure 5 (see Appendix) uses four low cost integrated circuits—three dual comparators (LM393) and a FET driver TC4428. The latch and overcurrent detection circuit are implemented with LM393 sections. This control circuit could be implemented as a low cost application specific integrated circuit (ASIC) which could also include the power FET Q1 and the high speed switching diode D1 if a high voltage was used.

The (average) input current is proportional to the input voltage; therefore this circuit presents a resistive load to the utility.

The duty ratio can be varied (if desired) to control the brightness of the LEDs to create a dimming LED ballast. Since the duty ratio has a maximum limit, the minimum time available for the inductor to discharge into the LED string is also known. Therefore, a peak current sense circuit is also provided to prevent the inductor from being over charged (for example during an input voltage surge) to the point where the LED string could be damaged.

The peak current sense circuit operates is that the device Q1 shuts off when a current greater than 450 mA is drawn through the transistor and inductor. This operation is accomplished by putting a resistor at the source of Q1 and feeding that node into one input of a comparator. The comparator will also have a reference voltage fed into the other input, this input voltage will be proportional to the peak current limit. Whenever the current through the switch Q1 reaches currents of 450 mA or greater the voltage at the source of Q1 goes low, shutting off Q1.
V. SIMULATION RESULTS

The circuit was simulated with an AC voltage source as shown in Figure 6. The switch Q1 is replaced with a voltage controlled switch and the overcurrent detection circuit is not included. The input voltage is the standard utility voltage of 120 Vrms at 60 Hz. The simulated input current waveform is shown along with the input voltage for one half of the utility cycle in Figure 7. It can be seen that the peak value of the inductor current is proportional to the input voltage. The triangular shape of the input current pulses is shown in Figure 8 where the simulation results near the zero crossing are displayed. The inductor current and voltage when operating near the peak of the line are shown in Figure 9.

VI. EXPERIMENTAL RESULTS

The LED driver circuit was tested initially with a dc power supply in place of the utility at the input as shown in Figure 10. This allows measurements of the circuits operation under steady state conditions over the range of dc-input voltages that are encountered during ac-operation. One important note that should be mentioned about the experiment results is that a series string of twenty Zener diodes (5 Watt, 3.3V, 1N5333) in reverse bias at the output instead of a LED array. This was done to avoid damaging the costly LEDs during testing. The Zener diode string is indicated in Figure 10.

The screen captures of the DC measurements show that the circuit behaves as expected. Figure 11 shows several captured waveforms when the input voltage was set at approximately 80 volts and the output is driving a 70-Volt series string of Zener diodes. The operation is at fairly light load. The oscilloscope is set for a quad display mode so each waveform can be displayed separately while using a large portion of the available vertical input. The vertical scale is for each “tick” on the center graticule. Channel 4 (green) is the gate drive pulse (at 5V per division) at the gate of the power transistor Q1. The duty ratio is measured at 19.3%. The waveform of Channel 2 (magenta) is the inductor current at 50mA per division. The peak inductor current is 170mA and the average inductor current is measure to be 35mA. The inductor current waveform shows that the inductor is charging and discharging linearly as expected. Furthermore, the inductor current is zero for a portion of each switching cycle indicating that the circuit is operating well into the DCM mode. The waveform of Channel 1 (yellow) is the voltage across the output Zener diode string that is used to simulate the LEDs. The output voltage during the discharge is approximately constant at 70 volts, although, the voltage does sag as the current becomes lighter. When the current goes to zero, the output voltage collapses. The output power is calculated by multiplying the inductor current waveform by the output voltage waveform and is displayed as Waveform A (orange) at 5 Watts per division. The oscilloscope is also
Figure 10. Test set up using Zener diodes in place of the LEDs.

Figure 11. Experimental Waveforms when operating at light load with an 80Vdc input.

Figure 12. Measured input impedance of the LED Driver as a function of input voltage. For a unity power factor, a constant input impedance is required which is independent of input voltage.

Figure 13. Measured input current and input voltage when operating on 120Vrms ac-voltage.

Figure 14. Measured input voltage and current near the zero crossing of the utility voltage waveform.

calculating the average output power at 1.2 Watts. The switching frequency is measured at 37.7kHz.

The input impedance of the converter is calculated from a measurement of the average (dc-) input current with a digital multi-meter as a function of the input voltage. The input impedance as a function of input voltage is plotted in Figure 12. This plot shows that the input impedance in nearly constant and independent of the input voltage. This is the condition that will result in a power factor near unity when operating on from an AC source.

In Figure 13, input current waveform (Channel 2 at 100mA per division) is shown along with the input voltage waveform (Channel 1 at 50V per division). This current is measured on the converter side of the input capacitor C1 and contains a large switching ripple. In Figure 14, the same waveforms are shown near the zero crossing.

609
VII. CONCLUSIONS

Our conclusion is that the circuit does indeed operate successfully. We have showed that this simple LED driver circuit, operating in DCM, provides power factor correction in an open loop mode. The converter operates with pulsating current, at the output, rather than with constant current, this reduces the component count and cost of the circuit compared to a conventional PFC (which uses complex feedback control). This also causes high peak stress in the power components.

VIII. REFERENCES


IX. APPENDIX DETAILED SCHEMATIC