A single-stage voltage sensorless power factor correction converter for LED lamp driver

Mahmoud S. Abd El-Moniem a,*, Haitham Z. Azazi b, Sabry A. Mahmoud c

a Petroleum Marine Services Company, Alexandria, Egypt
b Department of Electrical Engineering, Faculty of Engineering, Menoufia University, Egypt
c Faculty of Engineering, Menoufia University, Egypt

Received 23 April 2013; revised 16 July 2013; accepted 18 July 2013
Available online 20 August 2013

Abstract Light-emitting diode (LED) technology presents an effective and robust solution to decrease the energy demand. In this paper, a power factor correction (PFC) converter is proposed to solve the problems that appear when using LED lamps, such as reducing harmonic currents and reshaping the input current to be a sinusoidal waveform without using line voltage sensor, so the total cost can be reduced and increasing the efficiency. Thus, this technique is considered a simple and easy method which reduces the number of sensors required and achieves the noise isolation between the power circuit and the controller. Also, the proposed method is implemented using a zero-crossing processing, which allows a greater accuracy than other methods. Simulation and experimental results demonstrate the effectiveness and feasibility of the proposed circuit which show that the proposed control method has low inrush input current, high power factor (near unity), and fast dynamic response under transient operation. Also, a sinusoidal current waveform under a non-sinusoidal input voltage condition can be achieved.

© 2013 Production and hosting by Elsevier B.V. on behalf of Faculty of Engineering, Alexandria University.

1. Introduction

While Edison is credited with the development of the first commercially practical incandescent lamp in order to improve the lifestyle, conventional lighting sources have low efficiency and high energy consumption [1]. One of the key motivations for the recent development in LED lighting is the possibility for increasing efficiency and light output. LEDs are gradually replacing the conventional lighting sources due to their numerous advantages such as [2–4]:

- High efficiency which can emit more light per watt than incandescent lamps.
No ultra-violet (UV) or infrared (IR) output.

- Have a relatively long useful life, c. 100,000 h which is more than 10 times that of compact fluorescent lamps (CFLs).
- Can very easily be dimmed either by pulse-width modulation or lowering the forward current.
- LED lamp module is composed of many LEDs, when one LED fails there are many more for back-up.
- They can be dimmed smoothly from full output to off.
- Extremely robustness, those are difficult to damage with external shock, unlike conventional lamps, which are fragile.
- Small in size.
- No external reflector.

Like conventional PN junction diodes, LEDs are current-dependent devices with their forward voltage drop $V_F$, depending on the semiconductor compound (their light color) and on the forward biased LED current. Fig. 1 presents the $I$–$V$ characteristic curves showing the different colors available [5].

LEDs are operated from a low voltage DC supply. In general lighting applications, the LED lamps have to operate from universal AC input, so an AC–DC converter is needed to drive the LED lamp [6]. The efficient drive not only performs unity power factor (PF), but also regulates LED current [7].

The rectifier with filter capacitor is called a conventional AC–DC utility interface. Although a filter capacitor significantly suppresses the ripples from the output voltage, it introduces distortions in the input current and draws current from the supply discontinuously, in short pulses [8]. This introduces several problems including reduction in available power, and the line current becomes non-sinusoidal which increases the total harmonic distortion (THD) and increases losses. This results in a poor power quality, voltage distortion, and poor PF at input ac mains [9–11].

With the development of PFC converters, a sinusoidal line current can be made in phase with the line voltage, and this PFC circuit achieves the requirements of the international harmonic standards. For all lighting products and input power higher than 25 W, AC–DC LED drivers must comply with line current harmonic limit set by IEC61000-3-2 class C [12]. Single-stage PFC topologies are the most suitable converters for lighting applications, as PFC and regulator circuits can be merged together. They have high efficiency, a near unity PF, simple control loop, and a small size. In reality, the switching frequency is much higher than the line frequency, and the input AC current waveform is dependent on the type of control being used [13]. The inductor is assumed to be operated in continuous conduction mode (CCM) which is implemented using hysteresis current control method. Operation is possible throughout the line-cycle, so the input current does not has harmonic distortions [14,15].

There are various PFC control algorithms using input voltage sensorless approach [16–19]. A simple control method using current law has been described in [16,17] by using only an instantaneous input current and a proportional gain in controlling the dc link voltage constantly. However, these methods did not take in consideration the current compensation, so stable operation in the transition state and protect devices from overcurrent cannot be achieved. Nonlinear-control methods [18,19] provided good solutions to implement the control integrated circuit (IC) design effectively without using input voltage sensor. However, the output voltage regulation will be affected due to lack of input voltage information.

In this paper, boost PFC converter is used to drive LED lamps from universal AC supply due to its advantages such as [20–22]: (a) simple structure; (b) the input inductor can suppress the surging input current; and (c) the power switch is non-floating, so it is easy to design the driver circuit. An algorithm of PFC control is proposed without using line voltage sensor. The input voltage is estimated using the sensed inductor current and output voltage, which make the proposed method more simple and reliable than other methods.

---

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>ideal resistance</td>
</tr>
<tr>
<td>$L$</td>
<td>boost inductor</td>
</tr>
<tr>
<td>$D$</td>
<td>diode</td>
</tr>
<tr>
<td>$S$</td>
<td>MOSFET (Switch)</td>
</tr>
<tr>
<td>$V_s$</td>
<td>supply voltage</td>
</tr>
<tr>
<td>$i_s$</td>
<td>supply current</td>
</tr>
<tr>
<td>$V_{ph}(t)$</td>
<td>the rectified voltage</td>
</tr>
<tr>
<td>$V_{in}(t)$</td>
<td>the estimated input voltage</td>
</tr>
<tr>
<td>$i_l$</td>
<td>inductor (rectified) current</td>
</tr>
<tr>
<td>$i_{ref}$</td>
<td>reference current</td>
</tr>
<tr>
<td>$V_{ref}$</td>
<td>reference voltage</td>
</tr>
<tr>
<td>$V_{control}$</td>
<td>the controlled scaling factor of the rectified voltage</td>
</tr>
<tr>
<td>$V_{rms}$</td>
<td>RMS value of the input voltage</td>
</tr>
<tr>
<td>$V_o$</td>
<td>load voltage</td>
</tr>
<tr>
<td>$V_o(mean)$</td>
<td>mean load voltage</td>
</tr>
<tr>
<td>$I_o$</td>
<td>load current</td>
</tr>
<tr>
<td>$V_F$</td>
<td>forward voltage drop for LED lamp</td>
</tr>
<tr>
<td>$\omega_{line}$</td>
<td>angular line frequency</td>
</tr>
</tbody>
</table>

---

![Figure 1](image-url)  
*Figure 1  $I$–$V$ characteristics curves for different colors available.*
2. PFC control for LED lamp

Fig. 2 illustrates the boost PFC converter based on hysteresis current mode control for LED lamp driver. In the outer voltage loop, the error between the sensed output voltage and the voltage reference is the output of the proportional-integral (PI) voltage controller. The output of this PI controller is the scaling factor for the rectified voltage \( v_{\text{control}} \). The product of the scaling factor and the rectified voltage divided by the square of the root mean square (RMS) of input voltage is the reference current, \( i_{\text{ref}} \), as in Eq. (1). The inner current loop implements hysteresis current mode control to force the inductor current to follow the reference current [23].

\[
i_{\text{ref}} = \frac{v_{\text{control}} \cdot V_{\text{in}}(t)}{V_{\text{rms}}^2}
\]

The principle of hysteresis control is controlling the switches to be on or off as necessary to force the inductor current waveform to follow the sinusoidal reference within a given hysteresis band [24].

In boost PFC converter based on hysteresis current mode control, the inductor current is continuously compared with the reference current waveform to make the inductor current always within the upper and lower band. The error signal between the inductor and reference currents is fed to a hysteresis comparator. When the actual inductor current \( i_l \) goes above the reference current \( i_{\text{ref}} \) by the hysteresis band comparator, the current ramp goes down by changing the comparator state to make the boost converter switch to be off. When the actual current goes below the reference current by the hysteresis band comparator, the current ramp goes up by changing the comparator state again to make the boost converter switch to be on [24,25].

During operation of a boost converter in CCM, the inductor current \( i_l \) never becomes zero during a commutation cycle.

3. Proposed PFC control technique

This technique proposes a PFC control without using line voltage sensor to achieve a near unity PF for single phase rectifier. In boost PFC, shown in Fig. 2, the line voltage is sensed then rectified using absolute unit to the rectified voltage, \( V_{\text{in}}(t) \).
that is one of the inputs to the multiplier to have the reference current \((i_{ref})\) as in Eq. (1). In the proposed PFC, the rectified voltage can be estimated without using line voltage sensor depending on the sensed inductor current and output voltage as follows:

The boost converter assumes two distinct states [23,26]:

The on-state, in which the switch \((S)\) in Fig. 2, is closed, and then, there is a constant increase in the inductor current.

So the estimated input voltage \(\hat{V}_{in}(t)\) can be obtained as:

\[
\hat{V}_{in}(t) = L \frac{di_l}{dt}
\]  

(2)

The off-state, in which the switch \((S)\) in Fig. 2, is made open and the inductor current now flows through the diode \(D\), the capacitor \(C\), and the load (LED string). In this state, the energy that has been accumulated in the inductor transferred to the capacitor and LED String.

So the estimated input voltage \(\hat{V}_{in}(t)\) can be obtained as:

\[
\hat{V}_{in}(t) = V_o + L \frac{di_l}{dt}
\]  

(3)

After that, the estimated input voltage is fed to a zero-crossing detector, and the output of this detector is fed to sine wave look up table which provide a rectified input voltage with a unity amplitude. The proposed control method without using line voltage sensor is shown in Fig. 3.

The zero-crossing detector is used with the proposed control method in order to achieve a good performance under distorted supply voltage. While the supply voltage has a distortion waveform, the zero-crossing detector does not affected with the shape of supply voltage waveform, so a sine wave voltage waveform with unity amplitude can be achieved even a non-sinusoidal supply voltage waveform is used, so this approach has a simple control compared with other methods.

4. Simulation results

The control algorithm of the proposed control method has been developed and simulated using the MATLAB/SIMULINK software. The simulation allows investigation of both transient and steady-state operations for the proposed method which can also show the reducing in supply current harmonic distortion. The system parameters are reported in Appendix A.

The steady-state supply voltage \((V_s)\) and the supply current \((i_s)\) waveforms are shown in Fig. 4. It is clear that the input current is in phase with the input voltage for boost PFC converter without using line voltage sensor.

The steady-state simulation results of input current and its harmonic spectrum for hysteresis current control method are
shown in Figs 5 and 6, respectively. From these results, it is clear that the input current is nearly sinusoidal, and its total harmonic distortion is very low, 3.83%, and the PF is 0.9992.

The rectified voltage ($V_{\text{in}}$), the rectified current ($i_l$), and the reference current ($i_{\text{ref}}$) simulation waveforms are shown in Fig. 7. Simulation shows clearly that the rectified current is always very close to the reference current for proposed method.

The load voltage and current waveforms are shown in Fig. 8, which illustrate the very small ripples in both of them that do not have any effect on LEDs operation.

The steady-state supply voltage ($V_s$) and current ($i_s$) waveforms for the proposed method under distorted input voltage are shown in Fig. 9. It is shown that the input current has a sinusoidal waveform and being in phase with the input voltage without using line voltage sensor.

The simulation results of supply voltage and current due to ±25% step change in the input voltage for the proposed control method, without using line voltage sensor, are shown in Figs. 10 and 11, respectively. It is clear that a sinusoidal input current waveform is maintained under the input voltage changes.

The simulation results of load voltage and current due to ±25% step change in the input voltage for the proposed method are shown in Figs. 12 and 13, respectively. As seen from these figures, the decrease in the input voltage makes an increase in the line current and vice versa because the power is constant. The change in load voltage and current due to the change in the input voltage has a small duration (about 0.05 s), and then, the load voltage and current return to their initial steady-state values. Also, the error in load voltage due
Figure 11  Variation in supply current due to ±25% step change in the input voltage.

Figure 12  Variation in load voltage due to ±25% step change in the input voltage.

Figure 13  Variation in load current due to ±25% step change in the input voltage.

Figure 14  Error in load voltage due to ±25% step change in the input voltage.

Figure 15  Variation in load voltage and current due to negative and positive step change in reference voltage.

Figure 16  Error in load voltage due to negative and positive step change in reference voltage.
to ±25% step change in input voltage is shown in Fig. 14 which indicates that the proposed PFC control method has a fast response.

The variation in load voltage and current due to negative and positive step change in reference voltage (from 60 V to 56 V) is shown in Fig. 15 without using line voltage sensor. It is observed that the load current follows the load voltage which follows the desired reference voltage, so the dynamic responses of load voltage and load current for negative and positive step change in reference voltage are fast. Also, the error in load voltage due to negative and positive change in reference voltage (from 60 V to 56 V) is shown in Fig. 16 which indicates the fast response for the proposed PFC control method under these variations in reference voltage.

5. Experimental results

With the objective of evaluating the employed topology, a laboratory prototype is setup. The block diagram of the experimental setup and a real view of the complete control system are shown in Figs. 17 and 18, respectively. The main components of the system which labeled as in Fig. 18 are listed in Table 1. The proposed PFC control is done on a digital signal processor board (DS1104) plugged into a computer. The control algorithm is executed by “Matlab/simulink,” and downloaded to the board through host computer. The output of the board is logic signal, which is fed to IGBT through driver and isolation circuits.

5.1. LED lamp driver without PFC circuit

The experimental results of supply voltage and the supply current waveforms in steady-state in case of using single phase rectifier without PFC circuit to drive the LED lamps are shown in Fig. 19. It is illustrated from this figure that the high distorted input current has peak value in short duration, and there are voltage dips in the supply voltage due to the high value of input current.

The experimental results of the harmonics spectrum of the supply current and voltage are shown in Figs. 20 and 21, respectively. It is observed that the supply current has a high THD of 87.94% with a low PF of 0.75, and the supply voltage has THD of 6.6% as using single phase rectifier without PFC circuit to drive LED lamps.

The experimental results of the load voltage and current waveforms are shown in Fig. 22. It is observed that the load voltage and load current has a nearly DC value with a small ripples.

5.2. LED lamp driver with PFC circuit using proposed control technique

The steady-state experimental results of the supply voltage and supply current for single phase rectifier with PFC circuit
without using line voltage sensor to drive LED lamps are shown in Fig. 23. It is shown that the supply current has a nearly sinusoidal waveform, and it is in phase with the input voltage.

The experimental result of the harmonics spectrum of the supply current is shown in Fig. 24. It is indicated that, with using PFC circuit using proposed control technique, the input current has a low harmonic contents (THD) of 7.77% with high PF of 0.996.

The experimental results of the rectified current and reference current under the steady-state for the proposed method are shown in Fig. 25. It is observed that the rectified current is very close to reference current.

The steady-state experimental results of the load voltage and current are shown in Fig. 26. It is clear that the load voltage and current has a DC value with very small ripples and the LED lamps do not affected with these ripples.

The experimental results of the variation in the load voltage and load current due to negative step change in reference voltage (from 60 V to 55 V) and positive step change in reference voltage (from 60 V to 65 V) are shown in Fig. 27. It is shown that the load voltage follows the desired reference voltage, and hence, the load current follows the load voltage.

The experimental results of supply voltage and current due to ±25% step change in the input voltage for the proposed

Table 1

<table>
<thead>
<tr>
<th>Label</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Personal computer</td>
</tr>
<tr>
<td>I</td>
<td>DSP interface circuit</td>
</tr>
<tr>
<td>B</td>
<td>Base drive circuit</td>
</tr>
<tr>
<td>P.S.</td>
<td>All other power suppliers</td>
</tr>
<tr>
<td>P</td>
<td>Variable AC power supply</td>
</tr>
<tr>
<td>T</td>
<td>Single phase full wave bridge rectifier</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Voltage and current transducers</td>
</tr>
<tr>
<td>R</td>
<td>Load (LED lamps)</td>
</tr>
<tr>
<td>C</td>
<td>Capacitor</td>
</tr>
<tr>
<td>L</td>
<td>Inductor</td>
</tr>
<tr>
<td>D</td>
<td>Fast recovery diode</td>
</tr>
<tr>
<td>S</td>
<td>IGBT</td>
</tr>
</tbody>
</table>

Figure 19  Supply voltage and current waveforms.

Figure 20  Harmonics spectrum of supply current.

Figure 21  Harmonics spectrum of supply voltage.

Figure 22  Load voltage and current waveforms.
control method are shown in Figs. 28 and 29, respectively. It is clear that a sinusoidal input current waveform is maintained under the change in supply voltage, which is illustrated in the zoom of the variation in the supply voltage and current (from 0.95 to 1.2 s) under ±25% step change in the supply voltage as shown in Fig. 30.

The experimental results of load voltage and current due to ±25% step change in the input voltage for the proposed
The change in load voltage and current due to the change in the input voltage has a small duration then the load voltage and current return to their initial steady-state values. Also, the error in load voltage due to a 25\% step change in input voltage is shown in Fig. 32 which indicates that the proposed PFC control method has a fast response.

6. Conclusions

In this paper, a new control technique without using line voltage sensor to drive the LEDs current and produces high PF has been presented. This technique is characterized by its simplicity and its reliability to estimate the rectifier voltage compared with other PFC control algorithms. Also, a low cost digital controller can be used. The rectifier voltage is estimated based on sensed inductor current and output voltage. Simulation results showed that the boost PFC converter without using line voltage sensor has a nearly sinusoidal input current with low THD and high PF. Also a nearly sinusoidal input current can be achieved under supply voltage distortion. Also from these results, a better and accurate performance can be achieved due to use a zero-crossing detector. Better dynamic performance for positive and negative change in the input and reference voltages can be achieved. Performance of the proposed control technique was verified experimentally. The experimental results have approved that, the simulation results which have been illustrated by using AC–DC converter with PFC without using line voltage sensor to drive the LED lamps have a nearly sinusoidal input current waveform with low THD and high PF. Besides, a fast dynamic performance for step change in the input and reference voltages can be achieved. So, these experimental results have assured that the proposed control technique is good. There are slight differences between the simulation and experimental results because in simulation results the supply voltage has an ideal sine waveform but, in experimental results supply voltage is not ideal sine waveform. Also, the simulation results are done with sampling time 1e^{-5} s. But, the experimental results are done with dSPACE (DS1104) using sampling frequency 10 kHz (sampling time is 1e^{-4} s).
Appendix A

The simulation and the experimental results for the proposed method are taken with the following specifications:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply nominal voltage</td>
<td>$V_s$</td>
<td>220 Vrms</td>
</tr>
<tr>
<td>Line frequency</td>
<td>$f$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Step down voltage</td>
<td>$V_r$</td>
<td>220/24 Vrms</td>
</tr>
<tr>
<td>Inductor</td>
<td>$L$</td>
<td>3 mH</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>$C$</td>
<td>3000 μF</td>
</tr>
<tr>
<td>LEDs power</td>
<td>$P_o$</td>
<td>60 W</td>
</tr>
<tr>
<td>Load voltage</td>
<td>$V_o$</td>
<td>60 Vdc</td>
</tr>
<tr>
<td>Load current</td>
<td>$I_o$</td>
<td>1 Adc</td>
</tr>
</tbody>
</table>

Load contains three parallel branches, each branch has 19 LEDs and the current in each LED is 350 mA.

References

[12] Compliance Testing to the IEC 1000-3-2 (EN 61000-3-2) and IEC 1000-3-3 (EN 61000- -3) Standards, Application Note 1273, Hewlett Packard Co., December 1995.