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ORIGINAL ARTICLE

A current sensorless power factor correction control for LED lamp driver

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Zero-crossing detector

Abstract This paper proposes a new control technique to achieve a unity power factor at the input AC supply for light-emitting diode (LED) lamps controlled by AC–DC converter, without using a current sensor. Only two analog to digital converters (ADCs) for measuring the input and output voltages are used. This technique achieves isolation between power circuit and controller; it can be implemented by using a zero-crossing processing, which has a greater accuracy than other techniques. Simulation and experimental results illustrate the effectiveness and feasibility of the proposed control technique, which achieves low harmonic contents in the supply current, a near unity power factor (PF), a sinusoidal current waveform, and a fast dynamic response under transient operation.

1. Introduction

Today artificial lighting is a critical part of modern life. However, traditional methods of lighting such as fuel-based and incandescent lighting are highly inefficient. Therefore, the use of these products is being phased out across the industrialized world as in the European union [1]. Energy saving is becoming increasingly important, given that easily accessible energy resources are becoming scarce. Fluorescent tubes and compact fluorescent tubes (CFLs) have decreased the energy demand for lighting. Technology has yielded a surprising new lighting source which is LED lamps that are different from the traditional incandescent lamps, which use filaments to generate heat radiation, and fluorescent lamps, which use gaseous discharging. LED lamps present an effective and robust solution to replace the traditional lighting sources due to their advantages such as [2–4]:

- High luminous efficiency.
- Extremely long life, c.100,000 h.
- Extreme robustness because there are no glass components or filaments.
- No external reflector.

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Nomenclature

L	boost inductor
D	diode
S	MOSFET (Switch)
V_s	supply voltage
i_s	supply current
$V_{in}(t)$	the rectified voltage
i_l	inductor (rectified) current
$\hat{i}_l(t)$	the estimated inductor current
i_{ref}	reference current
V_{ref}	reference voltage
$v_{control}$	the controlled scaling factor of the rectified voltage
V_{rms}	RMS value of the input voltage
V_o	load voltage
$V_{o(mean)}$	mean load voltage
I_o	load current
t_k	sampling time
ω_{line}	angular line frequency

- LED lamp module is composed of many LEDs; when one LED fails, there are many more for back-up.
- Can be very easily dimmed either by pulse-width modulation or lowering the forward current.
- No ultra-violet (UV) or infra-red (IR) output.

LEDs have many superior characteristics and effective applications in background lighting, displays, street lighting, and so on. Today, LEDs are available in various colours and are also suitable for white illumination.

The LED driven by the AC source has the same flicker problem as that of the traditional lamp to which the human being is negligibly sensitive. Furthermore, if all LEDs are packaged into a single chip, the brightness is more focused and the flicker problem will be more reduced than ever [5,6].

LEDs can be operated from a low-voltage DC supply. In general, lighting applications, the LED lamps have to operate from a universal AC input. Therefore, an AC–DC converter is needed to drive the LED lamp [6]. The LED brightness is strongly dependent on its current, so an efficient control is needed to regulate the LED current. The efficient driver not only performs unity PF, but also regulates the LED current [7]. There are various LED driving circuits with AC–DC converters, which are discussed in Refs. [8,9].

Most of the applications that require AC–DC power conversion need the output DC voltage to be well regulated with good steady-state and transient performances. The rectifier with a filter capacitor is cost effective, but it severely degrades the quality of the supply, thereby affecting the performance of other loads connected to it besides causing other problems. Although, a large electrolytic capacitor suppresses the ripple from the output voltage, it introduces distortions to the input current and draws inrush current from supply [10]. This introduces several problems, including a reduction of available power; the line current becomes non-sinusoidal which increases THD, and increases losses. This results in poor power quality, voltage distortion, and poor PF at input AC mains [11].

With the deployment of non-linear loads, such as switched mode power converters, standards agencies around the world are developing requirements for harmonic contents of electronic power conversion systems to reduce the overall distortion on main supply lines. Input current can be reshaped to be a sinusoidal waveform which can be in phase with the line voltage; the losses can be decreased and hence, a nearly unity PF can be achieved. For all lighting products and input power higher than 25 W, AC–DC LED drivers must comply with the line-current harmonic limits set by IEC61000-3-2 class C [12] as illustrated in Table 1.

Table 1

Harmonic order (n)	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency (%)
2	2
3	30 $*$ circuit power factor
5	10
7	7
9	5
$11 \leqslant n \leqslant 39$	3

Single-phase PFC is an active research topic in power electronics because of the high power quality requirement, and significant efforts have been made on the developments of PFC converters. In these converters, the main effort is devoted to the quality of the input current waveform while, simple single switch topologies like boost converter as used in the proposed work, the dynamic response of the output voltage is sacrificed [13]. The inductor is assumed to enter the continuous conduction mode (CCM) operation which is implemented using hysteresis current control method. Operation is possible throughout the line-cycle, so the input current does not have harmonic distortions [14,15].

Classic PFC techniques usually need to sense the input and output voltages, and the input current. Sensing the input current is not a trivial issue. It is a common practice to utilize a resistive sensor, but it is the most problematic and expensive of the three usual sensors because it generates power losses, and heat must be evacuated. Besides, in the case of digital control, the voltage through the resistor should be digitized with an ADC and the input current frequency is equal to the switching frequency. Hence, this ADC used for sensing the input current should have been higher sampling frequency than the ADCs used for the input and output voltages, which change at the line frequency and can be low cost ADCs. There are various PFC control algorithms using a current sensorless approach. Current prediction is proposed to enhance the power section performance in Refs. [16,17]. In Ref. [18], a power factor correction without current sensor based on digital current rebuilding has a complicated mathematical calculation and the supply current has a distorted waveform and is not perfectly in phase with the input voltage. In Ref. [19], a current-sensorless digital controller for active power factor correction-based on Kalman filters has more mathematical calculations and the input current waveform is not a nearly sinusoidal waveform. A simple control method using current law has been described in [20,21] by using only an instantaneous input current and a proportional gain in controlling the DC link voltage constantly. However, these methods did not take into consideration the current compensation. Therefore, stable operation in the transition state and protecting devices from overcurrent cannot be achieved.

In this paper, a boost PFC converter is being used in the proposed technique. The simplicity of the circuit configuration and the control structure mean that no regeneration back to the power supply is necessary. Besides, the input inductor can suppress the surging input current, and the power switch is non-floating, so it is easy to design the driver circuit. The main novelty of the proposed technique is that, there is no current sensor used, which can help to reduce the total cost. The input current is estimated using two ADCs for sensing input and output voltages, which makes this proposed technique simpler and more reliable than other techniques. Also, a zero-crossing detector is used to make the proposed technique more accurate than other techniques, especially in transient operations, and when using distorted supply voltage, the input current has a sinusoidal waveform.

2. PFC control for LED lamp

The boost PFC converter-based on hysteresis current mode control is illustrated in Fig. 1. In the outer voltage loop, the error between the sensed output voltage and the reference voltage becomes the input of the proportional-integral (PI) voltage controller. The output of this PI controller is the scaling factor for the rectified voltage (v_{control}). The product of the scaling factor and the rectified voltage divided by the square of the root mean square (RMS) of the input voltage is the reference current (i_{ref}), as in Eq. (1). The inner current loop implements hysteresis current mode control to force the inductor current to follow the reference current [22].

$$i_{\text{ref}} = \frac{v_{\text{control}} \cdot V_{\text{in}}(t)}{V_{\text{rms}}^2} \tag{1}$$

In boost PFC converter-based on hysteresis current mode control, the inductor current is continuously compared to the reference current waveform which is obtained from the voltage

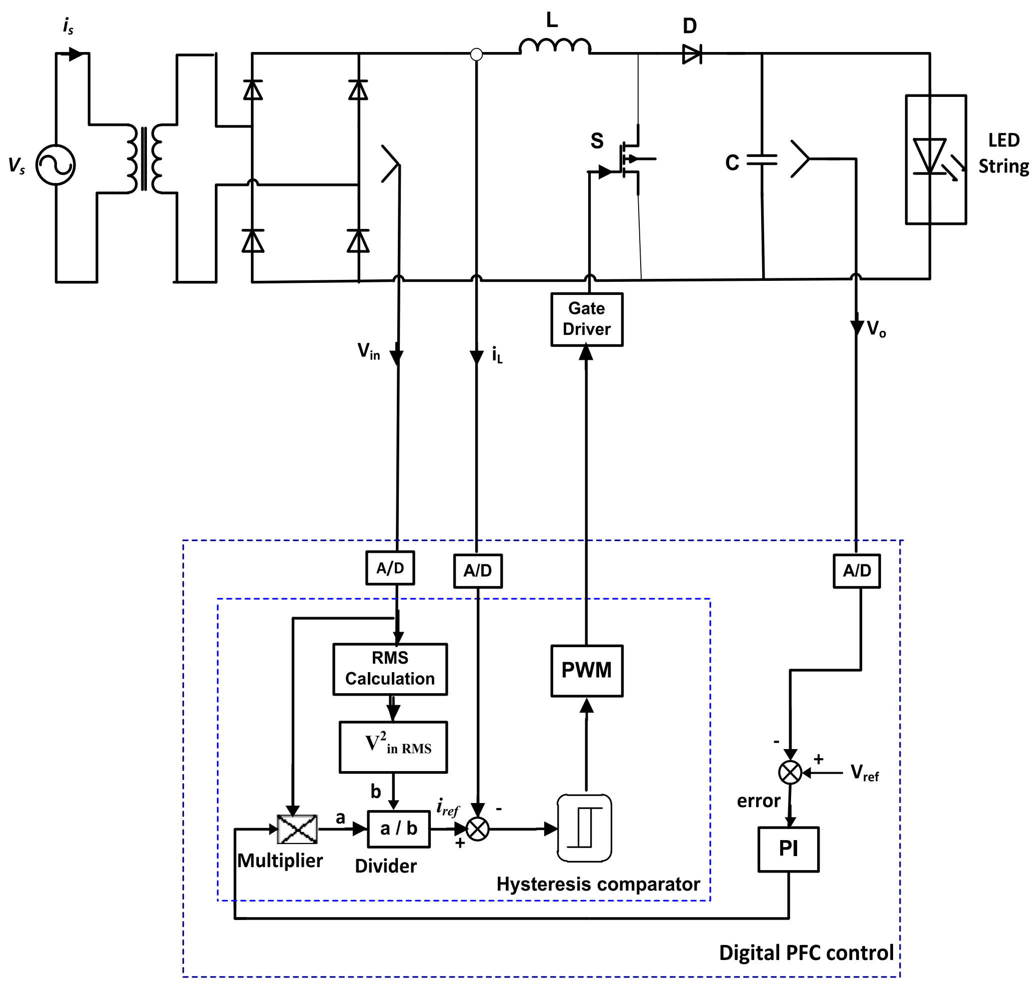

Figure 1 Boost PFC-based on hysteresis current mode control.

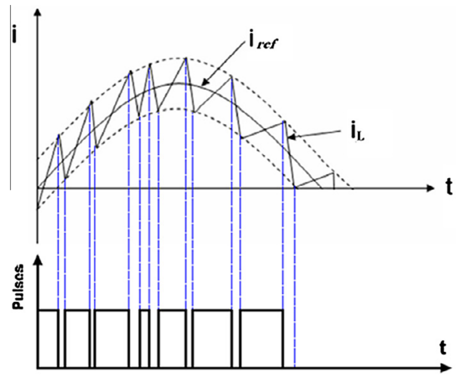

Figure 2 Rectified current (i_L), reference current (i_{ref}) waveforms and pulses of boost PFC with hysteresis control.

control loop and the error signal is fed into a hysteresis comparator to make the inductor current always within the upper and lower band. There are two distinct states of the hysteresis comparator [22,23] as shown in Fig. 2:

1. When the actual inductor current (i_l) goes above the reference current (i_{ref}) by the comparator hysteresis band, the current ramp goes down by changing the comparator state to make the boost converter switch off.
2. When the actual current goes below the reference current by the comparator hysteresis band, the current ramp goes up by changing the comparator state again to make the boost converter switch on.

3. Proposed control technique

The technique proposes a voltage control for LED lamp without using current sensor to achieve a near unity power factor. The inductor current $i_l(t)$ is sensed in order to be compared to the reference current i_{ref}. The difference between them is an input to the hysteresis comparator which generates pulses to switch (S). The inductor current can be obtained without using a current sensor depending on the sensed input and output voltages as follows:

The boost converter has two distinct states:

1. The On-state, in which the switch (S) in Fig. 1 is closed. The estimated inductor current $\hat{i}_l(t)$ can be expressed as:

$$l\frac{d\hat{i}_l}{dt} = v_{\text{in}}(t) \tag{2}$$

2. The Off-state, in which the switch (S) in Fig. 1 is made open. The estimated inductor current $i_l(t)$ can be expressed as:

$$l\frac{d\hat{i}_l}{dt} = v_{\text{in}} - V_0 \tag{3}$$

By integrating the two states, the estimated inductor current $\hat{i}_l(t)$ can be obtained. Also, the input voltage is fed to a zero-crossing detector; the output from this detector is fed to the sine wave look up table, so the rectified input voltage with unity amplitude can be achieved. The schematic diagram of the proposed control technique without using current sensor is shown in Fig. 3.

The zero-crossing detector is used with the proposed technique in order to achieve accurate control under transient operation, so this approach has a simple control compared to other techniques.

4. Simulation results

The proposed control technique has been simulated using the MATLAB/SIMULNK software. The simulation program

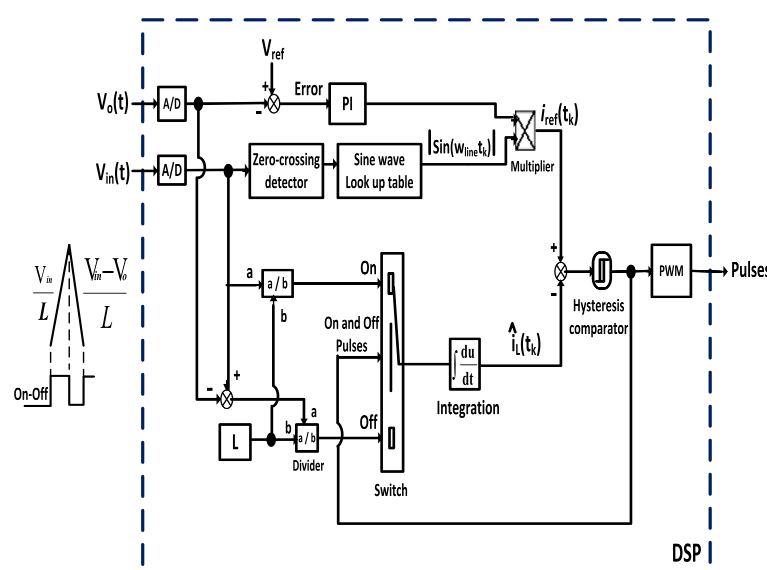

Figure 3 Proposed control technique without using current sensor.

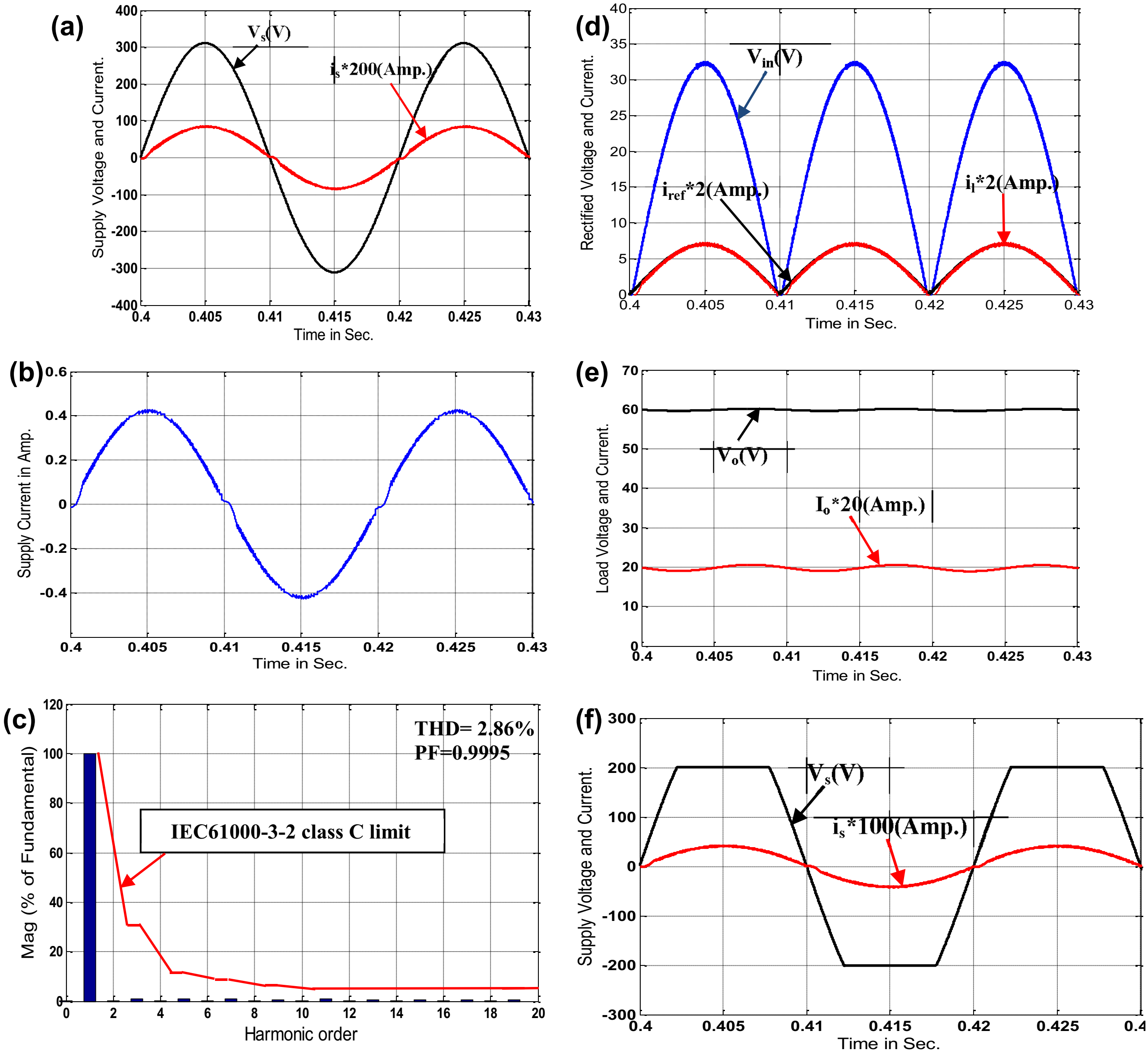

Figure 4 Steady-state performance: (a) Input voltage and current for ideal supply voltage; (b) Input current waveform; (c) Harmonics spectrum of supply current; (d) Rectified voltage, rectified current and reference current; (e) Load voltage and current; (f) Input voltage and current for distorted supply voltage.

allows investigation of both steady-state and transient operations, which can also show the reduction in supply current harmonic distortion. The system parameters are reported in Appendix A.

The steady-state supply voltage (V_s) and current (i_s) waveforms are shown in Fig. 4(a). It is clear that, the input current is in phase with the input voltage for boost PFC converter using the proposed technique.

The steady-state simulation results of input current and its harmonic spectrum for the proposed technique are shown in Fig. 4(b) and (c), respectively. It is clear that, the proposed technique has a nearly sinusoidal input current waveform with low harmonic contents, 2.86% and high power factor, 0.9995.

The rectified voltage (v_{in}), rectified current (i_l) and the reference current (i_{ref}) waveforms are shown in Fig. 4(d) which shows that the rectified current is always very close to the reference current for the proposed technique.

The load voltage and current waveforms are shown in Fig. 4(e). It is noted that the load voltage and current have a

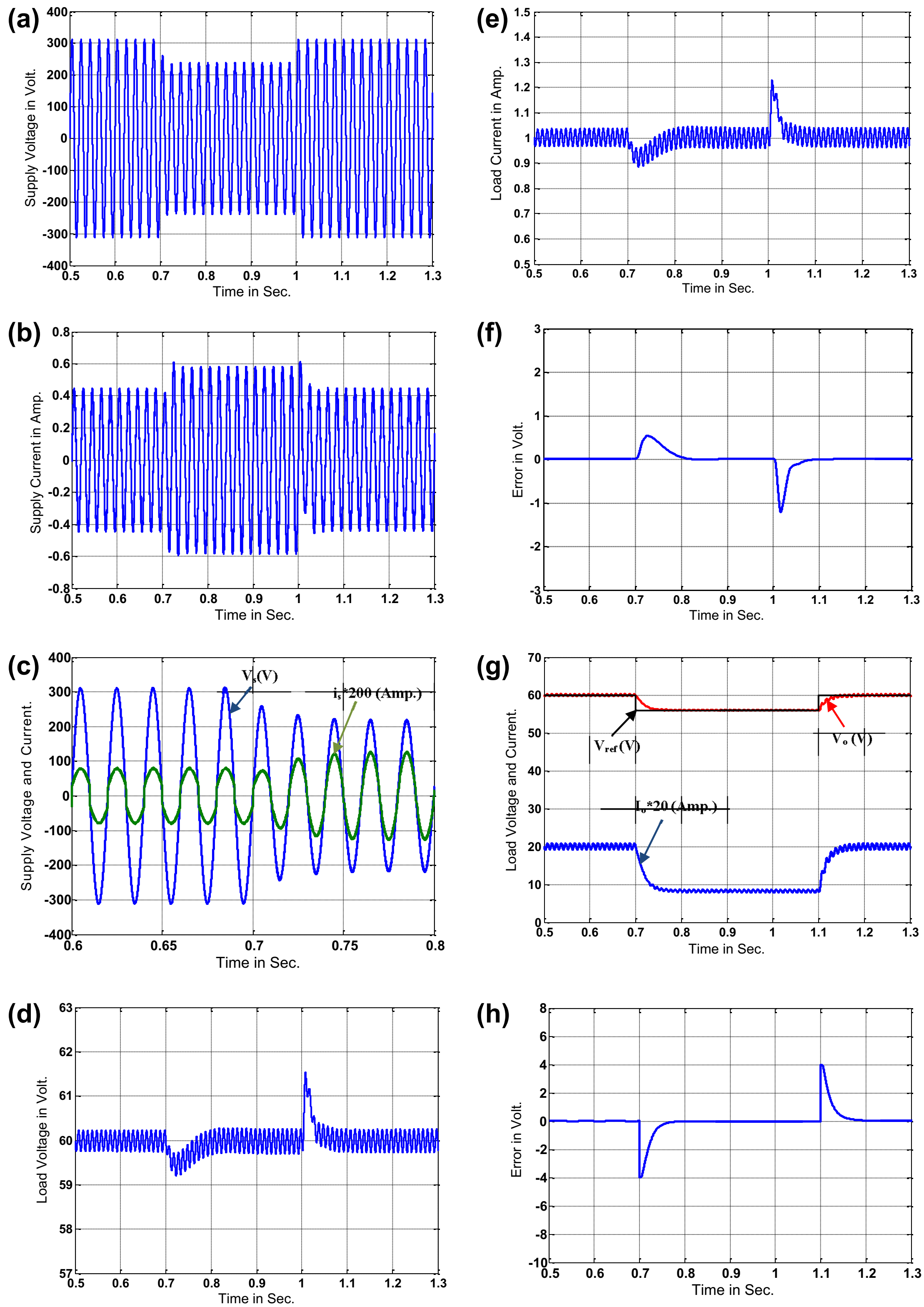

Figure 5 Transient response: (a) Variation of supply voltage due to ∓25% step change in the input voltage; (b) Variation of supply current due to ∓25% step change in the input voltage; (c) Zoom of the variation of supply voltage and current (from 0.6 to 0.8 Sec.) under ∓25% step change; (d) Variation of load voltage due to ∓25% step change in the input voltage; (e) Variation of load current due to ∓25% step change in the input voltage; (f) Error in load voltage due to ∓25% step change in the input voltage; (g) Variation of load voltage and current due to negative and positive step change in reference voltage; (h) Error in load voltage due to negative and positive step change in reference voltage.

nearly DC value with very small ripples that do not have any effect on LEDs operation.

The steady-state input voltage (V_s) and current (i_s) waveforms for the proposed technique under distorted supply voltage are shown in Fig. 4(f). It is shown that the input current has a sinusoidal waveform and being in phase with the input voltage without using a current sensor.

The simulation results of supply voltage and current due to ∓25% step change in the supply voltage for the proposed control technique are shown in Fig. 5(a) and (b), 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 of the supply voltage and current (from 0.6 to 0.8 s) under ∓25% step change in the supply voltage as shown in Fig. 5(c).

The simulation results of load voltage and current due to ∓25% step change in the input voltage for the proposed technique are shown in Fig. 5(d) and (e). As seen from these figures, the change in load voltage and current due to the change of 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 to ∓25% step change in the input voltage is shown in Fig. 5(f), which indicates that the proposed PFC control technique has a fast response.

Without using a current sensor, the variation of load voltage and current due to negative and positive step change in reference voltage (from 60 V to 56 V) are shown in Fig. 5(g). It is observed that, the load current follows the load voltage, which follows the desired reference voltage, so the dynamic response of the load voltage and current for negative and positive step change in reference voltage are being 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. 5(h), which indicates the fast response for the proposed PFC control technique.

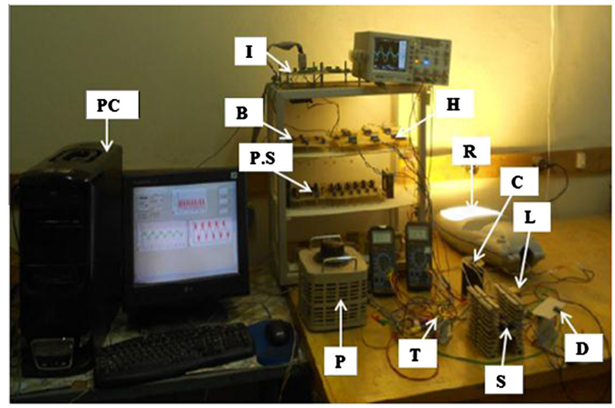

Figure 7 Experimental setup of PFC circuit for LED lamps.

5. Experimental results

For validating the control concept, a laboratory prototype is implemented. The block diagram of the experimental setup and a real view of the complete control system are shown in Figs. 6 and 7, respectively. The main components of the system which are labeled as in Fig. 7 are listed in Table 2. 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 the host computer. The output of the board is a logic signal, which is fed to IGBT through driver and isolation circuits.

The steady-state experimental results of the supply voltage and current waveforms, in case of using a single-phase rectifier without PFC circuit to drive the LED lamps, are shown in Fig. 8(a). It is shown that the input current has narrow pulses, which in turn increases its root mean square

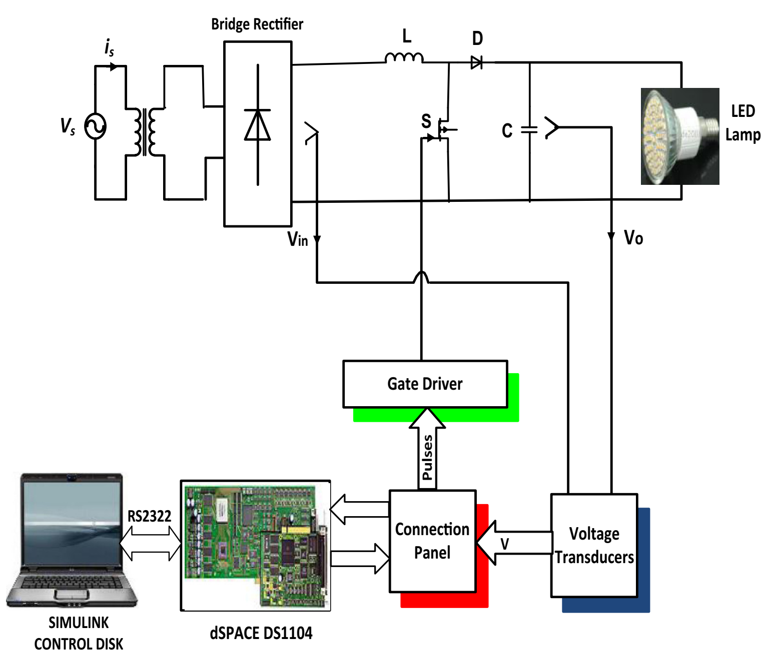

Figure 6 Block diagram of the experimental setup of PFC for LED lamps.

Table 2

Label	Component	Label	Component
PC	Personal computer	H	Voltage and current transducers
I	DSP Interface circuit	R	Load (LED Lamps)
B	Base drive circuit	C	Capacitor
P.S	All other power suppliers	L	Inductor
P	Variable AC power supply	D	Fast recovery diode
T	Single-phase full wave bridge rectifier	S	IGBT

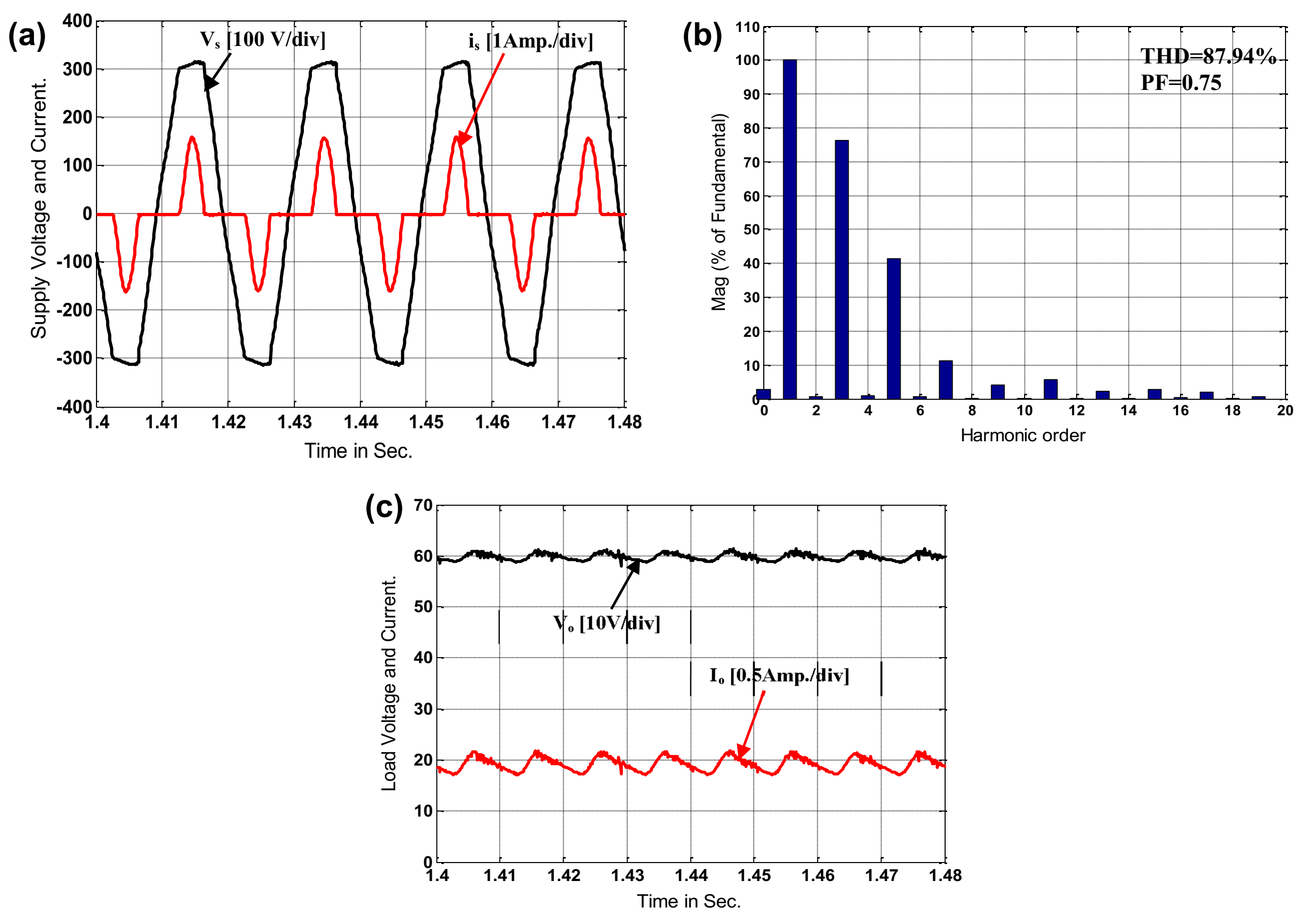

Figure 8 Experimental results for LED lamp driver without using PFC converter: (a) Supply voltage and current waveforms; (b) Harmonics spectrum of supply current; (c) Load voltage and current waveforms.

(RMS) value and consequently, a voltage dip in the supply voltage due to peak value of input current appears.

The experimental result of the harmonics spectrum of the supply current is shown in Fig. 8(b). It is observed that the supply voltage has THD of 6.6%, and the input current has a high THD of 87.94% with a low PF of 0.75 as using a single-phase rectifier without PFC circuit to drive LED lamps.

The experimental results of the load voltage and current waveforms are shown in Fig. 8(c). It is observed that the load voltage and current have a nearly DC value with small ripples.

5.1. LED lamp driver without PFC circuit

The steady-state experimental results of the supply voltage and current with PFC circuit using the proposed technique are shown in Fig. 9(a). It is illustrated that the input current has a nearly sinusoidal waveform and being in phase with the input voltage.

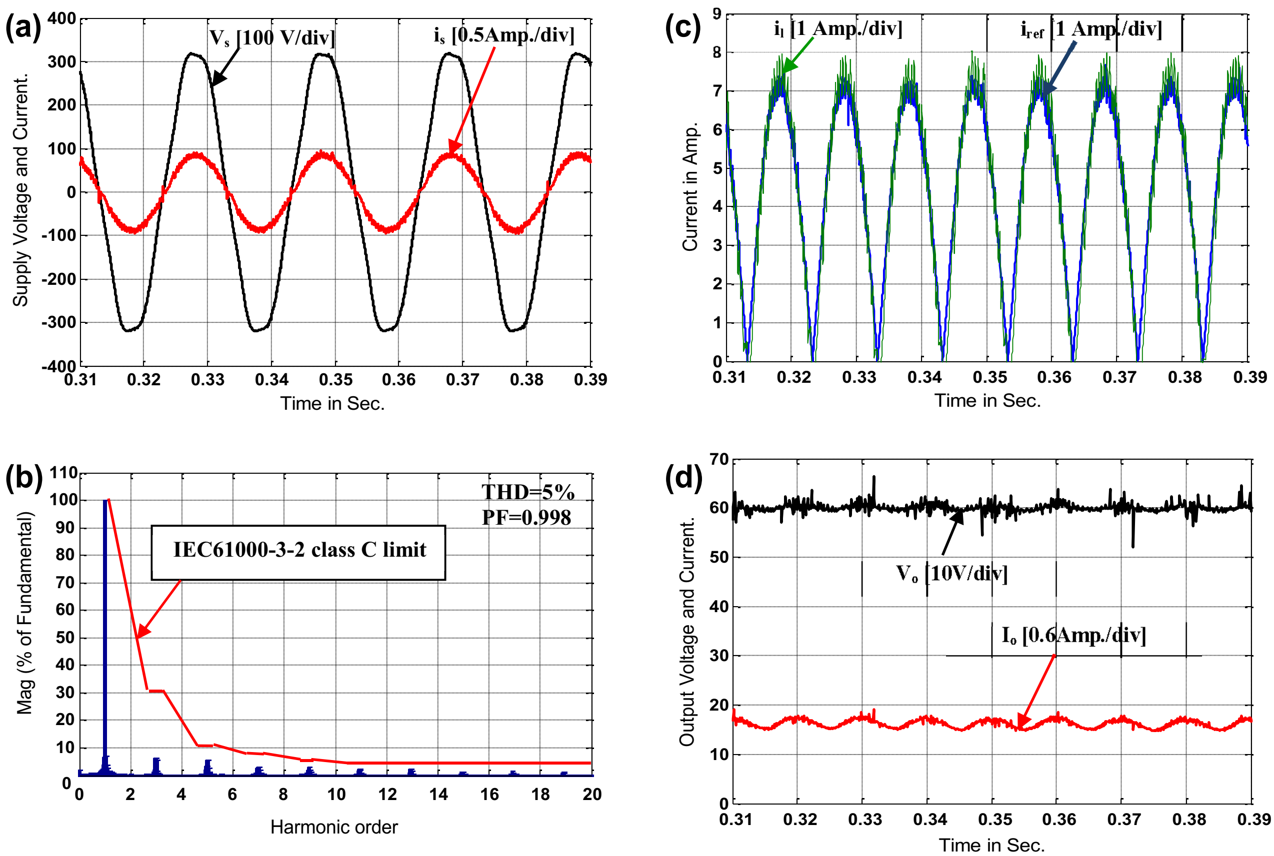

Figure 9 Experimental results (Steady-state performance for LED lamp driver using the proposed PFC technique): (a) Supply voltage and current waveforms; (b) Harmonics spectrum of supply current; (c) Rectified current and reference current waveforms; (d) Load voltage and current waveforms.

The experimental result of the harmonics spectrum of the supply current is shown in Fig. 9(b). It is seen that with the proposed control technique of PFC circuit, the input current has low harmonic contents (THD of 5%) with high PF of 0.998.

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

The steady-state experimental results of the rectified and reference currents for the proposed technique are shown in Fig. 9(c). It is observed that the rectified current is always very close to the reference current.

The steady-state experimental results of the load voltage and current are shown in Fig. 9(d). It is clear that the load voltage and current have a DC value with very small ripples, and the LED lamps are not affected by these ripples.

The experimental results of the variation of the load voltage and current due to negative and positive step change in reference voltage (from 60 V to 56 V) are shown in Fig. 10(a). It is shown that the load voltage follows the desired reference voltage and consequently, the load current follows the load voltage. 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. 10(b), which indicates a fast response for the proposed PFC control technique.

The experimental results of supply voltage and current due to −25% step change in the input voltage for the proposed control method are shown in Fig. 10(c) and (d), respectively. It is clear that a sinusoidal input current waveform is maintained under the change in supply voltage.

The experimental results of load voltage and current due to −25% step change in the input voltage for the proposed method are shown in Fig. 10(e). 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 −25% step change in the input voltage is shown in Fig. 10(f), which indicates that the proposed PFC control method has a fast response.

There are slight differences between the simulation and experimental results because in simulation results the supply voltage has an ideal sinusoidal waveform, but in experimental results supply voltage is not an ideal sinusoidal waveform. Also, the simulation results are done with a 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).

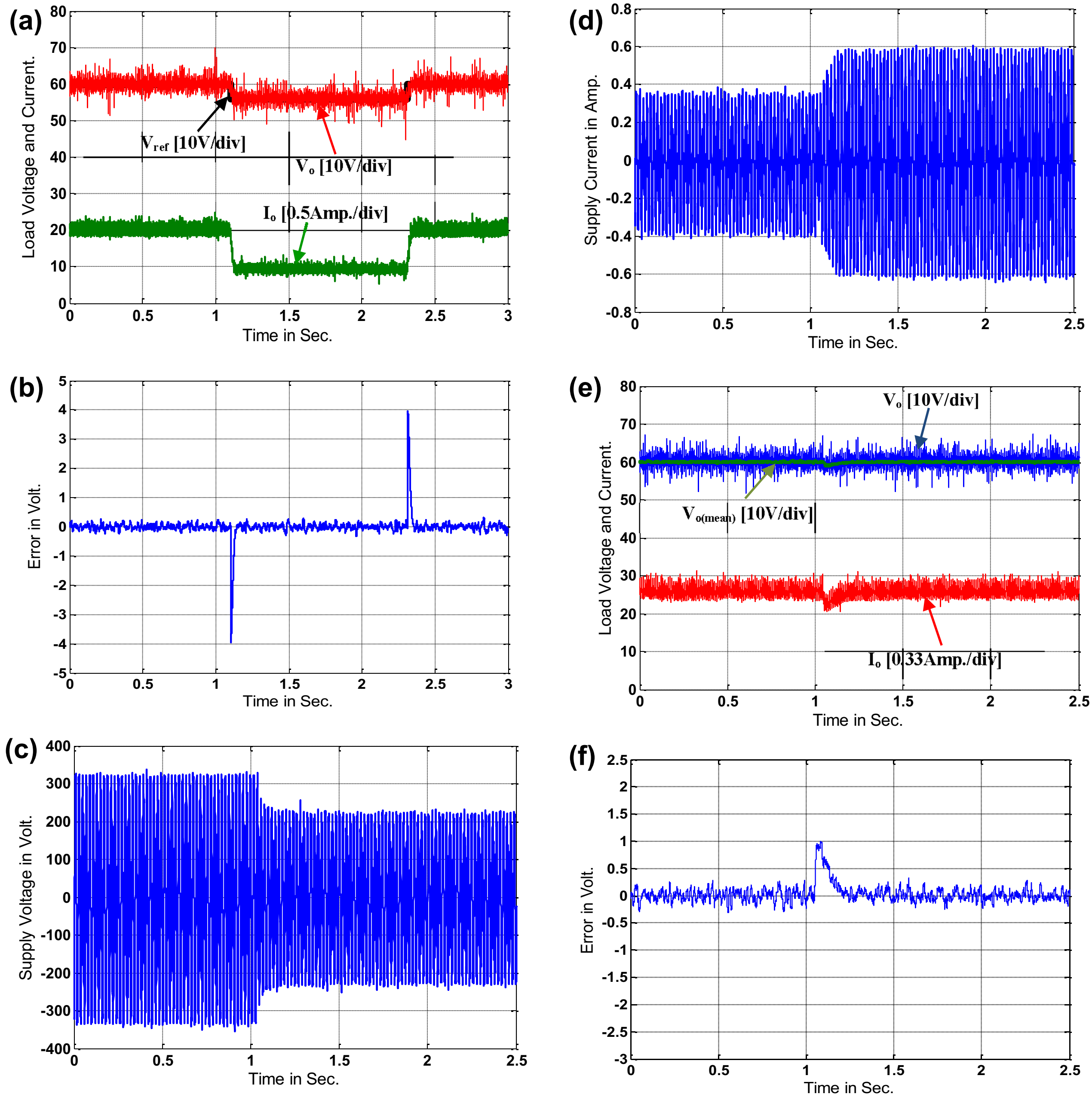

Figure 10 Experimental results (Transient response for LED lamp driver using the proposed PFC technique): (a) Variation of load voltage and current due to negative and positive step change in reference voltage; (b) Error in load voltage due to negative and positive step change in reference voltage; (c) Variation of supply voltage due to −25% step change in the input voltage; (d) Variation of supply current due to −25% step change in the input voltage; (e) Variation of the load voltage and current due to −25% step change in the input voltage; (f) Error in load voltage due to −25% step change in the input voltage.

6. Conclusion

In this paper, a novel control technique without using current sensor for LEDs driver and producing high PF has been presented. This technique is distinguished by its simplicity and reliability to estimate the inductor current, which overcomes the problems that appear when using a current sensor. Also, a low cost digital controller can be implemented due to the reduction in number of used sensors. The inductor current is estimated using two ADCs for sensing the input and output voltages. Simulation and experimental results from a laboratory prototype have been correspondingly shown to verify the feasibility of the proposed scheme. Results show that the proposed technique has a sinusoidal input current waveform with very low THD and high PF. Also, the input current has a sinusoidal waveform under a distorted supply voltage. The use of zero-crossing detector has resulted in a better and more accurate performance. Better dynamic performance for positive and negative change in the input and reference voltages can be obtained.

Appendix A

The simulation and experimental results for the proposed technique are taken with the following specification:

Parameter	Symbol	Value
Supply nominal voltage	V_s	220 Vrms
Line frequency	F	50 Hz
Step down voltage transformer	Tr	220:24 Vrms
Inductor	L	3 mH
DC link capacitor	C	3000 μF
LEDs power	P_o	60 W
Load voltage	V_o	60 Vdc
Load current	I_o	1 Adc

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

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