

# Analysis, Design and Development of a Single Switch Flyback Buck-Boost AC-DC Converter for Low Power Battery Charging Applications

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## ABSTRACT

The design and performance analysis of a power factor corrected (PFC), single-phase, single switch flyback buck-boost ac-dc converter is carried out for low power battery charging applications. The proposed configuration of the flyback buck-boost ac-dc converter consists of only one switch and operates in discontinuous current mode (DCM), resulting in simplicity in design and manufacturing and reduction in input current total harmonic distortion (THD). The design procedure of the flyback buck-boost ac-dc converter is presented for the battery charging application. To verify and investigate the design and performance, a simulation study of the flyback buck-boost converter in DCM is performed using the PSIM6.0 platform. A laboratory prototype of the proposed single switch flyback buck-boost ac-dc converter is developed and test results are presented to validate the design and developed model of the system.

**Keywords:** Single switch flyback converter, Power quality improvement, THD, Power factor

## 1. Introduction

The power electronic equipment connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification, which draws a nonsinusoidal line current due to the nonlinear input characteristic. With the steadily increasing use of such equipment (e.g. TVs, office equipment, battery chargers, electronic ballasts, household appliances, etc.) line current harmonics, power factor, low efficiency and output voltage ripple have become significant problems in these applications. There is a need in the input stage for a

reduction in line current harmonics, power factor correction (PFC), efficiency improvement and reduction in output voltage ripple. In recent years, many new alternatives for AC-DC conversion have been proposed which result in reduction of the harmonic distortion and the improvement of power factor<sup>[1]</sup>. Various international agencies have created standards such as IEEE-519<sup>[2]</sup> and IEC 61000-3-2<sup>[3]</sup> which impose strict limitations on the levels of harmonic current emissions. These standards have led to continuous research into different methods and approaches for reducing these harmonic currents and improving the power quality indices.

This paper presents a topology of a fourth order single switch buck-boost converter with minimal components. For low power applications, DCM (discontinuous conduction mode) operation of the flyback buck-boost

Manuscript received April 23, 2007; revised August 31, 2007

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converter topology is considered most suitable because the voltage follower approach is applied for the PWM control of the converter. It uses a simple control scheme, which only requires sensing of output voltage. The output voltage regulation is provided by the feedback loop where the output voltage is compared with a reference value and the error is amplified in a PI (proportional integral) controller, which is compared with a saw-tooth ramp, thus providing the pulses to the power switch. This topology has an inherent power factor correction feature with constant duty ratio and switching frequency, offering an attractive solution for low power applications<sup>[4]</sup>.

For high power applications, continuous conduction mode (CCM) operation, which causes less voltage stress on switching devices, is considered most suitable. The conceptual circuit diagram of a single switch AC-DC converter circuit in CCM operation with an average current mode control includes an inner current loop and an outer voltage loop. In the current loop, the input inductor current or capacitor voltage is detected, compared to a reference value and then processed by a suitable current error amplifier. The current error amplifier output is compared with the fixed ramp to generate a proper driving signal for the switch. The outer voltage loop provides the proper current reference signal by multiplying a scaled replica of rectified voltage by the output of the voltage error amplifier, thus providing the pulses to the power switch<sup>[5]</sup>. The use of only one switch and the relatively simple control circuit required are strong reasons for their choice<sup>[6]</sup>.

The conventional single switch flyback buck-boost converter is generally available for more than 35W rating for fluorescent lamp applications with THD less than 10%. This paper deals with the design of this AC-DC converter in detail and the experimental results confirm that this AC-DC converter can reduce THD to less than 5% to achieve sufficient suppression of output voltage ripple for less than 25W output power. The simulation is carried out using the PSIM6.0 platform for different load conditions of 20%, 50% and 100% of rated power. These results show the fast response of the PI (proportional integral) controller, where the output voltage is regulated to 24V after sudden application and removal of the load. The flyback buck-boost converter is implemented for constant

voltage battery charging applications with inherent power factor correction (PFC) and high frequency transformer isolation. The hardware implementation for the flyback buck-boost converter in DCM operation is carried out using the parameters designed and verified by the simulation results. The flyback buck-boost converter prototype in DCM is tested under different load conditions with a wide range of input voltage to demonstrate the improved steady state performance. The components are selected with closest specifications available in market, and the experimental results show that satisfactory performance is obtained.

## 2. Circuit and Operation

Fig. 1 shows the proposed single-phase, single switch flyback buck-boost converter in DCM operation. This converter consists of the AC power source  $V_{in}$ , input EMI filter of inductor  $L_f$  and capacitor  $C_f$ , bridge rectifier FWR, high frequency transformer with primary windings  $N_1$  and secondary windings  $N_2$ , high frequency diodes  $D_1$ , and capacitor  $C_o$ .

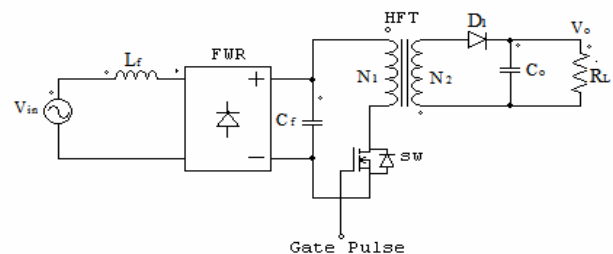


Fig. 1 Practical single-phase, single switch flyback buck-boost converter

The input filter is required to reduce the ripple in the input current and power factor correction. A large value of the input capacitor distorts the input current waveform as the input current becomes discontinuous due to the fact that the reactive energy of capacitor  $C_f$  can not be fed back to the input supply in the presence of the diode bridge. Thus, a small value should be selected for the input filter capacitor. Practical flyback converter operation is fundamentally different from other topologies in which energy is stored in the transformer when the switch is on and the power is delivered to the load when the switch is

off. In discontinuous conduction mode, the voltage follower approach is applied to the PWM control of the converter, which only requires output voltage detection. The output voltage regulation is provided by the feedback loop as shown in Fig.2, where the output voltage detected  $V_o$  is compared with a reference value  $V_{oref}$  and the error is amplified in a proportional integral (PI) controller which is compared with a saw-tooth ramp  $V_s$ , thus providing the pulse to the power switch. Therefore, this circuit is controlled by the change of the on-time interval and constant switching frequency  $f_s$ .

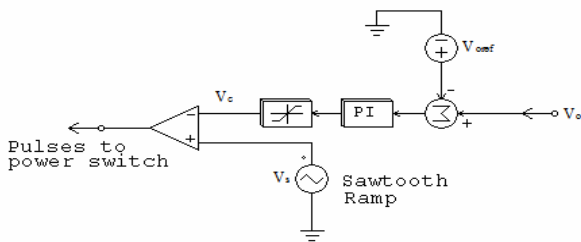


Fig. 2 Practical voltage follower approach circuit for PWM control

### 3. Design of the Flyback Buck-Boost Converter

Fig. 3 shows the ideal waveforms for switch and diode current and transformer primary voltage in DCM. The following analysis proves the resistor emulating property of the flyback converter in DCM operation. The different parts of the flyback buck-boost converter system are modeled using basic equations. The complete model of the flyback buck-boost converter can be defined as:

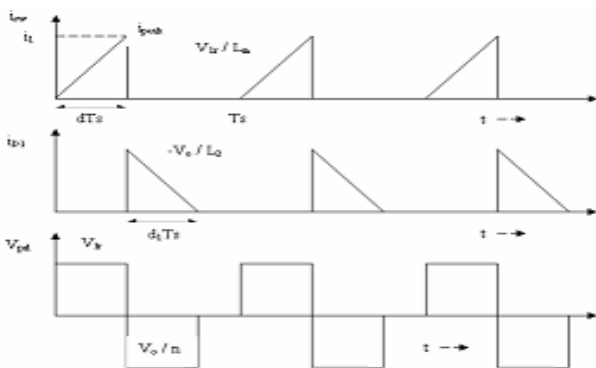


Fig. 3 Inductors voltage and current waveforms in DCM of flyback buck-boost AC-DC converter

Average input current ( $I_1$ ) over a switching cycle is given as:

$$I_1 = \frac{1}{2} I_{pk} d \tag{1}$$

where, input peak current ( $I_{pk}$ ) is given as:

$$I_{pk} = \frac{dT_s}{L_m} V_{lr} \tag{2}$$

where,  $v_{lr} = v_1 |\sin\omega t|$  represents the rectified voltage at output of FWR from a sinusoidal input voltage of the converter.

Now from eqns. (1) and (2):

$$I_1 = \frac{d^2 T_s}{2L_m} V_{lr} \tag{3}$$

Eqn. (3) presents PFC operation in DCM. It is clear that if the duty cycle and the switching frequency are kept constant, then the input current will be a linear function of the input voltage. Now Eqn. (3) for sinusoidal input current ( $i_1$ ) can be written as:

$$i_1 = I_1 |\sin\omega t| \tag{4}$$

where,  $v_{lr} = v_1 |\sin\omega t|$  (5)

$$I_1 = \frac{v_1 d^2 T_s}{2L_m} \tag{6}$$

The transfer function of the flyback buck-boost converter in DCM is given as:

$$V_o = \frac{dv_{lr}}{d_1 n} \tag{7}$$

For DCM operation,  $dT_s < 1$  (8)

where  $dT_s$  is the device conduction period and  $d_i T_s$  is the diode conduction period

From eqns. (7) and (8) for the desired maximum duty ratio ( $d_{max}$ ) at the minimum input voltage, the turn ratio ( $n$ ) can be obtained by satisfying the following inequality as:

$$n > \frac{dv_1}{(1-d_{\max})V_o} \quad (9)$$

However, it also affects the voltage stress across the switch. Thus, a compromise is made between  $d_{\max}$  and the voltage stress across the switch to get the turn ratio. The transformer magnetizing inductance is an important factor in deciding the mode of operation. In the flyback converter, it plays the role of a coupled inductor. There are two main criteria used to decide the magnetizing inductance of the transformer. The first one is to select the inductance in order to ensure DCM operation under maximum load conditions. The second criteria depends upon the maximum ripple allowed in the primary current. In order to ensure DCM of operation at maximum load, the following condition must be satisfied:

$$L_m < \frac{R_{L \min}}{4f_s \left( \frac{1}{n} - \frac{V_o}{V_{1 \min}} \right)^2} \quad (10)$$

where  $L_m$  is the critical inductance,  $f_s$  is the switching frequency,  $R_{L \min}$  is the minimum load resistance and  $V_{1 \min}$  is the minimum input voltage of the converter.

The output capacitor is selected on the basis of the maximum peak-to-peak ripple ( $r_v$ ) in output voltage ( $V_o$ ) as:

$$C_o > \frac{V_o}{w f_v R_L} \quad (11)$$

The input filter is required to reduce the ripple in the input current. A large value of the input capacitor distorts the input current waveform as the current becomes discontinuous due to the fact that the reactive energy of capacitor  $C_f$  can not be fed back to the input supply in the presence of a one-dimensional diode bridge. Thus, a small value should be selected for the input filter capacitor.

The peak current through switch ( $I_{\text{swpk}}$ ) is given as:

$$I_{\text{swpk}} = \frac{R_L d T_s}{L_m} \quad (12)$$

Peak voltage across switch ( $V_{\text{swpk}}$ ) given as:

$$V_{\text{swpk}} = V_1 + nV_o \quad (13)$$

Similarly, peak current through diode ( $I_{\text{dpk}}$ ) is as:

$$I_{\text{dpk}} = \frac{n^2 V_o d T_s}{L_m} \quad (14)$$

And, peak voltage across the diode ( $V_{\text{dpk}}$ ) can be given as:

$$V_{\text{dpk}} = \frac{V_1}{n} + V_o \quad (15)$$

The switch current at half of the ripple  $\Delta I_{\text{sw}}$  is given as:

$$\Delta I_{\text{sw}} = \frac{V_{1 \min} d_{\max} T_s}{L_m} \quad (16)$$

Switch RMS current ( $I_{\text{swrms}}$ ) is given as:

$$I_{\text{swrms}} = \sqrt{d_{\max} \left[ I_{\text{swpk}}^2 - \Delta I_{\text{sw}} I_{\text{swpk}} + \left( \frac{1}{3} \right) \Delta I_{\text{sw}}^2 \right]} \quad (17)$$

Similarly diode current at half of the ripple ( $I_{\text{dh}}$ ) is given as:

$$I_{\text{dh}} = \frac{I_{0 \max}}{(1-d_{\max})} \quad (18)$$

where,  $I_{0 \max}$  is the maximum output voltage of the converter.

The diode peak current ( $I_{\text{dpk}}$ ) for ripple  $\Delta I_d$  is given as:

$$I_{\text{dpk}} = I_{\text{dh}} + \frac{\Delta I_d}{2} \quad (19)$$

$$\text{where, } \Delta I_d = \frac{V_o (1-d_{\max}) T_s}{L_2} \quad (20)$$

Diode RMS current ( $I_{\text{dms}}$ ) is given as:

$$I_{\text{dms}} = \sqrt{(1-d_{\max}) \left[ I_{\text{dpk}}^2 - \Delta I_d I_{\text{dpk}} + \left( \frac{1}{3} \right) \Delta I_d^2 \right]} \quad (21)$$

These equations are used to get design data, which are used in the model of the proposed flyback buck-boost converter in PSIM6.0 to analyze the steady state and dynamic behavior of the converter. The simulation is carried out for different load conditions of 20%, 50% and 100% of rated power. The design procedure is presented here for DCM mode of operation for the specifications given in Table I. Based on the above design equations the experimental data is summarized in Table II.

#### 4. Modeling and Simulation

On the basis of the obtained design, the simulation of the converter was carried out in DCM operation. Fig.4 shows a PSIM model of the flyback buck-boost converter in DCM operation. As discussed already, it uses voltage mode control. It mainly consists of an EMI input filter and a transformer. The converter consists of a PWM control using the voltage follower approach. The simulated results are shown in Figures 5 - 12 and Table III summarizes the performance parameters of the flyback buck-boost converter.

Table 1 Circuit specifications for single switch flyback buck-boost converter

Input Voltage, $V_{in}$ (RMS)@ 50Hz	220V
Output Power, $P_o$	24W
Output voltage, $V_o$	24V
Output current, $I_o$	1A
Switching frequency, $f_s$	50kHz
Maximum Duty Ratio, $d_{max}$	0.5
Critical Inductance to operate, $L_{cr}$	45 $\mu$ H
DC Voltage Conversion ratio M	0.0434
Transformer primary to secondary turn ratio $N_1/N_2$	12
Minimum primary turns $N_1$ (min)	60
Secondary turns $N_2$	5
Minimum output capacitor $C_o$	22.5mF
Minimum turns in output inductor $N_{L1}$ min	3
Peak Switch Voltage $V_{swpk}$	567.5V
Peak diode voltage on secondary side	29.8V

$V_{dpk}$	
Peak Switch Current $I_{swpk}$	574.7mA
Peak Diode Current $I_{dpk}$	9.006A
Minimum input filter inductance $L_{in}$ (min)	2.073mH

Table 2 Design parameters of flyback buck-boost converter

Components	DCM Operation
Transformer turn ratio	12: 1
Transformer magnetizing inductance	2.5mH
Output capacitor	22.5mF
EMI filter	5.1mH, 100nF

Table 3 Power quality observation for flyback converter

Quantity	Experimental Results		Simulation Results	
	Output Power		Output Power	
	4.8W (20% load)	24W (100% load)	4.8W (20% load)	24W (100% load)
Power Factor	0.984	0.996	0.977	0.992
Volt Ripple (%)	0.3	0.9	0.4	1.1
Efficiency (%)	77.2	79.4	77.1	79.0
THD (%)	5.4	4.7	5.8	4.8

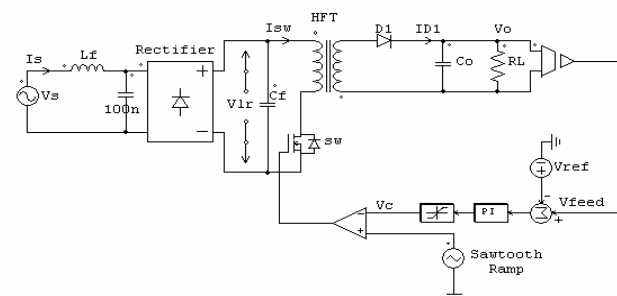


Fig. 4 PSIM model of Single-phase, single switch Flyback buck-boost AC-DC converter in DCM

#### 5. Hardware Implementation

A 24W isolated single switch flyback buck-boost converter prototype is developed with 24V output voltage having a transformer isolation with 50kHz switching

frequency and PFC in DCM operation. It includes the control supply and protection such as overload shutdown, input under voltage and output over voltage. The voltage follower approach is applied to the control using PWM controller chip UC3843. The hardware implementation is carried out using the parameters designed and verified through the simulation results. The photograph of the experimental setup of the flyback buck-boost converter is shown in Fig. 13. Extensive tests were conducted on the developed prototype of the converter and the test results are shown in Figs. 14-20. High input power quality is achieved with improved power factor and reduced source current distortion at full load. The controller shows a fast dynamic response to line and load disturbance with an output voltage ripple of 1% for 4.8W to 24W load changes.

These results show the suitability of DCM operation in low power applications. Table III summarized the power quality observation via comparison between experimental and simulation results of the flyback buck-boost converter. The components used in the hardware implementation of flyback buck-boost converter are summarized in Table IV with a detailed description.

Table 4 Specifications of components used in hardware implementation of flyback buck-boost converter

Component	Company	Description
Rectifier Diode	General Semiconductor	1N5408 ( $V_{\text{rrm}}=1000\text{V}$ , $I_{\text{f(max)}}=1\text{A}$ )
MOSFET	International Rectifier	2SK962(N Channel, $V_{\text{DSS}}=900\text{V}$ , $I_{\text{d}}=3\text{A}$ )
High Frequency Diode	On Semiconductor	MBR2045CT ( $V_{\text{rrm}}=45\text{V}$ , $I_{\text{f(max)}}=20\text{A}$ )
Transformer	EPCOS	EE25 (Ferrite Core), Material-N67
Input Inductor	EPCOS	EE20 (Ferrite Core), Material-N67
PWM Controller Chip	Unitrode	UC3843
Optocoupler Isolation Chip	Fairchild semiconductor	4N35

## 6. Result and Discussion

Fig.5 and Fig.11 show the PSIM6.0 simulated input voltage and current waveforms at 100% and 20% load, respectively, where Fig.7 and Fig.12 show the source current harmonic spectrum under the same load. From these curves, it is clear that the input current follows the input voltage and the circuit behaves as a resistor emulator where power factor is observed close to unity and THD is less than 5%. The simulated output voltage waveforms with less than 1% peak-to-peak voltage ripple at full load as shown in Fig. 6. The switch voltage and current waveform at full load is shown in Fig. 8. In order to analyze the control loop functionality and dynamic behavior of the converter, in terms of source voltage and source current, the waveforms are shown in Fig. 9 for the sudden application of 100% load and then removal of the load (20%-100%-20% load change) in DCM operation. Fig. 10 shows the output voltage and current, which remains regulated even at load change. This shows that improved steady state performance is achieved with the flyback buck-boost converter.

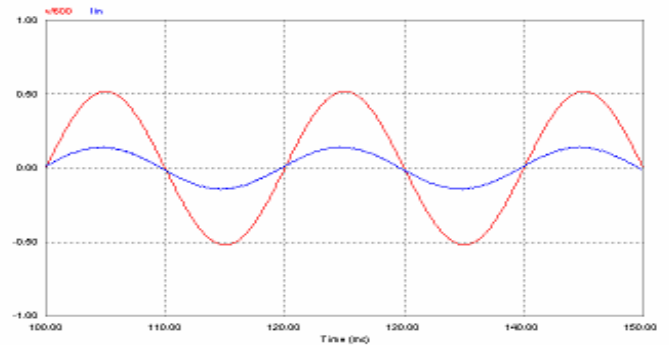


Fig. 5 Input voltage and current waveform at 100% load of flyback buck-boost converter in DCM

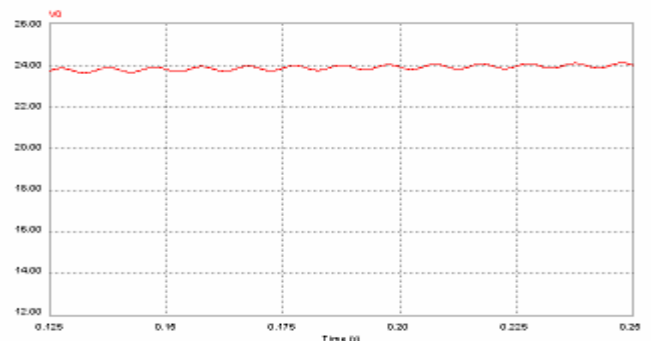


Fig. 6 Output voltage waveform at 100% load

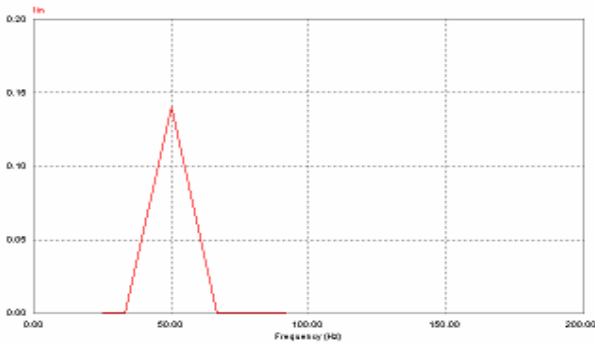


Fig. 7 Harmonic spectrum of source current at 100% load

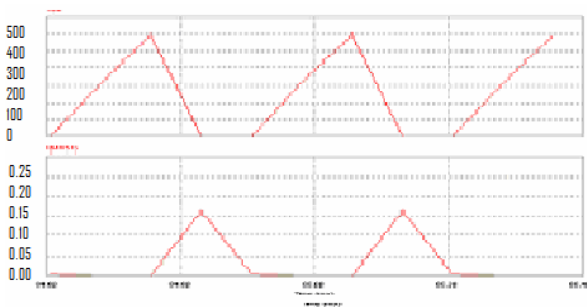


Fig. 8 Switch voltage and current waveform at 100% load

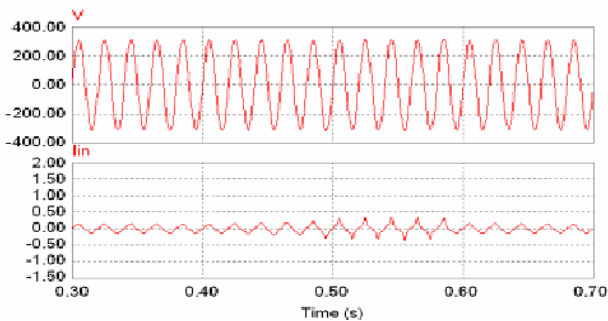


Fig. 9 Source voltage and current for load application and removal at 20% to 100% to 20% load

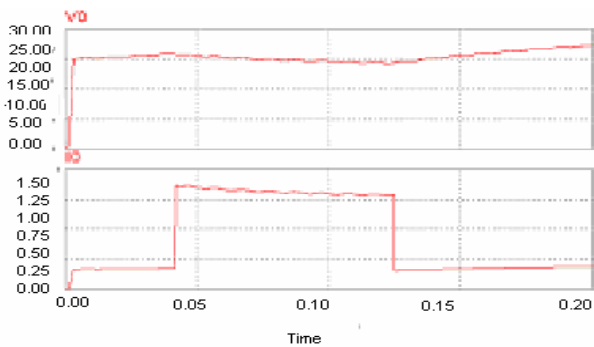


Fig. 10 Output voltage and current for load application and removal at 100% load

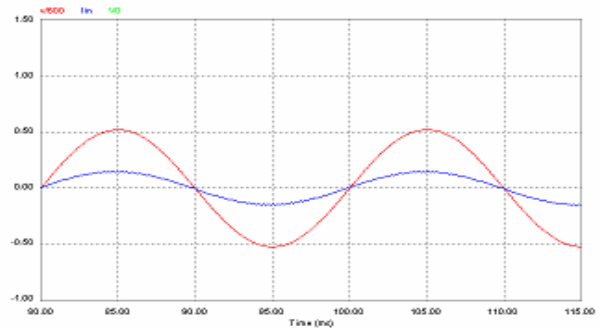


Fig. 11 Input voltage and Current waveform at 20% load

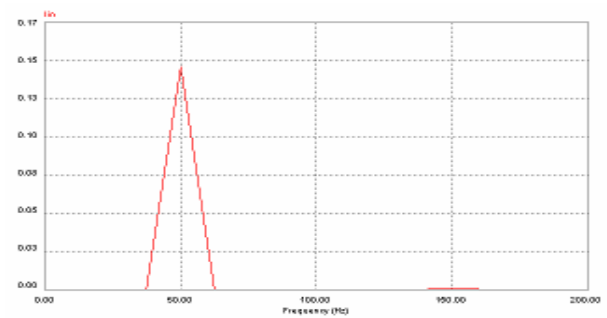


Fig. 12 Harmonic spectrum of source current at 20% load

Fig. 13 shows a photograph of the experimental setup of the flyback buck-boost converter. It includes the control supply and protection such as overload shutdown, input under voltage and output over voltage. To verify with the simulation input voltage and current waveforms at 100% and 20% load, the experimental waveforms are shown in Fig.14 and Fig.18. Practically, the power factor is achieved close to unity, which is similar to the simulated value at full load.



Fig. 13 Experimental setup of flyback buck-boost converter

The output DC voltage and current at full load are shown in Fig.15 and an enlarged view of the output DC voltage is shown in Fig.16 with nearly 245mV or 1% peak-to-peak ripple in practical implementation. Consequently, it is clear that the voltage follower control scheme is quite effective in suppressing the output voltage ripple in the proposed single switch flyback buck-boost converter in DCM operation. Additionally, the switch voltage and current waveform can be seen in Fig.17, where the peak to peak value of the switch voltage and current were observed at 400V and 280mA, respectively, which has satisfied the design value with simulated waveforms. The flyback buck-boost converter with sudden change of load from 4.8W to 24W and then reduction of the load from 24W to 4.8W is verified.

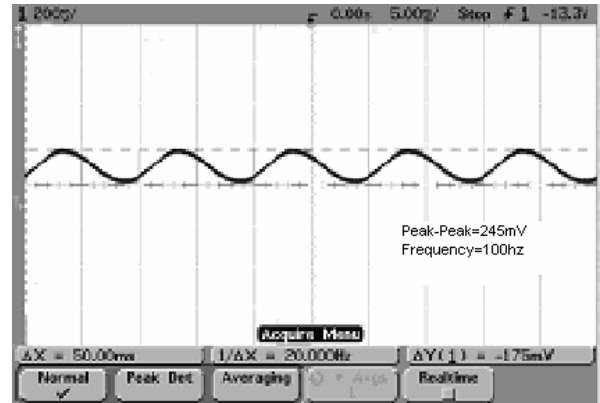


Fig. 16 Enlarged Output voltage waveform at 100% load Scale: 5V/div and 1ms/div

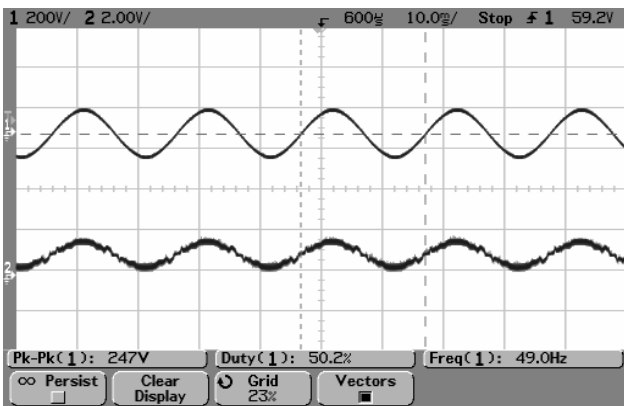


Fig. 14 Input voltage and current waveform at 100% load Scales: 300V/div, 0.5A/div and 5ms/div

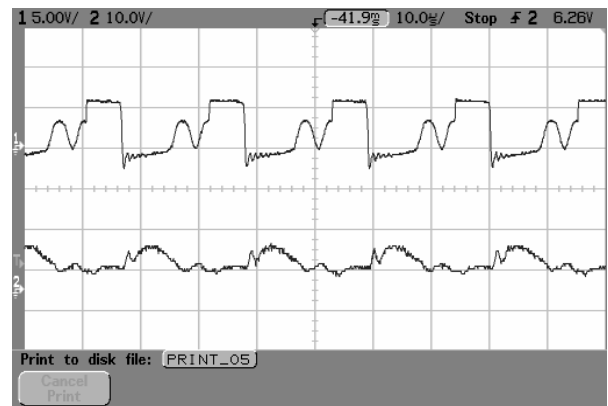


Fig. 17 Switch voltage and current waveform at 100% load Scales: 200V/div, 0.5A/div and 20µs/div

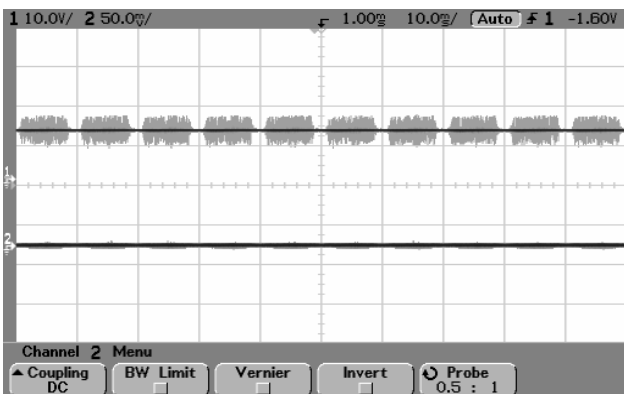


Fig. 15 Output voltage and current waveform at 100% load Scales: 5V/div, 0.5A/div and 1ms/div

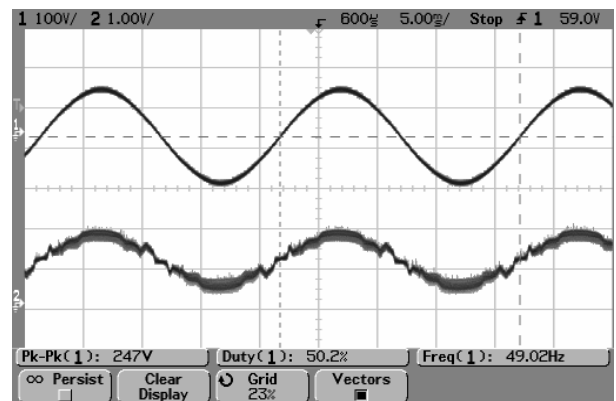


Fig. 18 Input voltage and current waveform at 20% load Scales: 100V/div, 0.1A/div and 5ms/div



Fig.19 shows the output voltage and current waveforms and Fig.20 shows the source voltage and current waveforms under dynamic conditions.

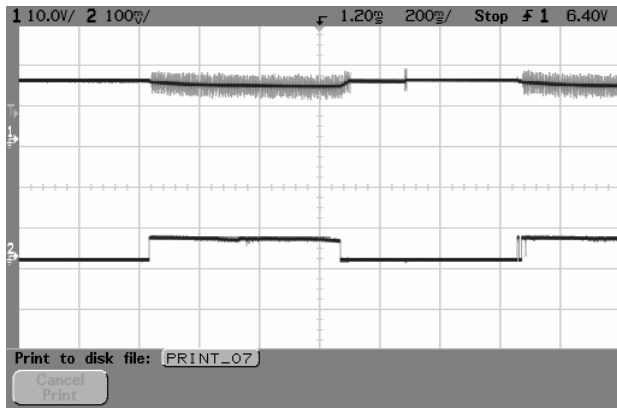


Fig. 19 Output voltage and current for load application and removal at 100% load, Scales: 5V/div, 2A/div and 1ms/div

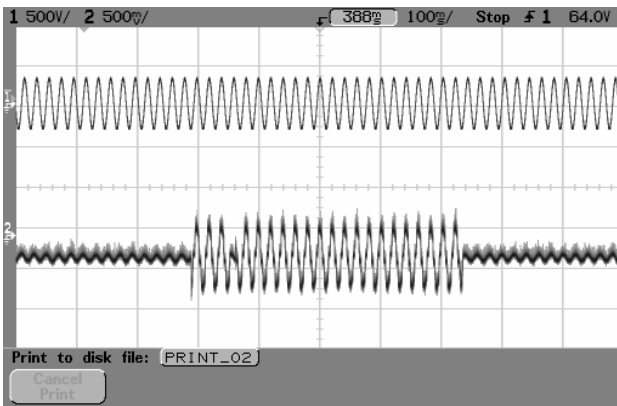


Fig. 20 Source voltage and current for load application and removal at 100% load, Scale: 300V/div, 0.5A/div and 0.5ms/div

These results show the fast response of the PI controller, where output voltage is regulated to 24V after sudden application and removal of the load at source voltage 220V rms. The converter source current THD, power factor, efficiency and output voltage at 10% to 100% load are summarized in Table V, which demonstrates the improved power quality and reduced THD of the flyback buck-boost converter.

Table 5 THD, PF, efficiency and output voltage ripple at different output power of single phase, single switch flyback buck-boost converter test for simulation

Output power (W)	Source current THD (%)	Power Factor	Efficiency (%)	Output voltage ripple (%)
2	5.7	0.981	76.8	0.3
4	5.4	0.984	77.2	0.3
6	5.3	0.984	77.5	0.4
8	5.2	0.985	77.6	0.5
10	5.1	0.985	77.7	0.6
12	5.0	0.986	78.2	0.7
14	5.0	0.988	78.5	0.7
16	4.9	0.991	78.8	0.7
18	4.9	0.992	78.8	0.8
20	4.8	0.993	79.0	0.8
22	4.8	0.996	79.1	0.9
24	4.7	0.996	79.4	0.9

## 7. Conclusions

The simulated and experimental results have revealed the improved performance of the proposed converter in low power battery charging applications. It has been observed from the results that the power factor at AC input mains is observed close to unity and the source current THD is less than 5% at full load. The experimental results for line and load disturbances show a fast dynamic response of the control circuit with a voltage dip of only 1.1% for a sudden load change from 20% to 100%. Thus, design and simulation studies have been carried out and the results have been verified experimentally. Hardware implementation shows the same reduced THD, power factor and output voltage ripple improvement as compared to the simulation results.

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