Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 4736 – 4750

doi:10.3906/elk-1502-213

A new method for active power factor correction using a dual-purpose inverter in a flyback converter

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Received: 25.02.2015 • **Accepted/Published Online:** 03.09.2015 • **Final Version:** 06.12.2016

Abstract: In this paper, a new active method for power factor correction (PFC) is presented and applied to a single-stage AC/DC flyback converter to reduce the total harmonic distortion of the input current, achieve better power factor compensation, and improve converter reliability. The proposed circuit consists of a low-power portable dual-purpose inverter that can work in 2 main modes. In the normal mode of converter operation, the PFC circuit operates as an active harmonic filter compensator. In the second mode, which occurs in converter outage conditions, the inverter behaves as a sinusoidal backup voltage power supply for the converter by using a backup battery and the SPWM control method. In this technique, the main switch of the converter operates in borderline conduction mode, but the RMS input current as well as peak and ripple currents are reduced significantly. Simulation analysis and experimental results are presented.

Key words: AC/DC converters, power factor correction, harmonic elimination, active filtering, dual-purpose inverter, backup power supply

1. Introduction

Nowadays, the applications of AC/DC switch-mode converters, such as computer power supplies, battery chargers, and other electronic equipment, are rapidly growing and result in some power quality problems. This equipment consists of semiconductor devices that show nonlinear behavior and work at high frequencies. Thus, these devices inject many harmonic disturbances into the network and reduce the power factor. In order to meet the current harmonic limitation standards, such as IEC 1000-3-2 in Europe and IEEE 519 in the United States, many power factor correction methods in switch-mode power supplies have been explored [1]. There have been many publications on the PFC converters recently. In some methods, converters operate in continuous conduction mode (CCM) [2–4]. These techniques have disadvantages, such as hard commutation in the switching devices. This leads to switching energy losses and stresses during hard-switched MOSFET turn-on and diode turn-off. The hard-switching state limits output power rating and higher switching frequency operation to reduce the size of the magnetic components and capacitors [5]. Thus, an additional snubber circuit is required [2,6]. CCM requires a larger inductor compared with the borderline conduction mode (BCM), which leads to high copper usage [7].

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Some converters are 2-stage, consisting of a PFC preregulator and a DC/DC converter [8,9]. Because they have 2 converter stages, the output power is processed through 2 stages and the total efficiency of the converter is reduced. Furthermore, the complexity of the circuit control and topology leads to high cost and large size.

Current-fed and voltage-fed converters are other types of PFC topologies [5,10]. Most of these PFC converters are implemented with only a single output voltage controller, and the input voltage is left unregulated [11]. Thus, load variations and drop in input voltage have significant impact on the converter's operation, while in the proposed method, the input voltage is sensed and controlled constantly. In the event that input voltage drops below the critical limit, the converter goes to the backup state.

The most conventional active control technique for PFC converters is the BCMC method. BCMC is widely used in low-power PFC converters. Because of the benefits of BCMC such as high power factor, zero-current turn-on for the main power switch, no reverse recovery of the diode, and low losses, it is still considered a good PFC method in the recent literature [12,13]. Nevertheless, this method has some drawbacks. In the BCMC method, RMS input current is high and ripple current is maximum, which causes it to be appropriate only for low-power converters. In addition, both high input current peak and ripple lead to increased electromagnetic interference (EMI) and increased size and weight of the EMI filter. To overcome the abovementioned problems and provide better compensation ability and higher reliability, this paper proposes a new technique, which combines the BCMC method and a low-power portable dual-purpose voltage source inverter (VSI). Compared to previous works, a fully active approach to control of AC/DC switch-mode converters is used in this paper, developing the control strategy to detect and eliminate a wider spectrum of harmonic and subharmonic components. In the proposed method, due to BCM control of the switch, the switching losses are reduced and the power conversion efficiency is improved in comparison with the CCM PFC method. The backup dual-purpose inverter provides ongoing control of the input voltage as well as the output voltage of the converter. Therefore, converter reliability in the power interruption condition can be greatly increased. Furthermore, unlike the 2-stage PFC converters consisting of a preregulator and DC/DC converter, the proposed converter is single-stage with less complexity, fewer losses, and lower cost. Due to accurate sampling and detection of a wide range of current harmonic components, the compensation quality is increased and the power factor is significantly improved. In this case, the control algorithm is implemented on a single-phase flyback converter.

2. Design procedure of the proposed method

The control mechanism of the PFC system with dual-purpose inverter includes borderline operation of the switch current and a low-power portable dual-purpose inverter, as explained in this section. The main switch is controlled to operate at the boundary of the CCM and DCM (Figure 1).

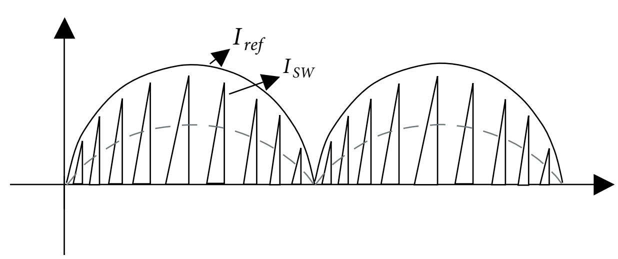


Figure 1. BCM method waveforms: reference signal versus switch current waveform in flyback converter.

The major intent of this strategy in the first section of the control is the realization of soft switching for both the transistor and diode, in which the transistor and freewheeling diode can turn on and off softly at zero current, respectively. Therefore, commutation losses and stresses are reduced. Moreover, a portion of THD and harmonic components of the line current are compensated. Thus, the compensation current through the inverter decreases and, consequently, the inverter capacity and its switches' current rating are reduced.

2.1. Dual-purpose VSI: normal operation of the converter

A single-phase voltage source inverter is used to eliminate harmonics over a wide range of frequencies and improve the power factor of the supply. During normal operation of the converter, this inverter is controlled as a current-controlled voltage source (CCVSI). Figure 2 shows the proposed PFC algorithm, which involves 3 sections. Section 1 is the BCMC method algorithm implemented on the main switch, and the 2 further sections of control correspond to the dual-purpose inverter.

In this state, the inverter follows the shunt active filter operation mechanism [14] and functions as a harmonic compensator. It senses the input line current and extracts its harmonic contents. Obtained harmonic components are then generated by the current controlled inverter and injected to the system with 180 degrees of phase difference. The scheme of the flyback rectifier topology with the control algorithm mentioned above is shown in Figure 3.

The input current is made up of the sum of fundamental and harmonic components. When the generated harmonic components are injected to the supply side in the opposite direction of the input current, their superposition leads to the reduction in harmonic currents as in the following equations:

$$I_g(t) = I_{gf}(t) + I_{gh}(t); \tag{1}$$

$$I_{inv}(t) = K_f I_{Lh}(t); \quad 0 \leq K_f \leq 1; \tag{2}$$

$$I_{gh}(t) = I_{Lh}(t) - I_{inv}(t) = (1 - K_f)\, I_{Lh}(t); \tag{3}$$

$$if: \ K_f \to 1 \ \Rightarrow \ I_{gh} \to 0 \ , \ I_{gh} \to; \tag{4}$$

where I_g is the input current, I_{gf} and I_{gh} are the fundamental and harmonic components respectively, I_{inv} is the compensation current, I_{Lh} is the load harmonic current, and K_f is the distortion compensation coefficient of the filter. Whenever the value of K_f is closer to 1, the compensation performance of the filter is improved. One of the most important parts of the mentioned dual-purpose inverter to control is current references generation. The output current of the inverter must be equal to the load current, including all the harmonic components, minus a modified fundamental current component. The modified fundamental current component includes the fundamental component of the load current synchronized with the supply voltage, plus or minus a signal generated by the DC voltage control unit. The current reference detection strategy being used is known as the unity power factor (UPF) method [15]. The intention of this method is to cause the load plus compensator to be viewed by the source as resistance. The source current space vector is desired to be in phase with the PCC voltage space vector. Assuming a sinusoidal source voltage, the compensated source current can be expressed as:

$$I_s(t) = K_c U_s(t) = K_c U_m \sin \omega t, \tag{5}$$

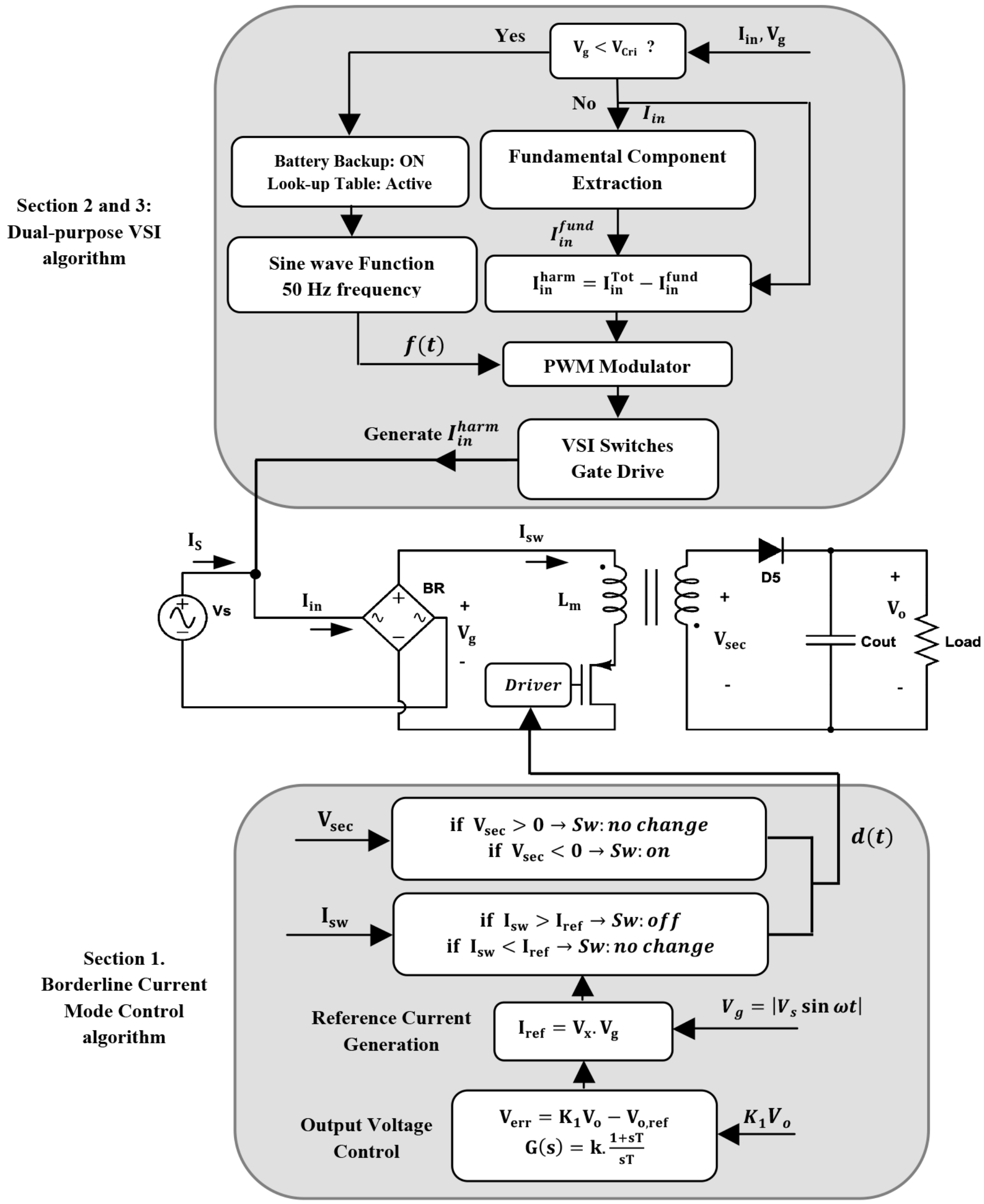


Figure 2. Proposed PFC control algorithm.

where U_s and K_c are the source voltage and constant multiple load conductance, respectively. The Fourier transform of the load current before compensation can be expressed as:

$$I_L\left(t\right) = \sum_{n=1}^{\infty} I_n \sin\left(n\omega t + \varphi_n\right) = K_c U_s\left(t\right) + I_q\left(t\right), \tag{6}$$

where $I_q(t)$ is the reactive component of the current, which cannot transfer active power, so:

$$\frac{1}{T}\int_0^T U_s\left(t\right).I_q(t)dt = 0. \tag{7}$$

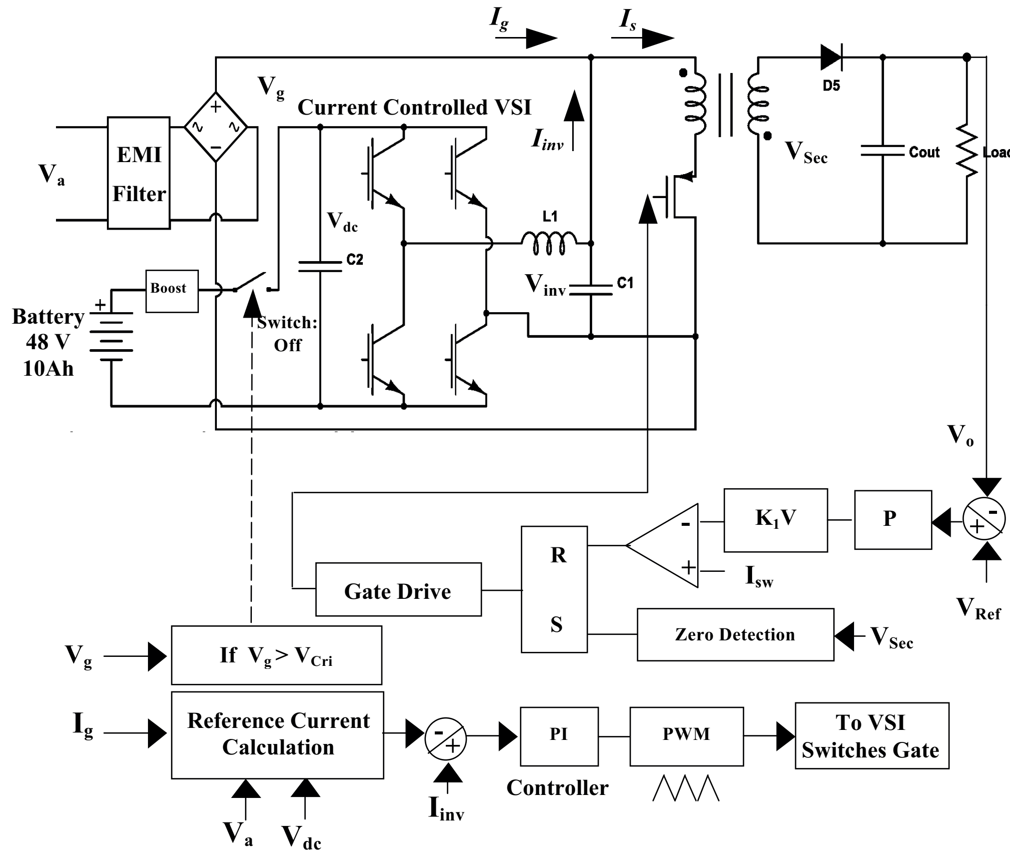


Figure 3. Circuit topology and control strategy of the DPI method during normal operation of the converter.

By substituting Eq. (6) into Eq. (7), the conductance K_c can be determined as:

$$K_c = \frac{\frac{1}{T}\int_0^T U_s\left(t\right) I_L(t)dt}{\frac{1}{T}\int_0^T U_s(t)^2 dt} = \frac{\bar{U_s} I_s}{\bar{U_s^2}}. \tag{8}$$

Finally, the current reference, the sum of the fundamental reactive power current and the harmonic current, is given by:

$$I_q\left(t\right) = I_L\left(t\right) - K_c U_s\left(t\right). \tag{9}$$

2.2. Dual-purpose VSI during a power interruption of the converter

In sensitive systems, such as medical and laboratory emergency power supplies, reliability and robustness are very important, because outages of the power supply lead to lost unsaved data and other imminent injuries. Normally, uninterrupted power supply devices (UPSs) should be installed to improve reliability, but they have large size, high cost, and some usage limitations. The proposed inverter has the capability to continually check the incoming voltage status. When the voltage amplitude falls below a critical level (V_{cri}), indicating that power interruption or fluctuation has occurred, the operation of the dual-purpose inverter changes to a voltage controlled voltage source (VCVS). It provides emergency power to the load when the source voltage fails or drops, protecting the converter against unexpected power disruption through the rechargeable backup battery.

The present battery module consists of three 48 V/8 Ah lithium batteries connected in a series and the battery charger. The battery module capacity can be chosen based on the requirements of the user. The batteries are recharged during normal operation of the converter. The inverter is controlled with the sinusoidal pulse width modulation (SPWM) technique as shown in Figure 4a to generate suitable pulses (Figure 4b) and an accurate sine wave signal.

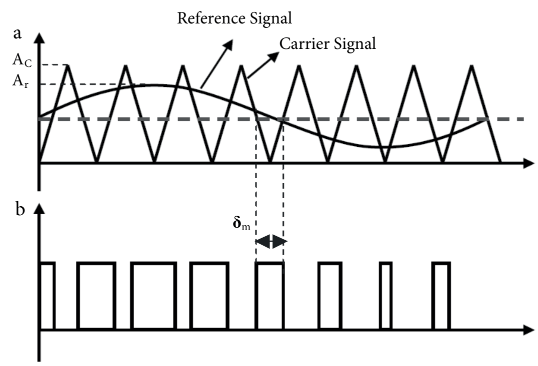


Figure 4. Sinusoidal PWM: (a) triangular carrier wave and sinusoidal reference signal, (b) gate pulse signal.

The frequency ratio of the triangular carrier signal to the reference signal is defined as the frequency modulation ratio (M_f), and the amplitude ratio of the reference signal to the carrier signal is defined as the modulation index (M_a), as:

$$M_f = \frac{f_{ref}}{f_{tri}} \quad , \tag{10}$$

$$M_a = \frac{V_{m,\,ref}}{V_{m,\,tri}} = \frac{A_r}{A_c} \quad , \tag{11}$$

where f_{ref} and f_{tri} are the reference signal and carrier signal frequencies, $V_{m,\,ref}$ is the reference signal peak, and $V_{m,\,tri}$ is the carrier signal peak. It is possible to adjust the output voltage range by adjusting the modulation index. The maximum output voltage can be achieved if the reference signal peak is equal to the carrier signal peak. This can be expressed as:

$$V_{out} = \frac{A_r}{A_c} V_{dc} = M_a V_{dc}. \tag{12}$$

Figure 5 shows the circuit topology and control strategy of the dual-purpose inverter during power interruption of the converter.

The switchover time to connect the backup battery to the circuit and change the control command should be small enough to prevent disruption in the converter's operation. The operation parameters of the dual-purpose inverter in VCVS mode are presented in Table 1.

Together with the inverter, the backup battery can provide power to the converter for a specified time interval, depending on the battery's Ah capacity. It works without causing any malfunction in the converter operation and leads to keeping the borderline conduction mode in the switches of the converter. The generation of the sinusoidal voltage with the same amplitude and frequency of the source voltage by using the inverter allows this circuit to be installed on available conventional switching power supplies.

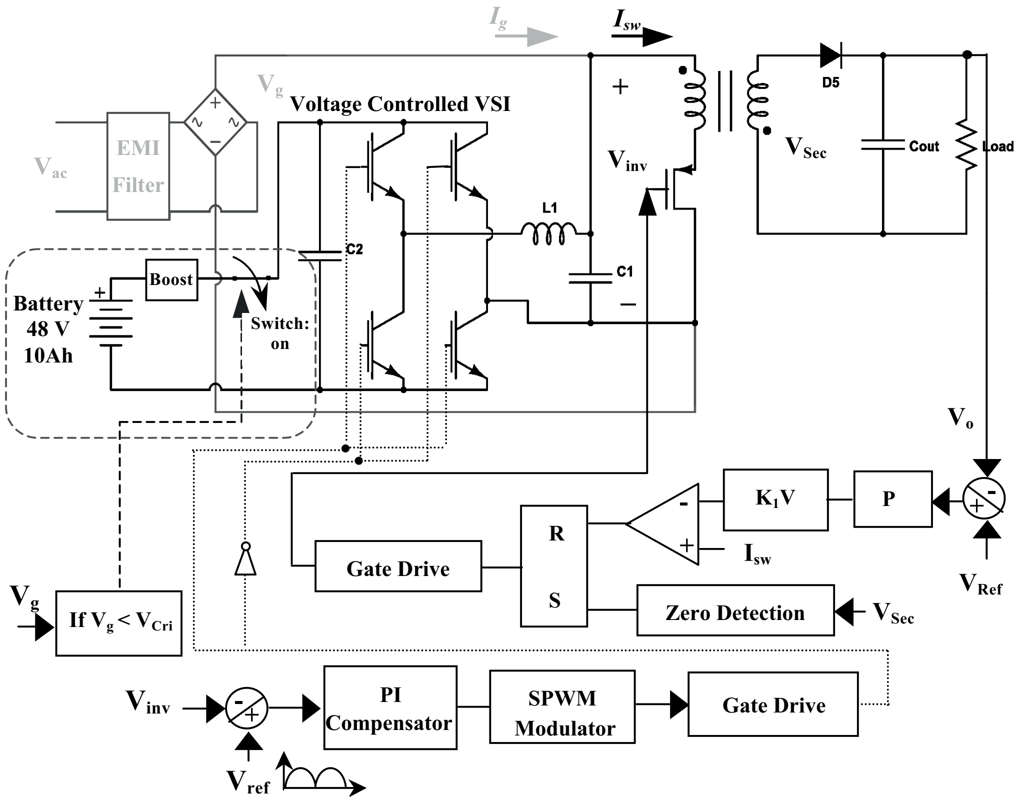


Figure 5. Circuit topology and control strategy of the DPI method during a power interruption of the converter.

Table 1. Operation parameters of the inverter in VCVS mode.

PARAMETER	VALUE
Critical RMS voltage (V_{Cri})	205 V
Switchover time	1 ms
Carrier signal frequency	15 KHz
Reference signal frequency	50 Hz
Batteries characteristics	48 V / 8 Ah

3. Simulation results and analysis

To analyze the behavior of the proposed system and evaluate its harmonic damping performance, the simulation of the control algorithm is carried out in a PSIM environment. The simulation is implemented on a single-phase flyback converter. The characteristics of the system and the converter are expressed in Table 2.

In the AC/DC switching converters without active power factor correction, a capacitor is usually connected across the output of the rectifier bridge in parallel with the converter input to regulate DC voltage and reduce current distortion (AC ripple current flows through the parallel capacitor). The converter waveforms, including the output voltage, the switch current, and the input current resulting from lack of harmonic compensation, are shown in Figures 6a, 6b, and 6c, respectively.

Table 2. Parameters of the system and relevant flyback converter.

Parameter	Value
Supply parameters	220 $\mathbf{V_{rms}}$ / 50 Hz
Converter output power	100 W
Converter output voltage	100 V
Switching frequency	35–60 KHz
Transformer ratio	0.5
Transformer leakage inductance	50 μH
Magnetizing inductance	0.47 mH

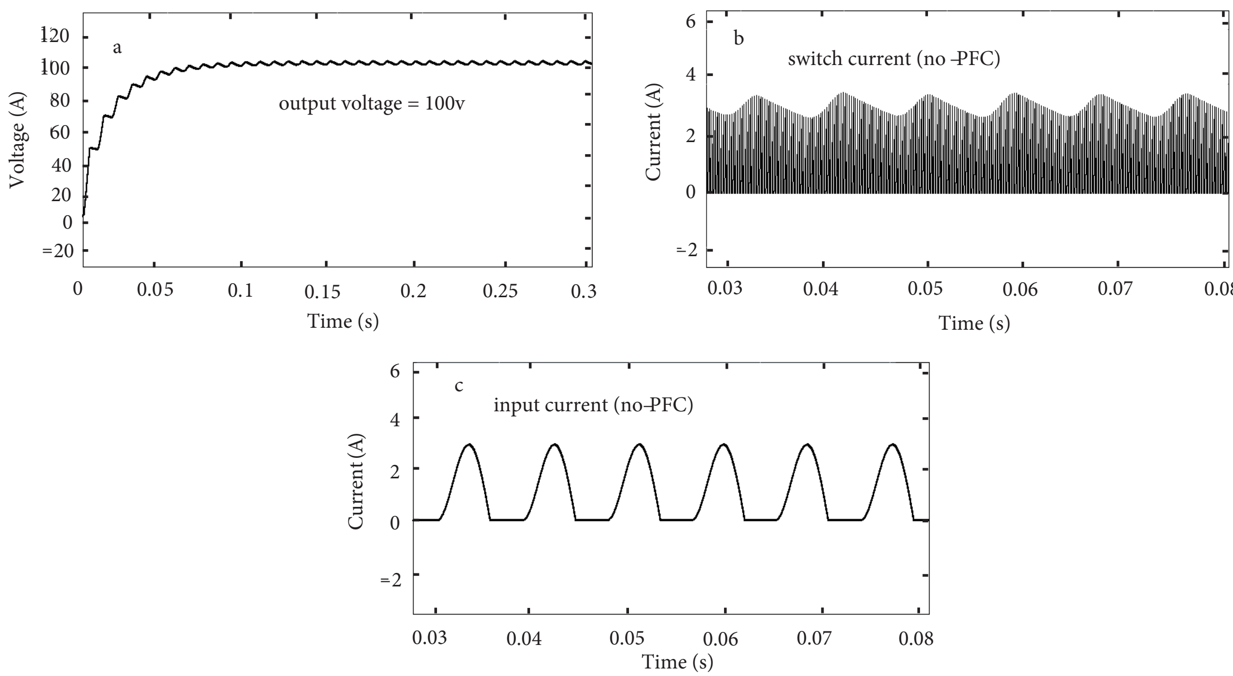


Figure 6. Simulation waveforms of the converter: (a) output voltage; (b) switch current without active PFC control (with regulation capacitor); (c) input current without active PFC control.

In this state, the amplitude of high-frequency harmonics is very high and the input current THD in the presence of the input parallel capacitor is 69.72%. Additionally, the power factor is low, equal to 0.770. The current waveforms in the BCMC state are shown in Figure 7a. It is obvious that the switch current peak follows the sinusoidal reference current in each switching cycle. Therefore, the average current waveform can be near the source voltage shape. This leads to a reduction in the amplitude of harmonic currents. Thus, the inverter's capacity is reduced and compensation quality is improved. Furthermore, the soft switching in the converter switches leads to lower switching losses and stress, easier thermal management, and electromagnetic interference (EMI) reduction due to less di/dt and dv/dt. The rest of the harmonic components are effectively mitigated using the dual-purpose inverter in the next step. Figures 7b and 7c show the relative voltages, the reference, and compensated input current with the proposed PFC method, respectively.

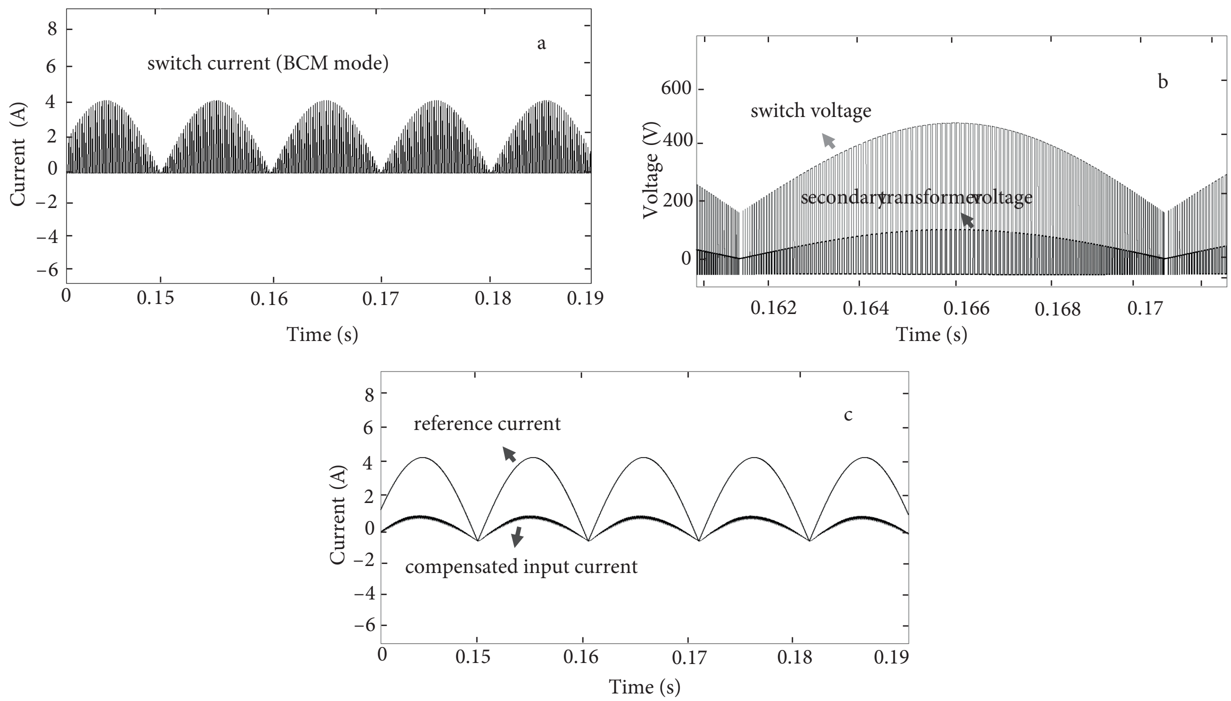


Figure 7. Simulation waveforms of the converter with proposed PFC method: (a) switch current with BCMC; (b) switch voltage and secondary transformer voltage; (c) reference current and compensated input current.

The power factor correction based on the dual-purpose inverter provides great flexibility for harmonic detection and elimination. The compensation can be performed in an extensive range of harmonics and subharmonics with various frequencies as well as various loads. Therefore, low THD, high power factor and efficiency, fast regulation of the output DC voltage, high reliability, and a more flexible control system are achieved. Figure 8 shows the harmonic components in the line input current (harmonic amplitude, percentage of fundamental versus harmonic order) before compensation (Figure 8a) and after PFC control (Figure 8b) using the new method. The percentage of THD with the proposed PFC method is 93.8% less than that of the unfiltered current and 71.1% less than that obtained by the BCMC method.

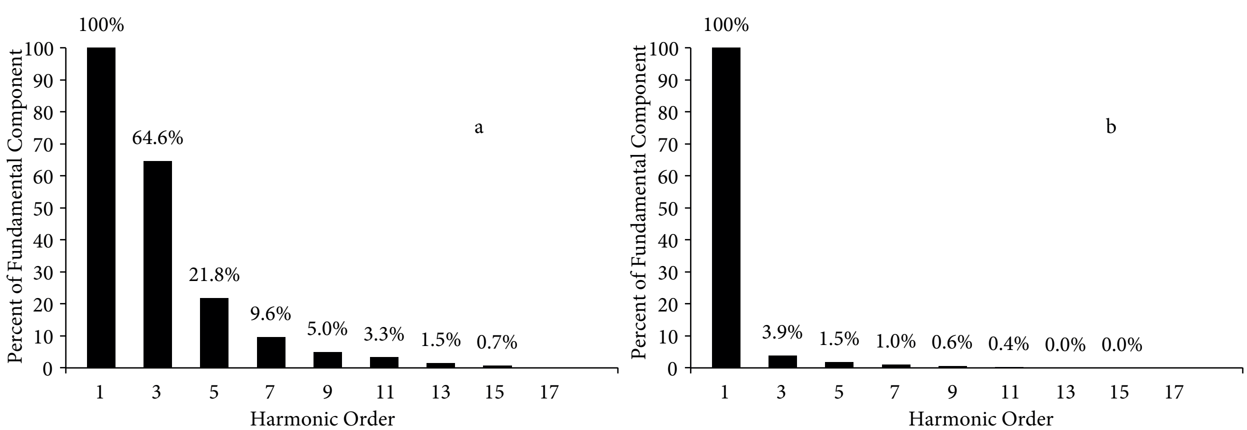


Figure 8. Frequency spectrum of the line current: (a) before compensation (THD = 69.35%); (b) after compensation (THD = 4.24%).

A comparison between the results obtained with the PFC control with BCMC and with the new dual-purpose inverter method at the full load output power of 100 W is presented in Table 3. Both the power factor and total harmonic distortion are dependent on the variation of the input voltage amplitude and the converter output power. As Figure 9a illustrates, the power factor changes with variations in the input voltages and the percentage of the output load. The changes of the line current THD with the variation of the rectified input voltage and the percent of output load are shown in Figure 9b.

Table 3. Comparison of the results in 3 states (in full load).

Method	THD_I	PF
Unfiltered	69.35%	0.770
BCMC	20.04%	0.988
Proposed method	4.24%	0.996

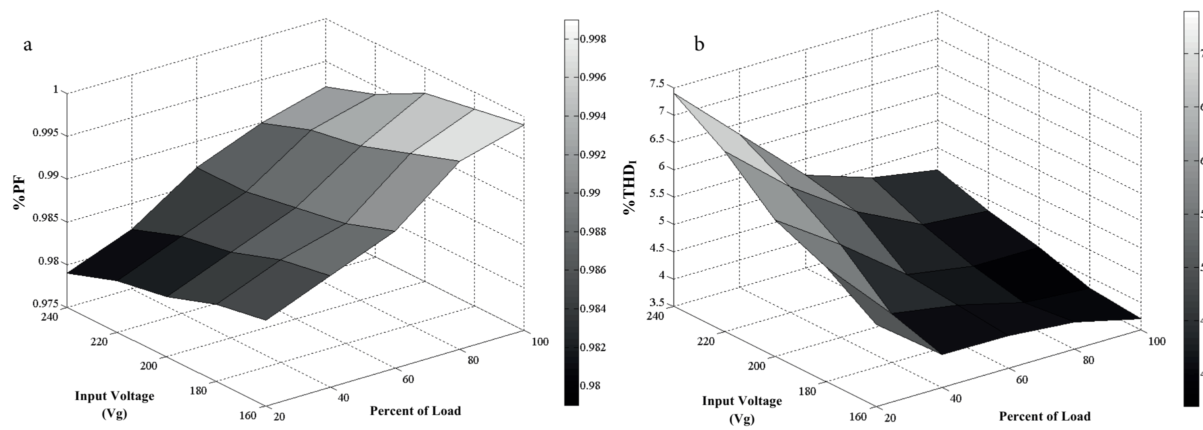


Figure 9. (a) Variations of the power factor in different input voltages and output loads; (b) variations of the THD_I in different input voltages and output loads.

The THD curve at high output power and low input voltage is less than that at low output power and high input voltage. In addition, the power factor at high output power and low input voltage is slightly more than that at light load and high input voltage, but still almost over 0.98. It is verified that the proposed PFC control strategy works well for wide input voltage and load power ranges.

4. Hardware implementation and experimental results

The prototype of the proposed PFC circuit with dual-purpose inverter on a flyback converter has been built and tested in the laboratory. The experimental results based on a laboratory 100-W prototype are provided to verify the effectiveness of the proposed control strategy. The test operating parameters of the prototype are as follows: input voltage: $V_{in,rms} = 220$ V; output DC voltage: $V_o = 100$ V; rated out power: $P_o = 100$ W; magnetizing inductance: $L_m = 470\ \mu$H; switching frequency: $f_{sw} = 35$–60 KHz; and line frequency: $f_{line} = 50$ Hz. Since the cost of the digital signal processors is high, it can limit practical applications of these devices in power converter modules. In this research, for the implementation of the control strategy on the main converter and the lateral inverter, the ATxmega128A1 microcontroller serves to reduce the total cost of the converter. The ATxmega128A1 chip was chosen with consideration of its high performance, simplicity in hardware design, software support, and low price, all of which make it a good candidate to develop digital control for power conversion systems. The measured input current in the cases of non-PFC mode, BCMC technique, and the proposed method are shown in Figures 10a, 10b, and 10c, respectively. As can be seen from the measurements, the input current in the new method is almost sinusoidal and in phase with the supply voltage.

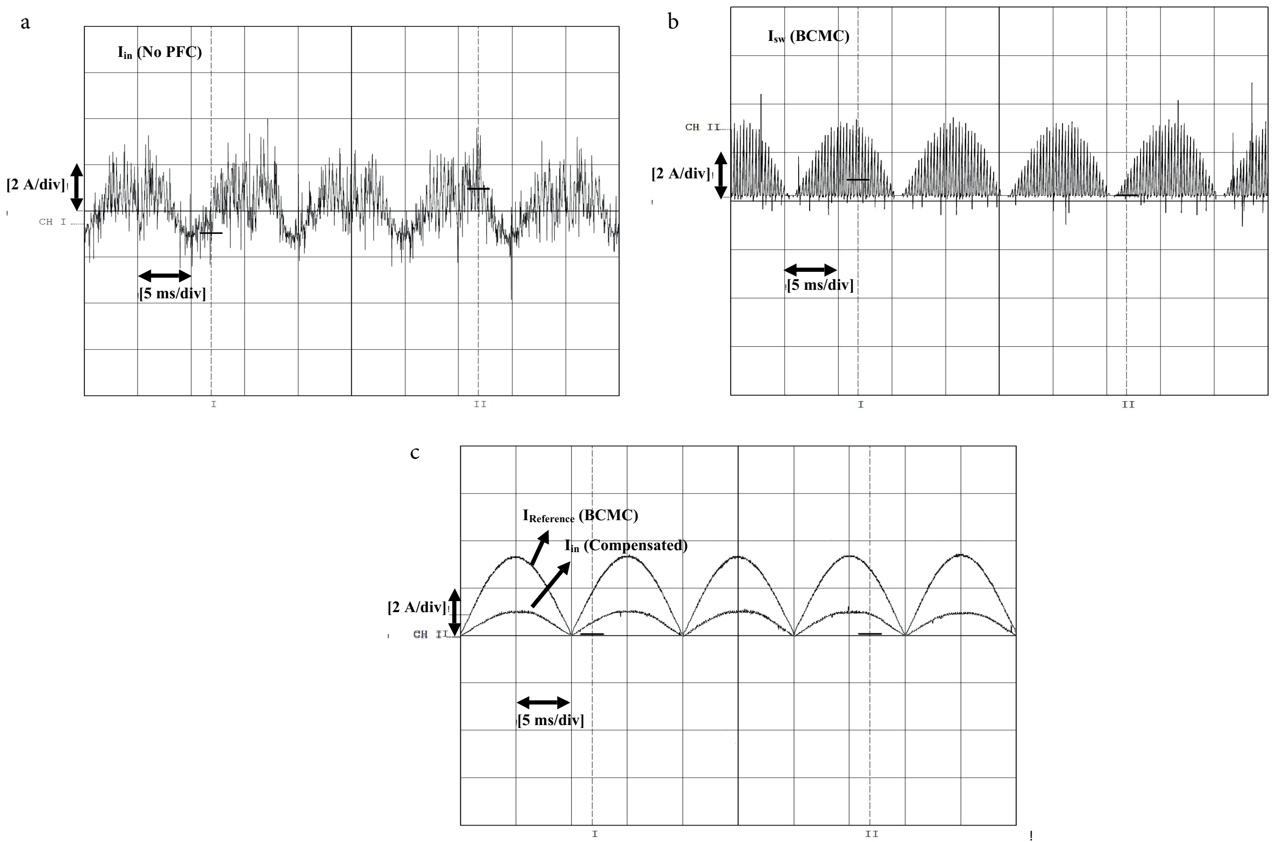


Figure 10. Measured waveforms of the converter: (a) unfiltered input current; (b) switch current with BCMC method; (c) compensated input current and reference current (sinusoidal and in phase with supply voltage).

The switch current can be seen in Figure 11a, which shows the soft-switching in the switches of the flyback converter. Figure 11b shows the sinusoidal output voltage of the inverter in the power interruption state.

In practical implementation, the results clearly show that significant improvement may be obtained in the current shape and the power factor after addition of the dual-purpose inverter. This leads to achieving unity power factor, reducing the line current harmonics, increasing the converter efficiency, canceling the current ripple, and improving reliability. The compensation procedure is fully active, so that even the parallel capacitor in the output of the rectifier bridge is deleted from the circuit. The prototype of the circuit and the workbench can be seen in Figure 12. The prototype board has only been utilized for testing purposes, and the size of the circuit board could easily be reduced with a redesign of the circuit layout.

The input current harmonic spectrum of the prototype for 50-Hz line frequency before and after PFC control are shown in Figures 13a and 13b. As can be seen from Figure 13, the frequency spectrum confirms the validity and effectiveness of the proposed method in harmonic elimination and power quality improvement. The variations of efficiency for different loads in 3 operation modes are shown in Figure 14. Although the proposed method is not quite cheap enough yet due to battery usage, it can be a good alternative method for UPS devices in sensitive power conversion systems.

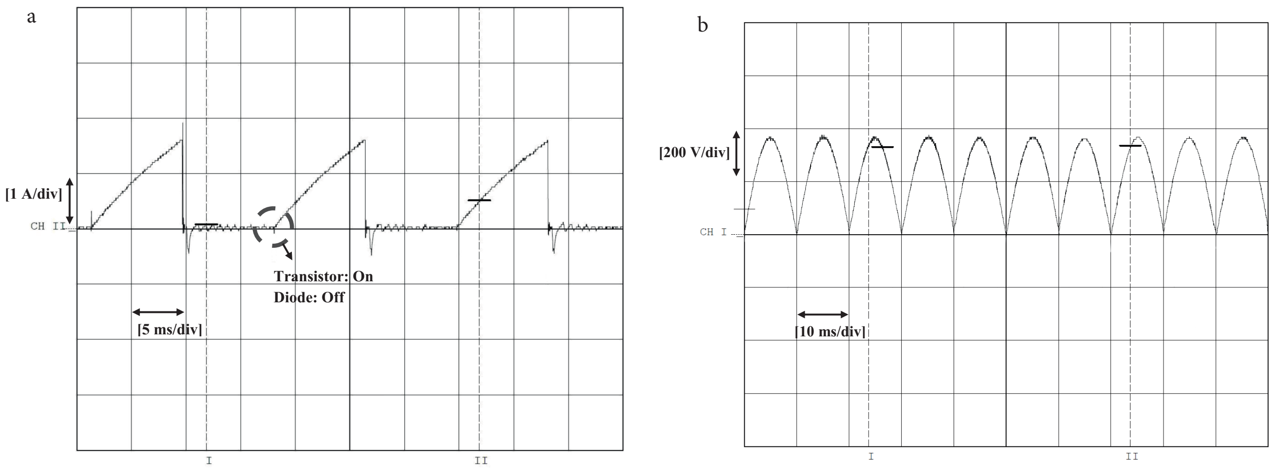
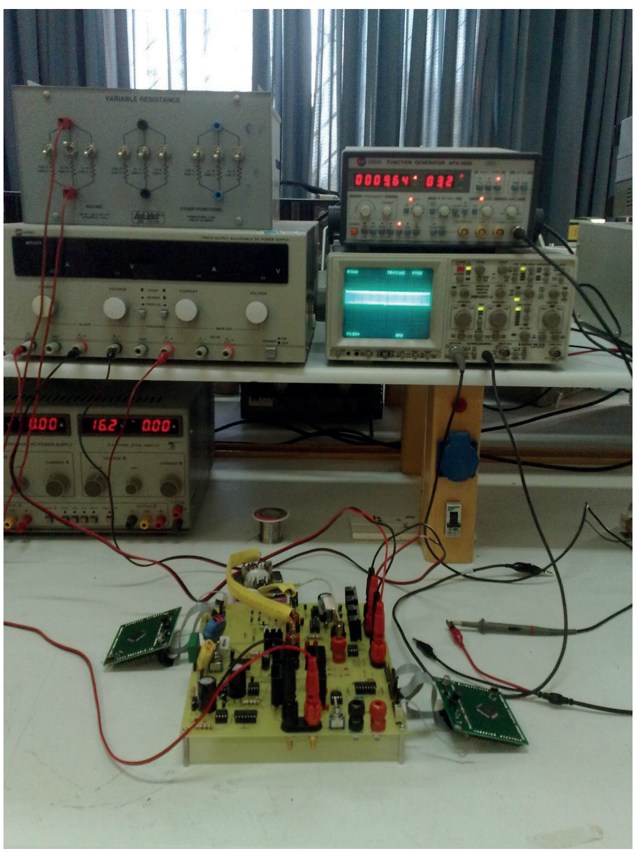


Figure 11. (a) Soft-switching in switch current; (b) generated sinusoidal output voltage of the inverter in the power interruption state.



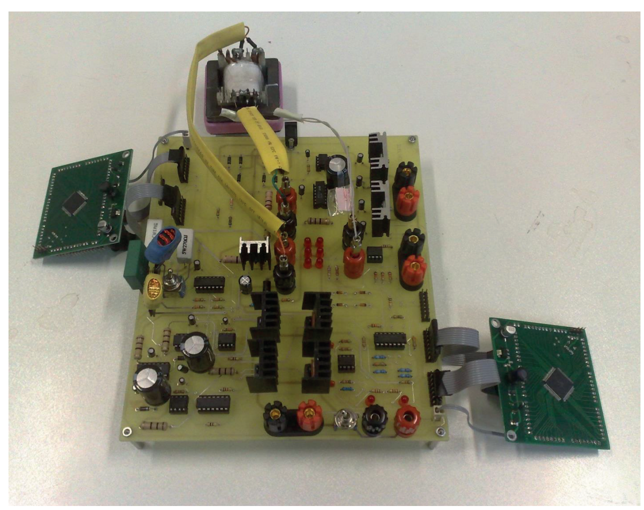


Figure 12. The prototype of the circuit and the workbench.

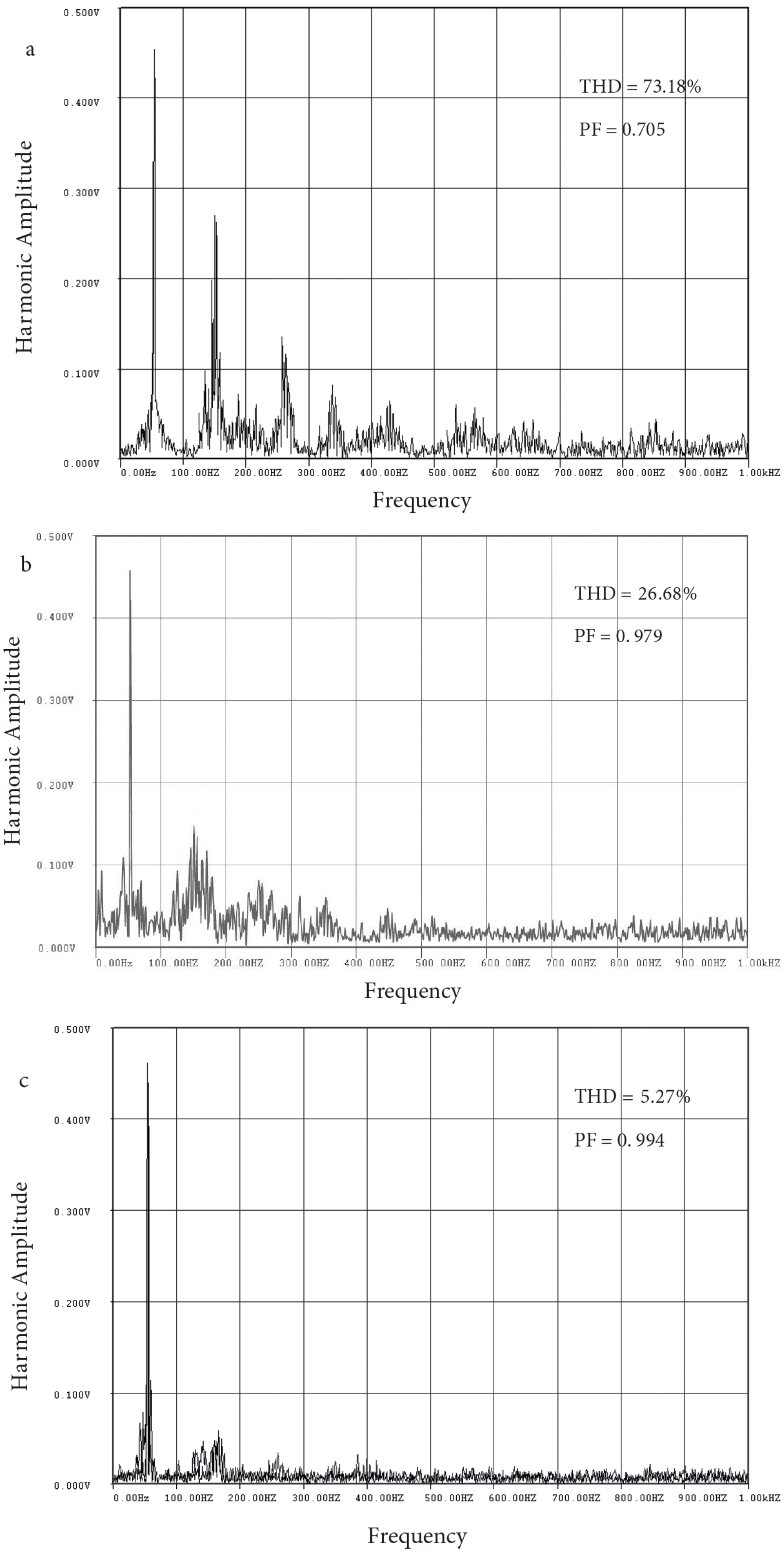


Figure 13. Harmonic spectrum of the line input current waveform: (a) before ompensation; (b) BCM control; (c) proposed method.

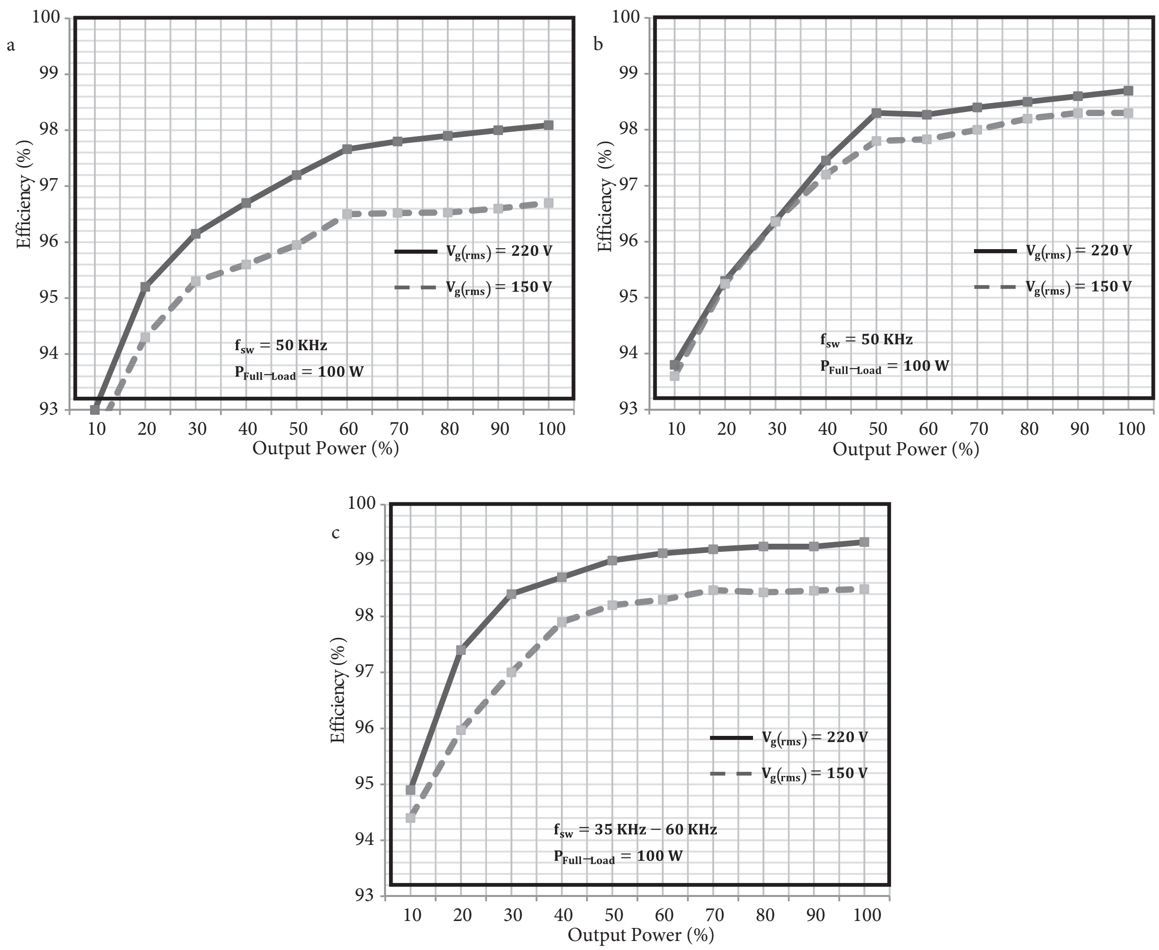


Figure 14. The variations of converter efficiency for different loads: (a) DCM mode; (b) CCM mode; (c) proposed method.

5. Conclusion

This paper has presented a new control strategy for single-phase PFC converters to reduce line current THD, improve the power factor and converter reliability in the power interruption duration of the converter, and reduce both input current peak and ripple. The proposed circuit consists of a low-power portable dual-purpose inverter with 2 independent operation modes. This inverter works as an active harmonic filter compensator during the normal mode of converter operation, while operating as a sinusoidal backup power supply during power outages of the converter. An experimental example has been presented, which confirms the effectiveness of the proposed procedure. The operation principle as well as the simulation and experimental results have been presented and analyzed. The simulation results show that, based on the new PFC control technique, near unity power factor can be achieved in the steady state under a wide range of input voltage and load current conditions. At the full load, the power factor is close to unity (0.998) and the total harmonic distortion of the AC line current is very low (4.24%). Both the simulation analysis and the experimental results verify the feasibility and validity of the proposed PFC circuit and control strategy. Furthermore, the analysis and design methodology of the dual-purpose inverter presented in this paper can also be used in other network compensators with VSI, such as shunt active power filters.

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