

Constant-Switching-Frequency AC-DC Converter Using Second-Harmonic-Injected PWM

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Abstract— This paper describes the operation of an ac-dc converter employing second-harmonic-injected PWM. The boost converter operating on the rectified output uses a constant switching frequency PWM and a discontinuous current mode to reduce the total harmonic distortion in the input current. The implementation and the characteristics of converter are presented.

I. INTRODUCTION

SWITCHED mode power supplies (SMPS) with an improved power factor and a reduced harmonic distortion of the input current have been receiving much attention. Active power factor correction in SMPS can be accomplished in many ways. In a boost circuit, the switching device handles only a portion of the output power and this property can be used to increase the efficiency. The efficiency can be further increased by keeping the ratio of input voltage to output voltage very close to unity. Even though the discontinuous-current mode is associated with a higher voltage or current stress, it has advantages like a reduced loss through zero-current switching, the absence of reverse recovery problem in the diode, and the possibility of a single control loop to control the output power and the output voltage [1], [2]. Boost type switching converters with discontinuous current are especially suitable for medium power levels.

In the discontinuous-mode of operation, there are two different methods of controlling the output, namely, constant-switching-frequency control and variable-switching-frequency control. In both methods, the average current concept is adopted to obtain a lower value of total harmonic distortion (THD). But due to the large variable-switching-frequency range, it is difficult to design the EMI filter. Also the THD value increases as the switching frequency decreases, especially, for higher ratio of input voltage to output voltage. In the constant-switching-frequency control, assuming a constant duty-cycle, the decay time of the inductor-current varies with the magnitude of the input voltage. The variation of the decay time with the input voltage results in a certain distortion in the input current. The THD in the input current increases with the ratio of input voltage to output voltage.

In the variable- as well as fixed-frequency-control methods, the turn-on time of the switching device is constant for a given

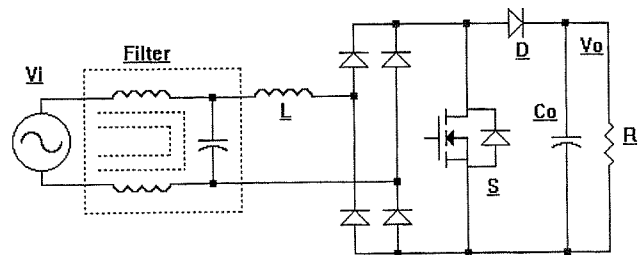


Fig. 1. Power circuit of the proposed ac-dc converter.

value of input voltage [3]. Even though the control is simple, the advantages of PWM are not fully utilized. The paper analyzes the performance of a boost-type ac-dc converter that uses a second-harmonic-injected PWM. The effect of second-harmonic in PWM in reducing the third-harmonic component in the input current is first established. In the converter, the switching frequency is kept constant and the output voltage is varied by varying the duty cycle.

II. PRINCIPLE OF SECOND-HARMONIC-INJECTED CONTROL

The power circuit of the ac-dc converter is shown in Fig. 1. The diode bridge rectifies the ac line voltage, and the Power MOSFET S, the inductor L, and the diode D operate as a boost chopper. The ripple in the output voltage is reduced by using the capacitor C_o . The input line-filter reduces the high-frequency components in the input current. The Power MOSFET is operated at a frequency of 10 kHz, and the output voltage is varied by varying the duty cycle. The control method used is of the constant-switching-frequency type which makes the design of EMI filter easy. In the proposed control, the on-time of the switch is changed periodically using PWM. It is the periodical change in the on-time that makes the value of THD much lower even when the ratio of input-to-output voltages is high.

In general, the input current in a constant-switching-frequency boost converter is composed of a charging component and a discharging component, as shown in Fig. 2. The charging component, which is due to the input voltage, is from 0 to DT and has an average value equal to $I_{on}(avg)$. The discharging component, which is due to the difference between the output and input voltages, is from DT to T_{off} and has an average value $I_{off}(avg)$. The value of $I_{on}(avg)$ is given by

$$I_{on}(avg) = \frac{V_i \cdot T \cdot D^2}{2 \cdot L} \quad (1)$$

Manuscript received January 3, 1995; revised August 24, 1995.

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Publisher Item Identifier S 0885-8993(96)00600-X.

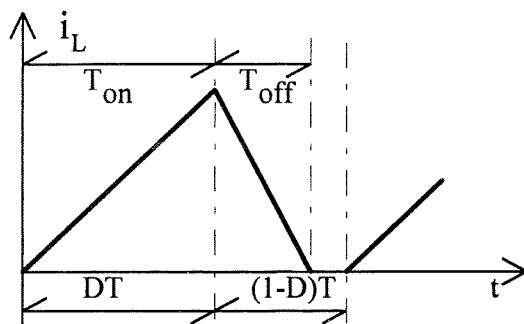


Fig. 2. Input inductor current in one switching period.

where V_i is the input voltage, T is the switching period, and D is the duty cycle. The value of $I_{off}(avg)$ is given by

$$I_{off}(avg) = \frac{V_i |V_i| \cdot D^2 \cdot T}{2 \cdot L \cdot (V_o - |V_i|)(1 - D)} \quad (2)$$

where V_o is the output voltage. For a given output voltage, D is constant. Since $I_{on}(avg)$ is proportional to V_i , it will not contain any lower order harmonic. However, $I_{off}(avg)$ is a nonlinear function of V_i and hence will contain several lower-order harmonics. The nonlinear term $X(V_i)$ given by

$$X(V_i) = \frac{V_i |V_i| \cdot D^2}{(V_o - |V_i|)(1 - D)} \quad (3)$$

contributes to the harmonics. Using Fourier analysis, $X(V_i)$ can be shown to contain several low-order harmonics. The significant lower-order harmonics are the third, fifth, and the seventh. Among the three lower-order harmonics, the third harmonic component has the largest amplitude and has to be attenuated using PWM.

In the new control method, the duty cycle D is varied by injecting a second harmonic to the reference signal. The variation of D is given by

$$D = k[1 + m \cdot \sin(2\omega_i t + \Omega)] \quad (4)$$

where ω_i is the input frequency, m is the modulation index, k is the proportional coefficient that controls the input power, and Ω is initial phase angle that controls the THD value in the input current. Substituting for D from (4) into (1) and (2), the expressions for $I_{on}(avg)$ and $I_{off}(avg)$ can be obtained. Simplified expressions including harmonics up to 5 are as follows:

$$I_{on}(avg) = I_1 \sin(\omega_i t) + I_2 \sin(\omega_i t) \cdot \sin(2\omega_i t + \Omega) \quad (5)$$

$$\begin{aligned} I_{off}(avg) = & I_3 \sin(\omega_i t + \alpha) + I_4 \sin(3\omega_i t + \beta) \\ & + I_5 \sin(\omega_i t + \alpha) \cdot I_6 \sin(2\omega_i t + \Omega) \\ & + I_7 \sin(3\omega_i t + \beta) \cdot \sin(2\omega_i t + \Omega) \\ & + I_8 \sin(5\omega_i t + \eta) \cdot \sin(2\omega_i t + \Omega) \\ & + I_9 \sin(5\omega_i t + \eta) \end{aligned} \quad (6)$$

where α , β , and η are phase angles and I_1 – I_9 are amplitudes. Equations (5) and (6) can be rewritten as follows:

$$I_{on}(avg) = I_{10} \sin(\omega_i t + \gamma) + I_{11} \sin(3\omega_i t + \delta) \quad (7)$$

$$\begin{aligned} I_{off}(avg) = & I_{12} \sin(\omega_i t + \phi) + I_{13} \sin(3\omega_i t + \mu) \\ & + I_{14} \sin(5\omega_i t + \lambda) + I_{15} \sin(7\omega_i t + \rho) \end{aligned} \quad (8)$$

where γ , δ , ϕ , μ , λ , and ρ are phase angles and I_{10} – I_{15} are amplitudes. The total input current $I_{total}(avg)$ is the sum of $I_{on}(avg)$ and $I_{off}(avg)$ and is given by

$$\begin{aligned} I_{total}(avg) = & I_{10} \sin(\omega_i t + \gamma) + I_{12} \sin(\omega_i t + \phi) \\ & + I_{11} \sin(3\omega_i t + \delta) + I_{13} \sin(3\omega_i t + \mu) \\ & + I_{14} \sin(5\omega_i t + \lambda) + I_{15} \sin(7\omega_i t + \rho). \end{aligned} \quad (9)$$

From (9), it is clear that if $I_{11} = -I_{13}$, and $\delta = \mu$, there will be no third harmonic in $I_{total}(avg)$. This can be achieved by adjusting the values of the proportionality constant k , modulation index m , and the initial phase angle Ω in (4). The total harmonics distortion (THD) is dependent on the values of all harmonic components and it is given by

$$THD \approx \sqrt{\frac{(I_{11} + I_{13})^2 + I_{14}^2 + I_{15}^2}{I_{10}^2}} \quad (10)$$

In (9), the value of I_{12} will be much smaller than I_{10} . Hence, the line-frequency component of $I_{total}(avg)$ will be approximately equal to $I_{10} \sin(\omega_i t + \gamma)$. In a practical converter, I_{14} and I_{15} will vary with the modulation index m . It is possible to get the optimal values of k and m , which make the THD as small as possible for given values of input and output voltages. The optimum values of m and k that result in a THD value of 5% or less are found out through simulation and later implemented in the experimental converter. In a boost converter without any modulation, the third harmonic component in the input current will be about 10% of the line-frequency component. Hence, the amplitude of the injected second harmonic in the proposed method needs to be only small. Hence, the modulating index m in (4) and the variation in the turn-on time of the main switch are small.

III. SIMULATION AND EXPERIMENT

The block diagram of the control circuit for the proposed converter is shown in Fig. 3. A phase locked loop (PLL) (CD 4046) generates a second-harmonic sinusoidal signal, which is synchronized to the ac line voltage. A sine waveform generator (ICL 8038) and a synchronizing circuit can also be used to generate the second-harmonic sinusoidal signal. The signal from the waveform generator is combined with the ac input voltage to generate the modulating signal that is applied as the control input to a pulse width modulator (TLC 494). A feedback from the output voltage may be added. The modulator uses a switching frequency of 10 kHz. The modulated output is applied to the gate of the Power MOSFET through a driver. In the circuit, the amplitude and phase angle of the second-harmonic voltage can be independently controlled.

In the new control scheme, the PWM signal is obtained by monitoring the input and output voltages only. Since the power factor is a steady-state quantity, the dc output voltage and dc value of the rectified input voltage are used. There is no need to monitor the current as in the case of continuous current

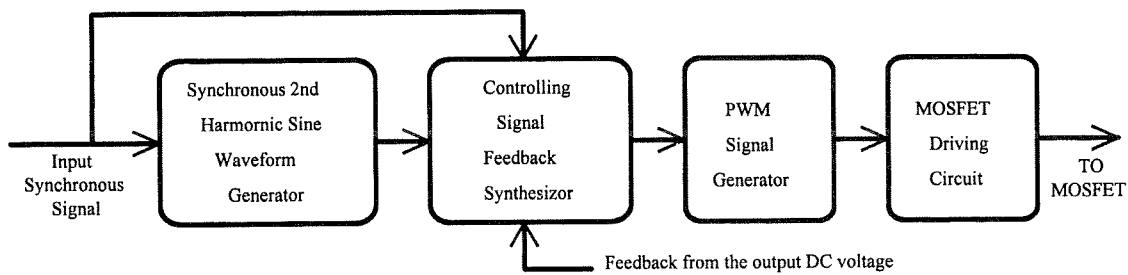
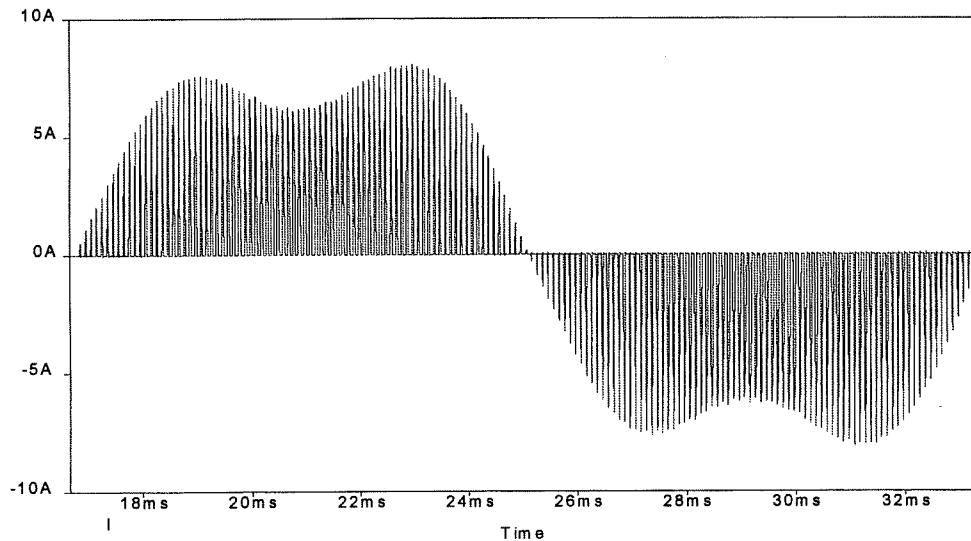
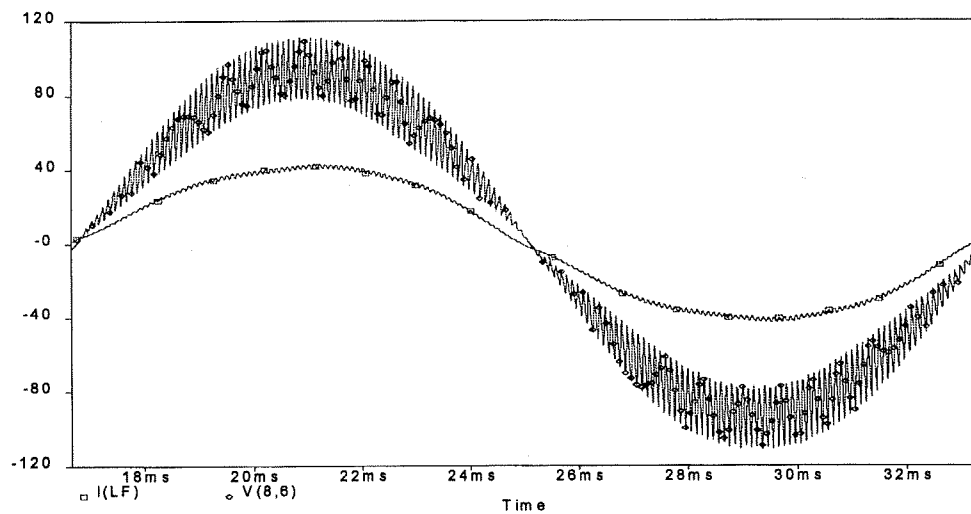


Fig. 3. Block diagram of control circuit.



(a)

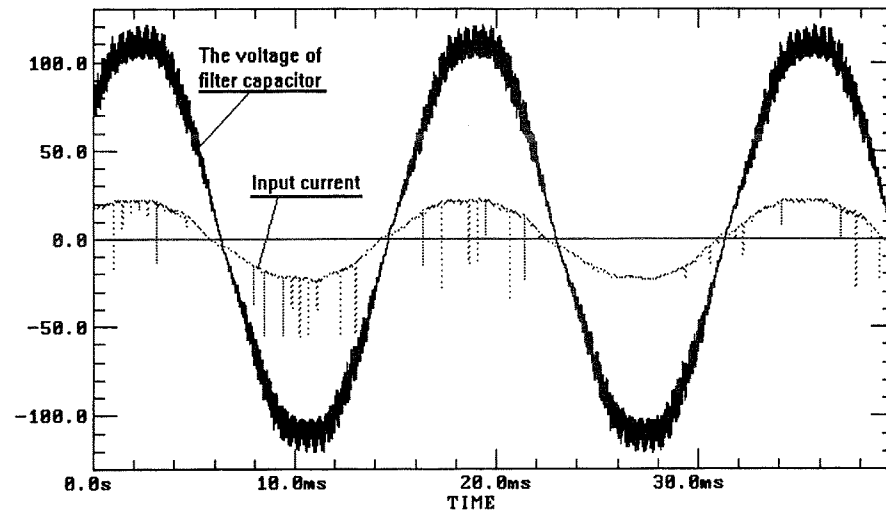


(b)

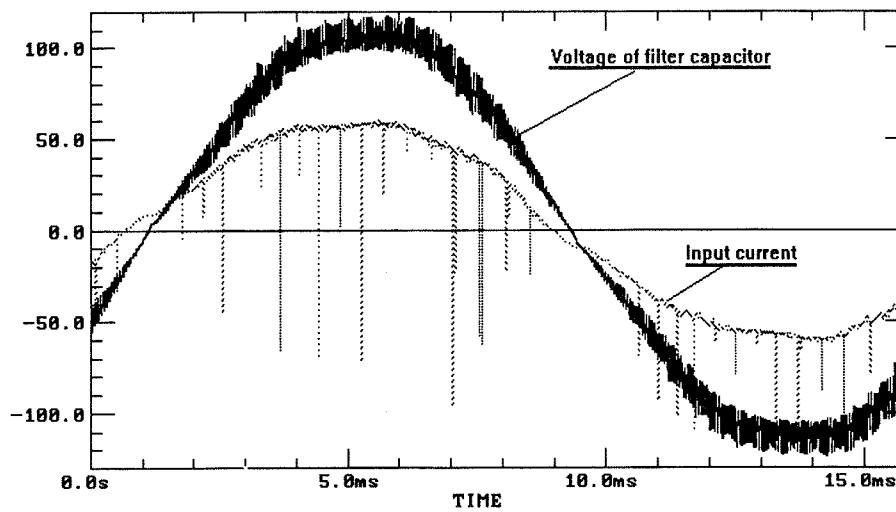
Fig. 4. Simulated waveforms. (a) Current through input inductor. (b) Input current and output voltage of filter.

mode of operation. Thus the present method eliminates the use of a current sensor. So the monitor circuit is very simple. The use of a constant-switching frequency allows the circuit implementation with the help of commercially available PWM IC's. Since the boost circuit works in discontinuous mode, stability is not a problem.

The second-harmonic injected ac-dc converter was simulated using PSPICE. Fig. 4 shows the waveforms of input current and voltage obtained from simulation. The results of the simulation show that it is possible to keep the value of THD lower than 5%, even for higher ratios of input to output voltage, by selecting suitable values of k , m , and Ω . For



(a)



(b)

Fig. 5. (a) Waveforms of input current and voltage across input filter capacitor. (b) Waveforms of input current and voltage (expanded).

example, for an input voltage of 120 V (amplitude), an output voltage of 200 V dc, an output power of 300 W, a switching frequency of 10 kHz, and input inductor of 500 μ H, the value of THD is obtained as 4.07%.

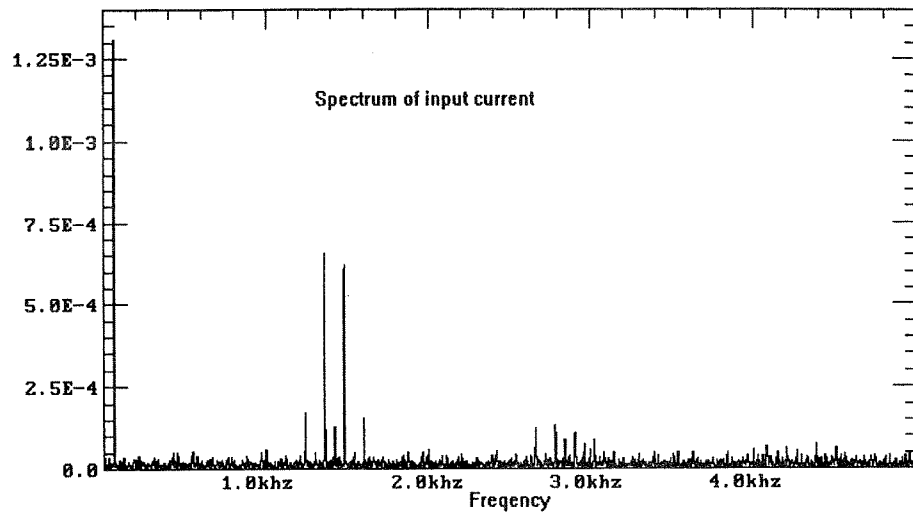
Since the mathematical expression for the input current $I_{total}(avg)$ is very complex, it is difficult to obtain the relation between the amplitude of injected second harmonic and the dc component in (4). In other words, it is difficult to obtain a relation between k and m . But from the simulation of the circuit, for certain input and output voltages, it is found that the modulation index m is to be kept constant in order to have a low value of THD. This means the amplitude of injected second harmonic is varied linearly with the input voltage and the initial phase angle Ω is kept constant. These observations are very important in simplifying the control circuit.

The experimental waveforms of the ac-dc converter are recorded using a digital storage oscilloscope. The input voltage to the converter is 120 V peak and the output voltage is chosen as 200 V dc. Fig. 5 shows the waveforms of the current

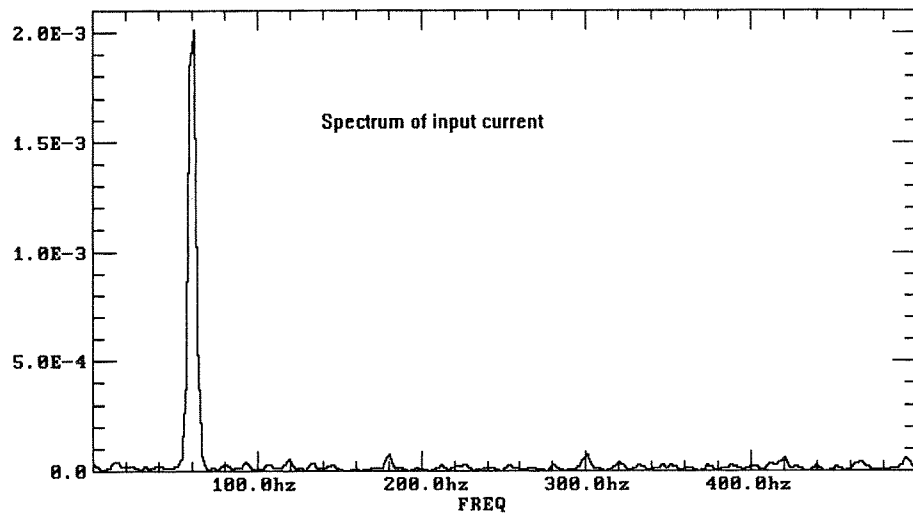
TABLE I
HARMONIC COMPONENTS AND THD

Harmonic Number	Simulation	Simulation	Experiment	Experiment
	With 2nd Harmonic	Without 2nd Harmonic	With 2nd Harmonic	Without 2nd Harmonic
1	1	1	1	1
3	0.03451	0.2093	0.0347	0.217
5	0.01327	0.04156	0.02047	0.02299
7	0.01646	0.01313	0.0146	0.00676
THD	4.07%	21.386%	4.3%	21.8%

through the inductor L and the output voltage of filter. The frequency spectrum of the input current is obtained using a digital data processing software and is shown in Fig. 6. The amplitudes of the lower order harmonics are measured from the frequency spectrum of the input current and shown in Table I. The corresponding results from simulation are also shown in Table I. It is seen that most of the lower order har-



(a)



(b)

Fig. 6. (a) Frequency spectrum of input current (full band). (b) Frequency spectrum of input current (lower band).

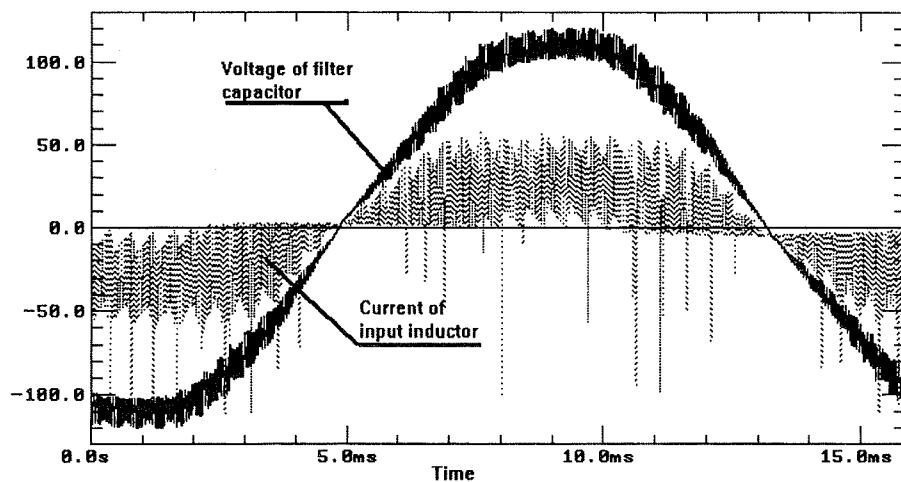


Fig. 7. Experimental waveforms of inductor current and filter output voltage.

monics are attenuated. The simulated and experimental results agree fairly closely. The performance of the ac-dc converter

without second-harmonic injection was also analyzed, and the results are included in Table I. It is found that the value of

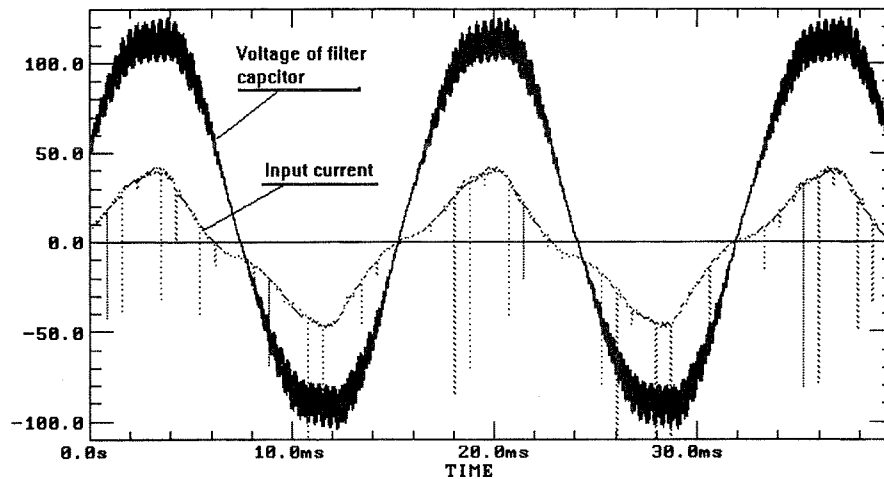
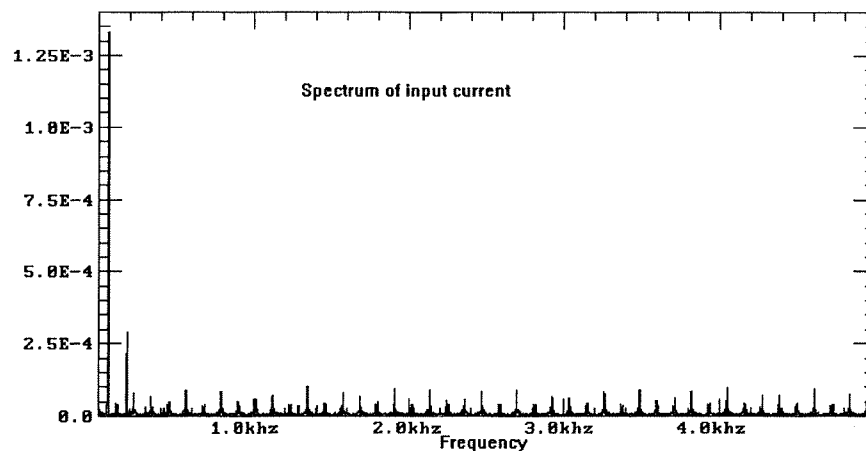
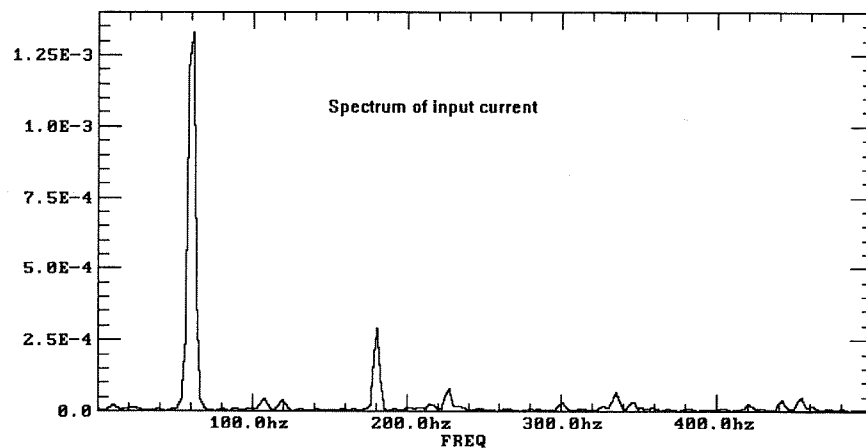


Fig. 8. Waveforms of input current and voltage without second-harmonic injection.



(a)



(b)

Fig. 9. (a) Frequency spectrum of input current without second-harmonic injection (complete range). (b) Frequency spectrum of input current without second-harmonic injection (lower band).

THD is much higher. The waveforms and frequency spectra are shown in Figs. 7–9.

IV. CONCLUSION

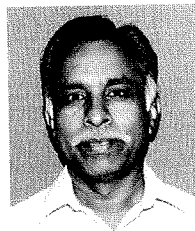
The paper studies the performance of a boost-type ac-dc converter that uses a second-harmonic-injected PWM. It

is found that the third harmonic, which is the lowest-order harmonic (LOH), can be attenuated by adjusting the amplitude and phase of the second-harmonic component in the modulating signal. The paper develops the complete control circuit of the converter and studies its performance. The proposed converter is first simulated using PSPICE, and the parameters

of the control circuit are determined. Experimental waveforms obtained on the converter are shown. The frequency spectrum of the input current and a table showing the amplitudes of the harmonics are presented. It is found that the total harmonic distortion (THD) is less than 5%.

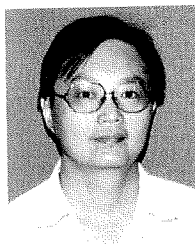
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