TWO-SWITCH BOOST CHOPPER-BASED PFC RECTIFIER FOR ELECTRONIC BALLAST

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ABSTRACT - This paper presents a two-switch boost chopper with a sinewave current shaping and power factor correction scheme, which is applied for driving electronic ballast using high frequency resonant inverter.

A working principle of the proposed one-converter type electronic ballast with power factor correction and active filtering schemes is described on the bases of the equivalent circuit of each operation mode, together with operation analysis. The steady-state performance evaluations of this electronic ballast are illustrated and discussed in experiment.

1. INTRODUCTION

In recent years, it has been often observed that the harmonic current interference occurs in the AC utility power line because switching-mode inverters and converters have been widely used as power conversion supplies of the electronic and electrical systems. Regarding this harmonic current interference, the guideline on the maximum limits of the total harmonic distortion factor of the input current was specified by IEC. Especially, this restriction for illumination equipments are very strict. For the last few years, many type inverters with some sorts of PFC converter as electronic ballast for fluorescent lamps have been reported.[1]-[5]

In this paper, a modified two-switch boost chopper topology for active power factor correction (PFC) converter, which can be effectively applied for one-converter type electronic ballast is presented. Based on experimental results and on analysis of equivalent circuits in each operating mode, some performances of the modified boost chopper type PFC converter are evaluated as compared with a basic performances of a conventional PFC converter. It is proved that this new topology of the active PFC converter treated here can decrease the harmonic distortions of the input line current under a condition of a constant duty ratio due to two switches.

The proposed active PFC converter consists of the boost chopper and high-frequency resonant inverter with a discharge lamp load. Two switching devices can be conveniently used not only as active switches of the proposed PFC converter but also as active switches of a half-bridge-type high-frequency resonant inverter for discharge lamp. New conceptional "one-converter type" electronic ballast can be realized by combining two common active switching blocks. As an experimental result, it is verified that the proposed electronic ballast is able to reduce the harmonic distortion of the input line current with a unity power factor. In this case, the modified boost chopper inverter provides a high power factor of 98% from an experimental point of view.

2. NEW CIRCUIT DESCRIPTION OF ELECTRONIC BALLAST

Fig.1 shows a prototype circuit configuration of the proposed electronic ballast with PFC scheme that is composed of boost chopper with two switches and high-frequency resonant inverter with two common switches. The first power processing stage in Fig.1 operates as a rectification with a DC smoothing circuit. And the second power processing stage operates as high-frequency inverter circuit with discharge lamp loads. The rectification with a DC smoothing circuit consists of 4 diodes bridge, an inductor L_1, a smoothing capacitor Cs and two switching devices; T_1 and T2. And then, the resonant half-bridge inverter circuit with two common switches consists of a series resonant inductor L2, a

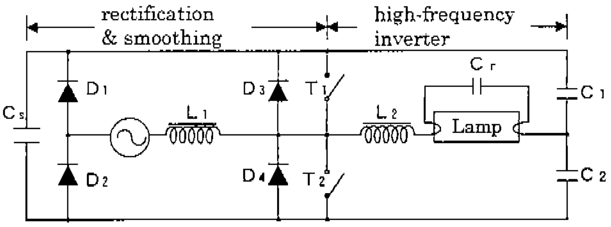


Fig.1 Circuit configuration of PFC converter

resonant capacitor Cr, two voltage-dividing capacitors, C1, C2 and discharge lamp load.

3. OPERATING PRINCIPLE OF MODIFIED BOOST CHOPPER TYPE PFC RECTIFIER

Fig.2 illustrates the circuit operation of the modified boost chopper type single phase PFC rectifier. There exist four states under a condition of the direction of the input current and on/off states of switches. Fig.3 displays the relation between the inductor current and switching periods in case of Discontinuous Inductor Current Mode (DICM). The operations of the proposed circuit are analyzed under the assumption that each device works ideally.

Inductor Current during State (a)

In the first place, during the period as the operation state (a), the inductor current i_1 increases at a function of time. At the end of operation state (a), a peak vaue i_{1p} of the inductor current is estimated as

$$i_{1p} = \frac{1}{L}\int V_i dt = \frac{V_{in}}{L} t_{on} = \frac{V_{in}}{L} T_{on} \tag{1}$$

And the energy stored in L is estimated by,

$$p_{on} = \frac{L}{2} i_{1p}^2 = \frac{V_{in}^2}{2L} T_{on}^2 \tag{2}$$

Inductor current during State (b)

In the next place, during a period of the state (b), the inductor current i_2 decreases because of the energy release and is estimated as

$$i_2 = \frac{V_{in}}{L} t_{on} - \frac{V_{CS} - V_{in}}{L} \cdot t \tag{3}$$

And the energy released from L is calculated by,

$$p_{off} = \frac{V_{in}\,(V_{CS} - V_{in})}{2L} t_{off}^2 \tag{4}$$

The time t_{off} required for the energy release is derived from setting $i_2 = 0$ in (3)

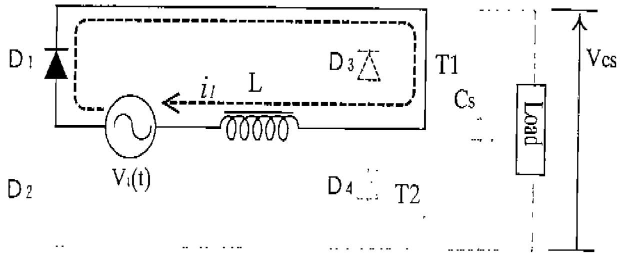
$$t_{off} = \frac{V_{in}}{V_{CS} - V_{in}} T_{on} \tag{5}$$

Input power

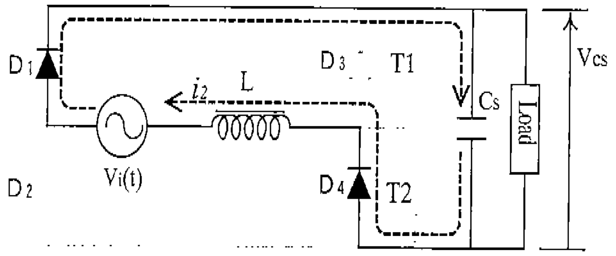
The input energy during n-th switching period depends on an input voltage as shown in (2) and (4). If an input voltage is expressed as $V_{in}(t) = V_I \sin\omega t$, then an input energy p_n during n-th switching period is

$$p_n = \int_0^{t_{on}} p_{on}(t)dt + \int_0^{t_{off}} p_{off}(t)dt = \frac{T_{on}^2 \cdot V_{CS}}{2L} \cdot \frac{V_{in}(t)^2}{V_{CS} - V_{in}(t)} \tag{6}$$

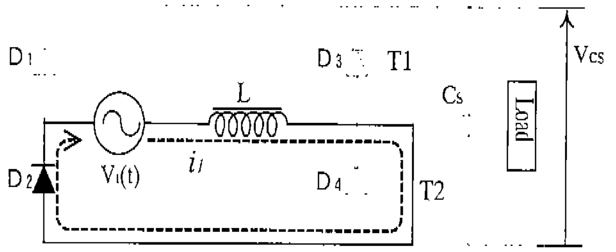
therefore, input power is



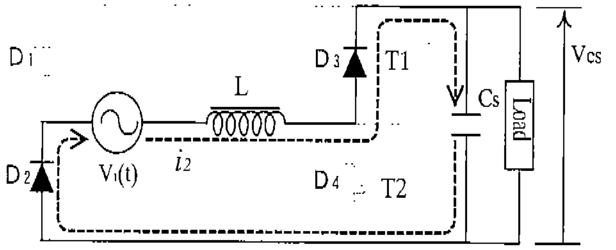
State (a) (T1:on, T2:off)



State (b) (T1:off, T2:on/off)



State (c) (T1:off, T2:on)



State (d) (T1:on/off, T2:off)

Fig.2 Operation mode of proposed boost chopper

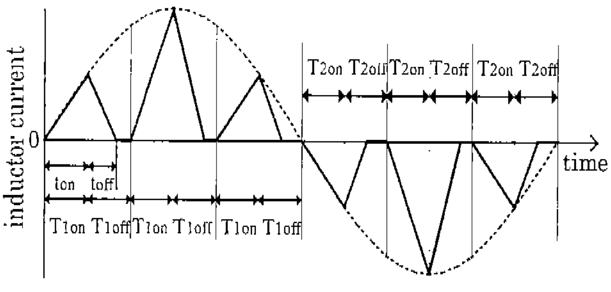


Fig.3 Inductor current waveform in utility power line

$$W = \sum_{n=0}^{f} p_n = \frac{T_{on}^2 \cdot V_I^2 \cdot f}{2\pi L}\int_0^{\pi} \frac{\sin^2\theta}{1-a\sin\theta}\,d\theta$$

$$= \frac{V_I^2 \cdot D^2}{2\pi\, f\, L}\int_0^{\pi} \frac{\sin^2\theta}{1-a\sin\theta}\,d\theta \qquad (7)$$

where, $a = \frac{V_I}{V_{CS}}$, D : duty cycle

f : switching frequency.

The input power is directly proportional to the square of duty cycle, and inversely proportional to a switching frequency. The statements mentioned above are true for the state (c) and the state (**d**). This expression of W is the same form as the expression obtained from an analysis of a conventional active filter as shown in Fig. 4.

Experimental Result

To verify the functions of the proposed PFC converter circuit, some experiments are carried out under the conditions as follows. The power is supplied from 100Vrms of commercial AC power source through Low Path Filter. The oscillating circuit using power MOSFETs is a separate excitation scheme which are driven by a gate-driver IC IR2155. In this case, the duty cycle is 50%.

Fig.5 shows the comparative results in experiment between the proposed circuit and a conventional active filter. The horizontal axis indicates an output power W_{out}. Vertical axes indicate input power W_{in}, output voltage V_{dc}, power factor $\cos\varphi$ and efficiency η. Fig.5 proves that the proposed PFC converter circuit has almost the same functions as the conventional active filter.

Fig.6 illustrates an example of input line current waveform in the modified boost chopper type PFC rectifier with two switches. As results of frequency spectra analysis with FFT, it is clarified that total harmonic distortion factor of the input line current meets the allowable limits of Class C specified by IEC I000-3-2.

4. MODIFIED BOOST CHOPPER FOR ELECTRONIC BALLAST

Because the modified boost chopper needs two switching devices, it looks as if it has disadvantage as compared with a basic performance of a conventional active rectifier. But as shown in Fig.1, these two switches can be commonly utilized for a high-frequency resonant inverter. The case that Power MOSFETs are used as two switching devices, the flywheeling diodes as shown D3, D4 in Fig.1 can be replaced respectively by the body-diodes in Power MOSFET.

Fig.7 shows the equivalent circuits to explain the operating principle of the proposed high-frequency electronic ballast. There exist four operating states in accordance with the operation of the modified boost chopper. By resonance caused by an inductor L2 and a capacitor Cr, high frequency voltage is applied to a fluorescent lamp.

State (A)

During a period of state (A), the energy is stored in the inductor L1 as mentioned in section 3. At the same time,

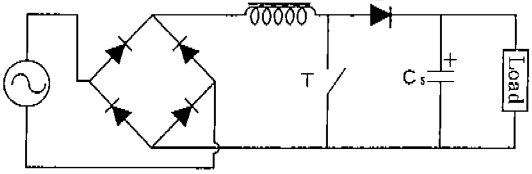


Fig.4 Conventional active filter

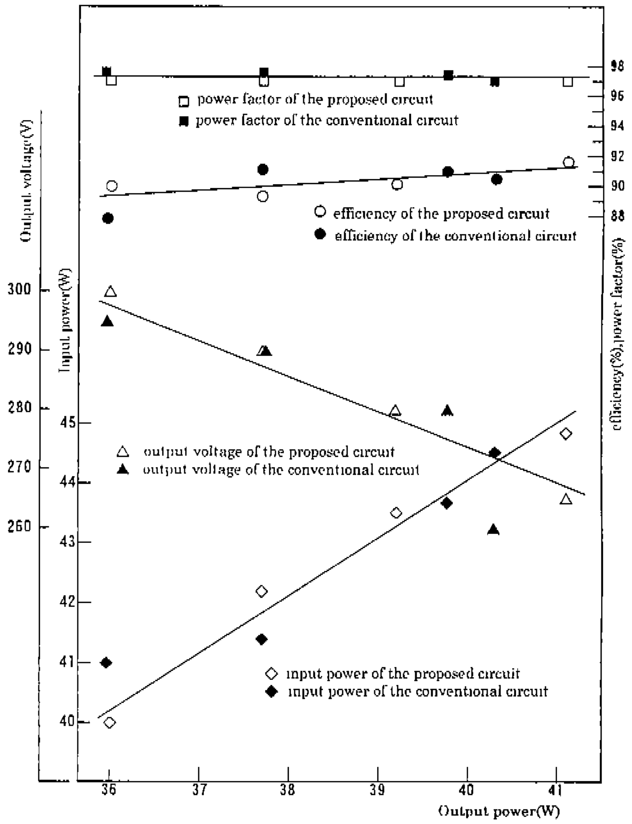
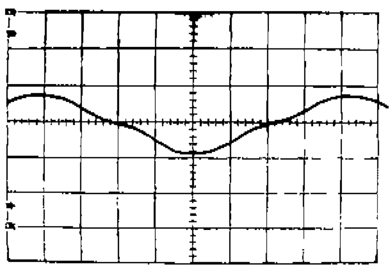


Fig.5 Comparison between the proposed chopper and the conventional chopper



I:540mA/div, T:2ms/div

Fig.6 Typical input current waveform

the smoothing capacitor Cs supplies an electric power for second power stage.

State (B)

During a period of state (B), the energy is released from the inductor L1 and then the capacitor Cs is boosted. At the same time, the capacitor Cs supplies an electric power for second power stage.

State (C)

During a period of state C, the energy is stored in the inductor L1. But in this case, the inductor current flows the reverse direction of state (A). It is a remarkable characteristic of the proposed circuit that the inductor current flows with a bilateral direction. The supply of electric power from smoothing capacitor Cs becomes analogous to the operation of state (A).

State (D)

During a period of state (D), the energy is released from the inductor L1 and then the capacitor Cs is boosted. At the same time, the capacitor Cs supplies an electric power for second power stage.

Experimental Results

To verify that two switching devices can be used not only as switches of the modified boost chopper but also as switches of a half-bridge type high-frequency inverter for a fluorescent lamp, some experiments are performed under the conditions as follows. The power is supplied from utility power source through Low Path Filter LPF. The operating frequency is approximately 80kHz. Two power MOSFETs driven by a gate-driver IC IR2155 are used with a 50% duty cycle. Fig.8 demonstrates the experimental set-up. The design parameters of the PFC converter are

Inductor L1:1.02mH, L2:1.60mH
Capacitor Cs:10 μF, Cr:3.3nF, C1=C2=4.7nF
Lamp : FLR42T6W

Fig.9 shows some observed voltage and current waveforms of the input utility power source. The proposed high-frequency inverter type electronic ballast can make the current waveform a quasi sinusoidal curve.

Fig.10 gives a frequency spectrum analysis for line current in the input utility power source-side. The harmonic distortion of the input current in the case of 100V AC meets sufficiently the maximum limit of IEC 1000-3-2 Class C. And the high-frequency inverter can realize the high power factor of 0.99

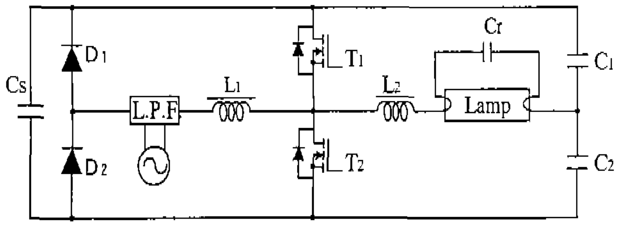
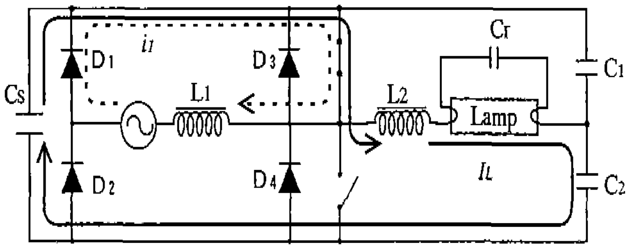
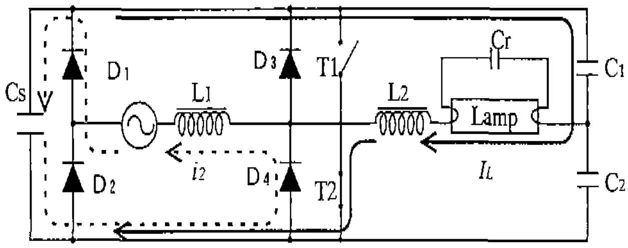


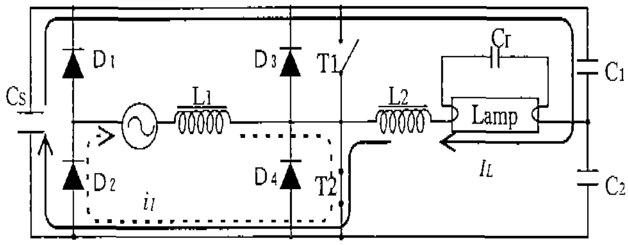
Fig.8 Configuration of experimental circuit



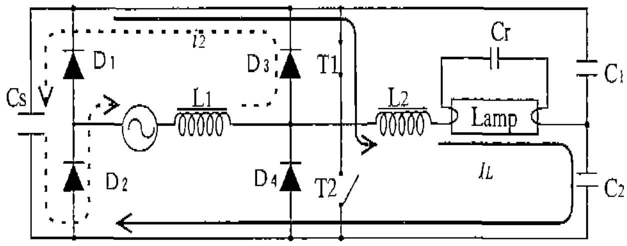
State (A) (T1:on, T2:off)



State (B) (T1:off, T2:on/off)

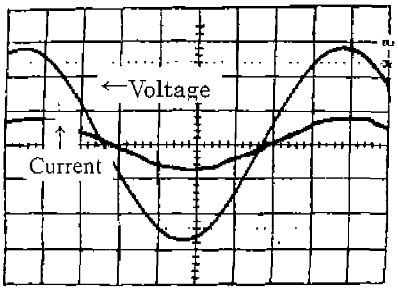


State (C) (T1:off, T2:on)



State (D) (T1:on/off, T2:off)

Fig.7 Behaivior of the proposed electronic ballast



V:50V/div, I:470mA/div, T:2mS/div
Fig.9 Observed waveforms of input voltage and current

Fig.11(a) shows observed waveforms of terminal voltage and current of a fluorescent lamp. And Fig.11(b) illustrates observed waveforms in case of expanded sweep. From these waveforms, it can be confirmed that the current waveform of a fluorescent lamp is a quasi sinusodal curve.

5. CONCLUSIONS

In this paper, a novel prototype of two-switch boost chopper-bast PFC rectifier has been proposed for a high-frequency resonant inverter type electronic ballast. Its operating principle was described on the basis of equivalent circuits of each operating state, together with its unique features.

The feasible high-quality operating voltage and current waveforms of this unique power conversion circuit with a boost chopper type PFC rectifier using two active switches and a high-frequency resonant inverter with a fluorescent lamp load has been demonstrated in experiment. As experimental results, it was proved that the harmonic distortion of the input current obtained by proposed electronic ballast meets the maximum restriction of IEC 1000-3-2 class C sufficiently.

In the future, a boost chopper type PFC rectifier operating under a basic principle of zero voltage soft-switching or zero current soft-switching should be investigated in order to minimize the switching losses of power devices in a high-frequency operation and electromagnetic noises based on switching voltage and current surges.

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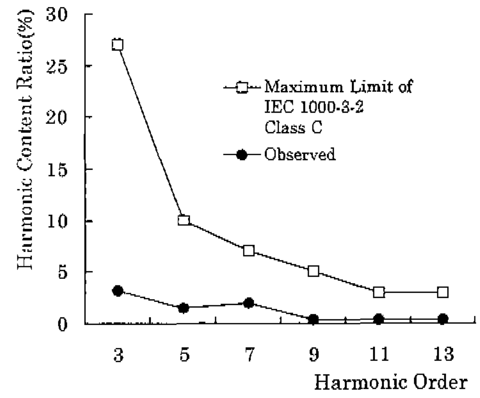
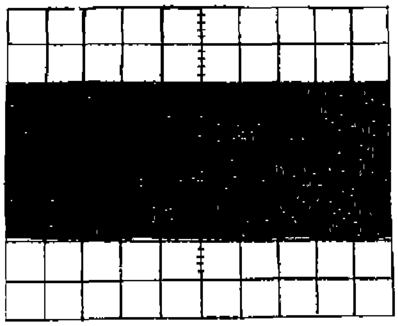
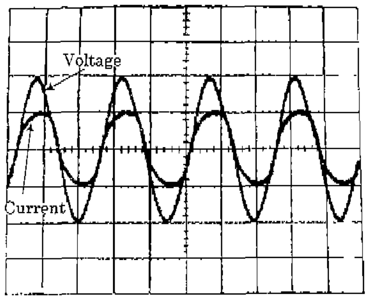


Fig.10 Harmonic current contents



IL:200mA/div,VL:100V/div, T:2mS/div

Fig.11(a) Observed waveforms of lamp voltage and current



IL:200mA/div,VL:100V/div, T:5 μ S/div

Fig.11(b) Observed waveforms of lamp voltage and current (in case of expanded sweep)