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Novel PFC ac-dc converter of high efficiency used in 2 kW fire electric installation

Dong-Kurl Kwak[a)]

Department of Electrical and Electronic Engineering, University of Hanzhong
San 119 Jiheungdong, Donghaesi, Gangwondo 240–713, Korea
a) *dkkwak@hanzhong.ac.kr*

Abstract: This paper proposes a novel power factor correction (PFC) ac –dc converter of high efficiency used in fire electric installation operated with generally rated power 2 kW. The input current waveform in proposed converter is got to be sinusoidal waveform in proportion to magnitude of ac input voltage under constant duty cycle switching. The proposed converter is driven with discontinuous conduction mode (DCM), and then the control circuit requirement is simple. As results of these, the input power factor is nearly unity and the control method is simple. Also the switching devices in converter are operated with soft switching by partial resonant method. The results are that the switching power loss is very low and the efficiency of converter is high. The validity of analytical results is confirmed from some simulative results on computer and experimental results.

Keywords: PFC, ac-dc converter, DCM, soft switching, partial resonant method, loss-less snubber

Classification: Science and engineering for electronics

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1 Introduction

The some fire electric installations in doors are generally operated with dc motor (water pump) of input rated about 2 kW, dc 300 V using a boost ac-to-dc power converter. The electricity energy of the installations is usually supplied from either ac generator of fire engine or auxiliary ac generator equipment. The normally generated ac 100 V is boosted dc about 300 V by power converter (boost ac-dc converter). The boost ac-dc converter is necessarily required high power factor and high efficiency to make the most use of the provided energy.

Recently, the PFC techniques for boost ac-dc converter have received great attention and a number of new techniques have been proposed [1, 2, 3, 4]. There are two input current control modes for the converter of this usage. One is continuous conduction mode (CCM) of dc input current and another is discontinuous conduct- ion mode (DCM) of that. The DCM control method is used by a large number of converters, because the control circuit and technique of DCM are simple. Also in discontinuous mode, the ac input current is nearly sinusoidal waveform with the constant duty cycle switching [4, 5]. Another merit of this mode is that turn on of switches in converter occurs at zero current switching (ZCS). Therefore switching loss caused by switching operation is very low. However, the control devices are switched off at the maximum current and a certain level of voltage in one cycle of the carrier frequency. It causes the large current stress of the switching device and electromagnetic interference. As a result of these, the converter brings on low efficiency. To improve these, a large number of soft switching topologies included resonant circuits have been proposed [5, 6, 7, 8]. But these topologies increase number of switching device in circuit and complicate sequence of switching operation.

This paper describes a novel PFC boost ac-dc converter operated with new soft switching for partial resonant method and driven with DCM. The partial resonant operation makes zero current switching and zero voltage switching (ZVS) for control switches without switching losses so called "soft switching" [6, 8]. Also the partial resonant circuit is driven by not continuously resonant operation but partially enforcement at only switching turn-on time and turn-off time. It reduces capacity division and stresses of resonant devices. The proposed PFC converter achieves high efficiency and high power factor from the results mentioned above.

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2 Circuit configuration and operation principle

Figure 1 (a) and (b) show the conventional PFC boost ac-dc converter and the proposed new PFC boost ac-dc converter used in fire electric installation. The proposed converter is composed of controlling devices, step-up inductor L_r, and snubber capacitor C_r used in conventional boost converter.

The switching devices in proposed converter are operated with soft switching by partial resonance technique and with control of constant duty cycle. The partial resonant circuit makes use of a step-up inductor and a loss-less snubber capacitor. It is for the accumulated energy in snubber capacitor to regenerate into input side without the power loss of snubber circuit produced in conventional boost converter. The current flowing through inductor is controlled to be discontinuous like Figure 1 (c), and then turn-on operation of the switching devices S_1 and S_2 becomes to be ZCS. And turn-off of switches is worked on ZVS by the partial resonant operation. Therefore the proposed converter is operated with high efficiency. Also the input current waveform is got to be sinusoidal waveform in proportion to magnitude of ac input voltage under the constant duty cycle switching by DCM, as shown Fig. 1 (c). The input power factor is nearly unity and the control method is simple.

Figure 1 (d) shows four equivalent circuits of operational modes in one cycle switching of the proposed converter. If the inductor of output side is bigger than the inductor of resonant circuit, the load side can consider with a constant current source during one cycle switching. At initial condition, the current flowing through inductor L_r is zero. Switch S_1 and S_2 are off-state and capacitor C_r is charged at the same voltage magnitude of dc output voltage V_{cd}. The ac input voltage v_{in} and the output voltage of full bridge rectifier v_r is expressed as like eq. (1) and eq. (2).

$$v_{in} = V_m \sin \omega_s t \quad (1)$$

$$v_r = |v_{in}| = |V_m \sin \omega_s t| \quad (2)$$

Mode 1 ($\mathbf{T_1 : t_0 \leq t \prec t_1}$)

Mode 1 begins by turning on both S_1 and S_2 at the same time. The input voltage v_r and the capacitor voltage v_{cr} are added and applied to the inductor L_r. Then this mode takes form of a series LC resonance circuit. The capacitor C_r discharges its electric charge through the inductor L_r. Turn-on of the switching devices occurs in zero current state. Hence this is ZCS. The capacitor voltage v_{cr} is expressed in eq. (3) and the inductor current i_{Lr} increases as like eq. (4).

$$v_{cr} = (v_r + V_{cd}) \cos \omega_r t - v_r \quad (3)$$

$$i_{Lr} = \frac{v_r + V_{cd}}{X} \sin \omega_r t \quad (4)$$

where $\omega_r = 1/\sqrt{L_r C_r}$, $X = \sqrt{L_r / C_r}$.

This mode ends when $v_{cr} = 0$. And the inductor current I_1 at the end of this mode is given by

$$I_1 = \frac{1}{X}\sqrt{V_{cd}^2 + 2 v_r V_{cd}} \quad (5)$$

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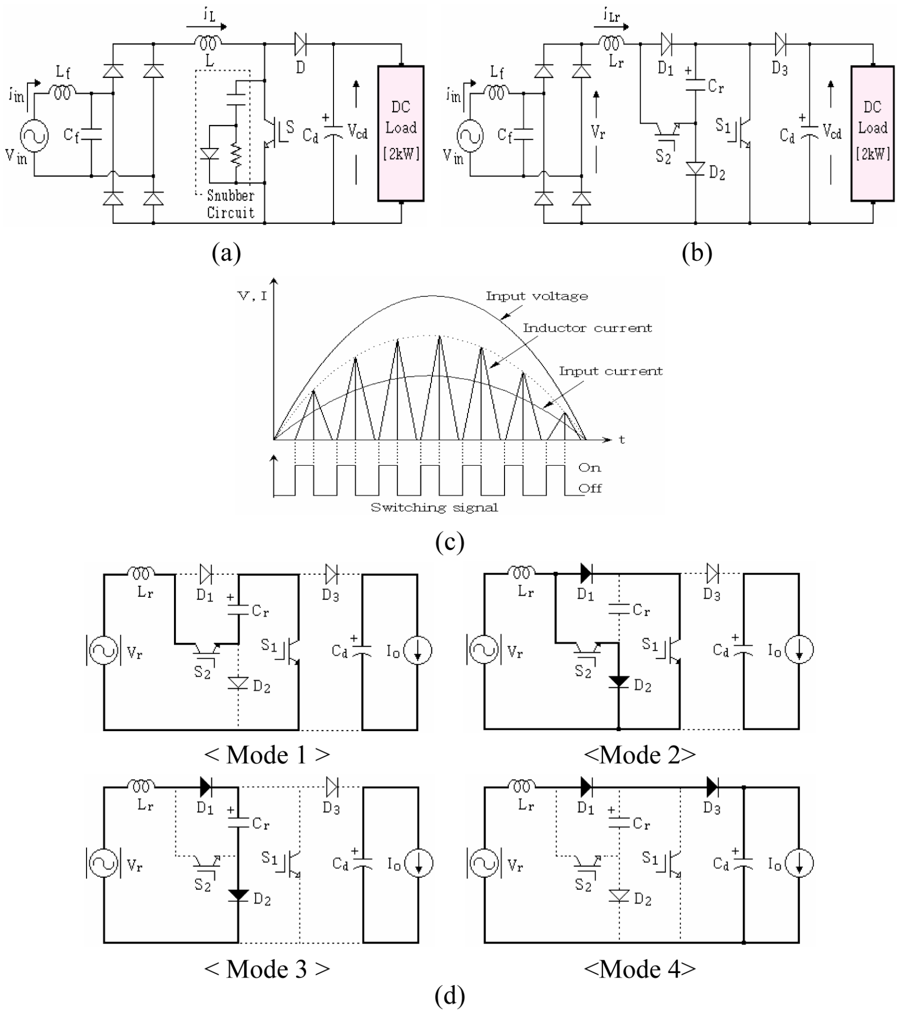

Fig. 1. Configuration of (a) conventional and (b) proposed PFC boost ac-dc converter. (c) Input waveforms of DCM. (d) Equivalent circuits of operational modes in one cycle switching of proposed converter.

Mode 2 ($T_2 : t_1 \leq t \prec t_2$)

Mode 2 begins when the voltage across C_r achieves zero. Then the diode D_1 and D_2 start conduction. The inductor current is divided into two paths of D_1-S_1 and S_2-D_2. The inductor current is linearly increased as follows until the switches are turned off.

$$i_{Lr} = \frac{v_r}{L_r} t + I_1 \tag{6}$$

This mode ends when both switch S_1 and S_2 are turned off, and the inductor current I_2 at the end of the mode is given by eq. (7). Where, The period T_{on} is on-time of switch. In Mode 2, the inductor L_r stores a suitable energy.

$$I_2 = I_1 + \frac{v_r}{L_r} \left\{ T_{on} - \sqrt{L_r C_r} \cos^{-1} \left(\frac{v_r}{v_r + V_{cd}} \right) \right\} \tag{7}$$

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Mode 3 ($\mathbf{T_3 : t_2 \leq t \prec t_3}$)

Mode 3 begins by turning off both S_1 and S_2 at the same time. The current flowing through L_r takes a route of D_1-C_r-D_2 and charges C_r. Then this mode takes form of a series LC resonance circuit. Turn-off of S_1 and S_2 occurs in ZVS because the voltage of C_r is zero. In this mode, the voltage of C_r and the current of L_r are evaluated as follows

$$v_{cr} = v_r + \sqrt{\frac{L_r}{C_r}} I_a \sin(\omega_r t + \theta) \tag{8}$$

$$i_{Lr} = I_a \cos(\omega_r t + \theta) \tag{9}$$

where $I_a = \sqrt{\frac{C_r}{L_r} v_r^2 + I_2^2}$, $\theta = \sin^{-1}(-\frac{v_r}{\sqrt{v_r^2 + \frac{L_r}{C_r} I_2^2}})$.

$v_{cr} = V_{cd}$ is achieved and diode D_3 begins to conduct, then this mode ends. The inductor current at the end of this mode can be assumed by the constant value I_2, because of the very short period of this mode.

Mode 4 ($\mathbf{T_4 : t_3 \leq t \prec t_4}$)

By the conducting of diode D_3, the inductor current flows into the load. The current is decreased linearly as following to the next equation and achieved to zero at the end of mode 4.

$$i_{Lr} = \frac{v_r - V_{cd}}{L_r} t + I_2 \tag{10}$$

3 Computer simulation and Experimental results

The proposed PFC ac-dc converter was analyzed by Pspice simulation program. The simulation circuit was regulated at dc 300 V output with ac 100 V input.

The diodes are ideal, and the switches replace with equivalent circuit consisted of a variable resistance and an ideal diode. L_r and C_r were selected at 60 μH and 90 nF, respectively. The smoothing capacitor C_d used 2000 μF, and the output load was replaced with a constant current source 3 A. The switching frequency was 40 kHz and the duty cycle was regulated at 30%. The filter inductor L_f and filter capacitor C_f about input LPF were selected at 3 mH and 5 μF, respectively.

Figure 2 (a) shows waveforms of each part in one cycle switching in order to certify the partial resonant operation and the soft switching operation of control devices. In Figure 2 (a), the controlling switches are turned on at t_0, and C_r is begun to discharge. v_{cr} is achieved to zero at t_1. At t_2, the switches are turned off, and C_r is charged with i_{Lr} and achieved to V_{cd} at t_3. At t_4, i_{Lr} is achieved to zero, and the switches are kept off till the next cycle. As the current flowing switches is zero at t_0, the switches are turned on with ZCS. Also, as the voltage across switches is zero at t_2, the switches are turned off with ZVS. The simulated results are confirmed the validity of the analytical results for each mode as previously stated.

Figure 2 (b) shows input waveforms and frequency spectrum of input current through input LPF of conventional PFC converter. The amplitude

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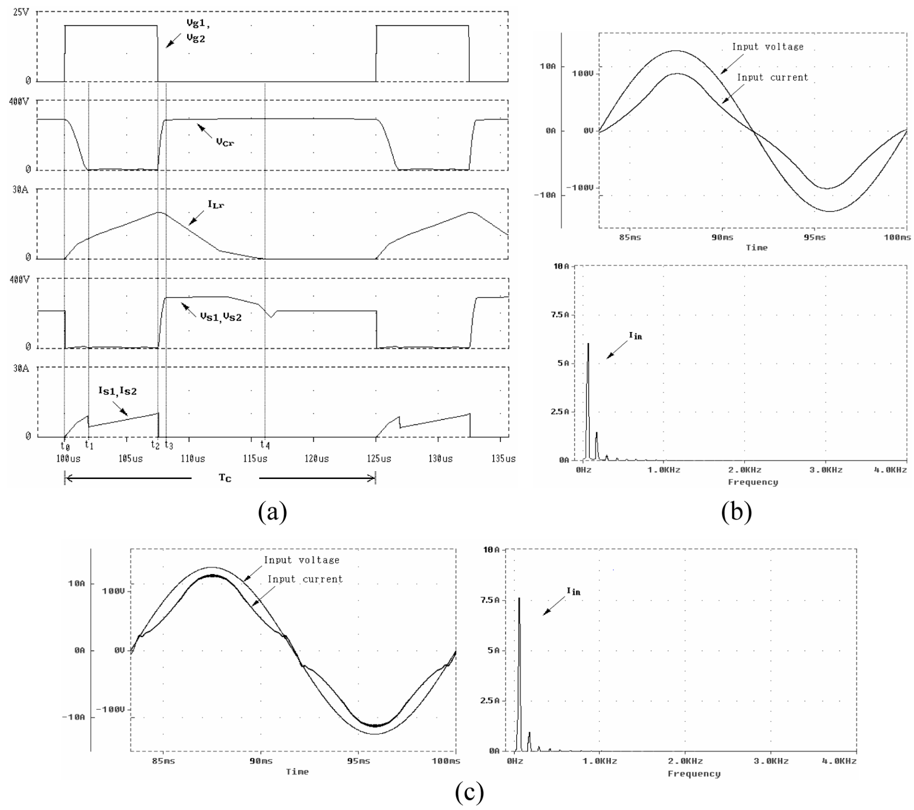

Fig. 2. Simulation waveforms: (a) Waveforms of each part in one cycle switching, Input waveform analyses of (b) the conventional PFC converter and (c) the proposed PFC converter.

of input current is smaller than a sinusoidal wave around the zero cross point. Hence the current includes quite a little of the third harmonics. Figure 2 (c) shows input waveforms and frequency spectrum of input current through input LPF of proposed PFC converter. Because the accumulated energy of capacitor C_r is applied to inductor L_r through input source for the partial resonant operation at Mode 1, the amplitude of input current is increased around the zero cross point. Hence the current is more similar to a sinusoidal waveform.

In order to confirm the feasibility, the proposed converter was experimented to a rated output power 2.0 kW. The output load was regulated from a drain pump of 2 kW dc motor. The used power switch was implemented by a Fuji IGBT series 1MBH40-60 ($V_{CE} = 600$ V, $I_C = 40$ A, and $T_{off} = 640$ ns). And the power diodes were used by FRD (fast recovery diode) type. Figure 3 (a) and (b) show waveforms of each part in one cycle switching (switching frequency 40 kHz and duty cycle 30%). The switches using in converter were operated with soft switching, namely turn-on at zero current and turn-off at zero voltage, according to partial resonant operation. Also the partial resonant circuit is driven by not continuously resonant operation but partially enforcement at only switching turn-on time and turn-off time. It reduced capacity division and stresses of the resonant devices.

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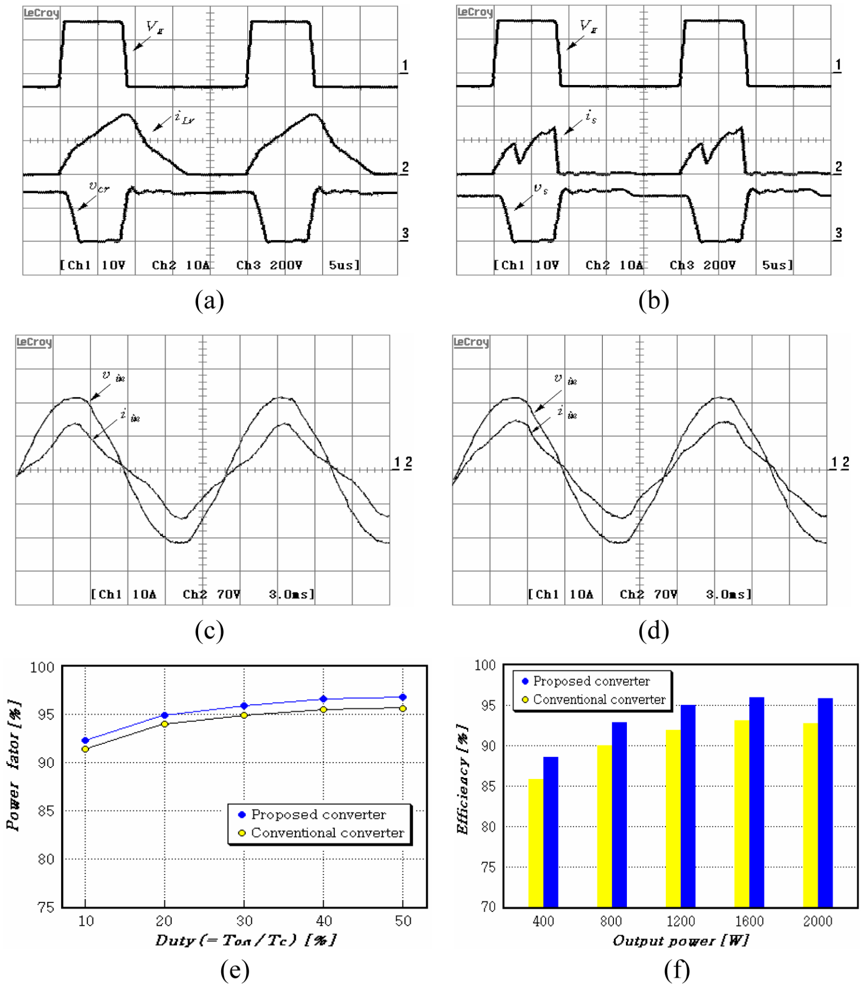

Fig. 3. Experimental waveforms: (a) and (b) are waveforms of each part in one cycle switching. Input waveforms of (c) the conventional PFC converter and (d) the proposed PFC converter. (e) Measured power factor comparison. (f) Measured efficiency comparison.

Figure 3 (c) and (d) show input waveforms of the conventional PFC converter and input waveforms of the proposed PFC converter, respectively.

The above experimental results are in accord with the computer simulation results as previously stated.

Figure 3 (e) shows the relation between power factor PF and duty cycle D_c. The proposed PFC converter maintains high power factor in wide operational range. Figure 3 (f) shows the relation between system efficiency and output power. The efficiency of the proposed soft switching converter was increased more than that of the conventional converter.

4 Conclusion

This paper described a novel PFC boost ac-dc converter of high efficiency used in fire electric installation operated with generally rated power 2 kW. The input current waveform was got to be sinusoidal waveform in proportion

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to magnitude of ac input voltage under the constant duty cycle switching. The converter for DCM eliminated the complicated control circuit requirement. Therefore, the input power factor was nearly unity and the control method is simple. Also the switching devices in the converter were operated with soft switching by partial resonant method. The partial resonant circuit made use of a step-up inductor and a loss-less snubber capacitor. It was for the accumulated energy in the capacitor to regenerate into input side without the power loss of snubber circuit produced in conventional PFC boost converter. The input power factor of proposed PFC converter for the regenerated energy was higher than that of conventional PFC converter.

The proposed PFC boost converter was operated with high efficiency and high power factor from the above results.

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