A Study on Isolated DCM Converter for High Efficiency and High Power Factor

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Abstract - This paper is studied on a novel buck-boost isolated converter for high efficiency and high power factor. The switching devices in the proposed converter are operated by soft switching technique using a new quasi-resonant circuit, and are driven with discontinuous conduction mode (DCM) according to pulse width modulation (PWM). The quasi-resonant circuit makes use of a step up-down inductor and a loss-less snubber capacitor. The proposed converter with DCM also simplifies the requirement of control circuit and reduces a number of control components. The input ac current waveform in the proposed converter becomes a quasi sinusoidal waveform in proportion to the magnitude of input ac voltage under constant switching frequency. As a result, it is obtained by the proposed converter that the switching power losses are low, the efficiency of the converter is high, and the input power factor is nearly unity. The validity of analytical results is confirmed by some simulation results on computer and experimental results.

Keywords: Buck-boost isolated converter, DCM, Soft-switching technique, Loss-less snubber, Quasi-resonant circuit

1. Introduction

An input current drawn by the phase controller or diode rectifiers creates a number of problems for the power distribution network and for other electrical appliances. Therefore, recently the power factor correction (PFC) techniques have received great attention and a number of new techniques have been proposed. To improve input current waveform and to control the power factor (PF) of unity at the same time, it is proposed to use an active converter, which includes step-up chopper or step-down chopper for the rectifier circuit [1]-[3].

There are two control modes for the chopper of this usage. One is the continuous conduction mode (CCM) of dc current and another is the discontinuous conduction mode (DCM) of dc current [3]-[6]. In continuous mode, input ac voltage and current are detected, and the input current is formed to be nearly sinusoidal waveform by using PWM with variable switching frequency. Specially, the converter for this mode requires a current sensor and synchronization control circuit, and then the control system is complicated. In discontinuous mode, the input ac current becomes a quasi sinusoidal waveform in proportion to the magnitude of input ac voltage under constant switching frequency with PWM. The control circuit for the DCM converter eliminate- es the complicated circuit control requirement and reduces the number of components [4]-[5]. Moreover, in this mode, the turn-on of chopper switching devices occurs at zero current, that is, zero current switching. Therefore, the switching losses caused by switching turn-on operation are very low. However, the switching devices are switched off at the maximum current corresponding to a certain level of voltage in one cycle of the switching frequency, so-called hard switching. It causes the large current stresses of the switching devices and variable electromagnetic interference.

In this paper, we propose a buck-boost isolated converter for PFC including a novel soft-switching step up-down chopper by DCM. The switching devices in the proposed converter are operated by a soft switching technique using a new quasi-resonant circuit, that is, the quasi-resonant operation makes zero current switching (ZCS) and zero voltage switching (ZVS) for the turn-on and turn-off of control switches without switching power losses, so called "soft switching" [6]-[9]. The quasi-resonant circuit is composed of a step up-down inductor and a loss-less snubber capacitor [10]-[12]. The resonant operation of the quasi-resonant circuit is partially enforced at only switching turn-on time or turn-off time in order to reduce the losses and stresses of the resonant devices. Particularly, an accumulated energy in the snubber capacitor regenerates into the input power source without the power losses of the snubber circuit by quasi-resonant operation. It results in not only increasing input power factor but also elevating output dc voltage in comparison with a conventional PFC buck-boost isolated converter.

The soft-switched operation of the proposed buck-boost isolated converter is verified by simulation results and experimental results, and the proposed converter is analyzed in comparison with the conventional PFC buck-boost isolated converter.

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2. Circuit Configuration of Proposed Converter

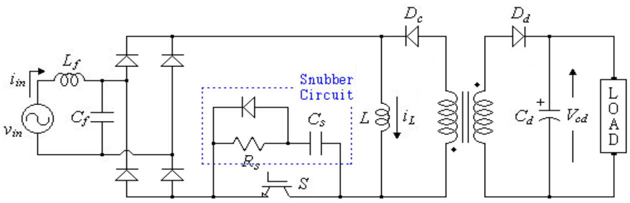
Fig. 1(a) shows a conventional PFC buck-boost isolated converter. To improve input ac current waveform while operating at unity power factor, the conventional converter is constructed by a bridge diode rectifier and a step up-down chopper. The operation of the converter is controlled by a DCM of the inductor L in order to obtain some merits of simpler control, such as constant switching frequency, without a current sensor and synchronization control circuit.

The turn-on of the switching device in the discontinuous mode is a ZCS. On the other hand, the device must be switched off at a maximum inductor current. Therefore, to relieve turn-off stress, a snubber circuit is connected in parallel with the switch S of the conventional converter as shown in Fig. 1(a). The L_f and C_f are a filter circuit to remove the switching frequency component from the input ac current.

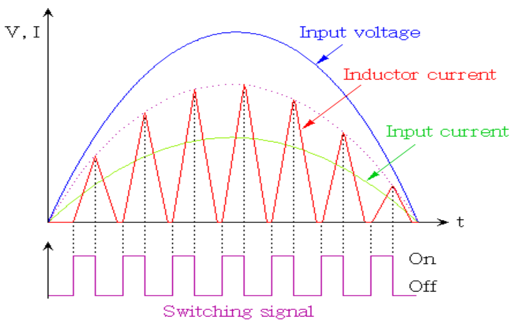
Fig. 1(b) shows an example of the waveforms of input current, voltage, and inductor current for DCM according to PWM. The output voltage of the converter is also regulated by the PWM control of the switch.

Fig. 2 shows the circuit configuration of the proposed PFC buck-boost isolated converter. The proposed converter is composed of controlling devices, a step-up inductor L_r, and a snubber capacitor C_r used in similar way for the conventional converter. It can be considered that the snubber circuit in the conventional converter is partly replaced by a quasi-resonant circuit in the proposed converter. The quasi-resonant circuit consists of a parallel connected switch-diode pair with a resonant capacitor, which is operated to a loss-less snubber capacitor.

The switching devices in the proposed converter are operated with the soft switching by quasi-resonance and with constant switching frequency. When the switching devices, S_1 and S_2, are turned off, the inductor L_r current charges the capacitor C_r by the quasi-resonant operation. Therefore, the turn-off of the S_1 and S_2 is ZVS. Since the current pulses in DCM converter always begin at zero, the turn-on of the S_1 and S_2 in the proposed converter is ZCS. Specially, at the turn-on of the S_1 and S_2, an accumulated energy in the snubber capacitor regenerates into the input power source by quasi-resonant operation without the power loss of snubber circuit which is generally produced in the conventional buck-boost converter. As a result, the proposed converter using a quasi-resonant circuit achieves the soft switching (ZCS at turn-on and ZVS at turn-off). The power losses of the switching devices are drastically decreased and the proposed converter is operated with high efficiency. The input power factor is also increased.



(a) Conventional PFC buck-boost isolated converter



(b) Input waveforms of DCM

Fig. 1. Circuit configuration and input waveforms of conventional PFC buck-boost isolated converter.

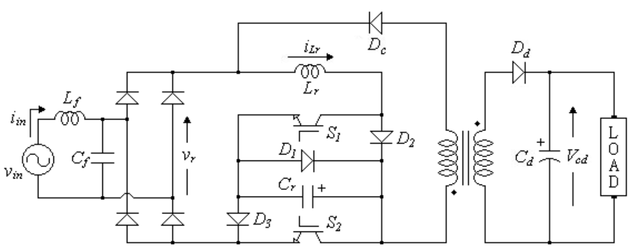
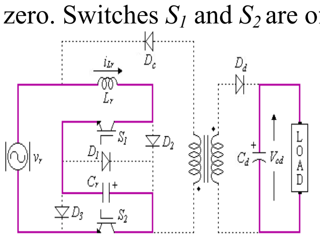


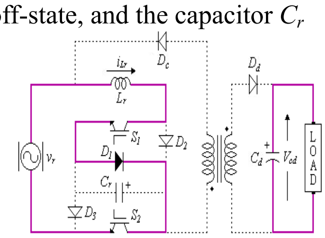
Fig. 2. Proposed PFC buck-boost isolated converter.

3. Operation Principle of Proposed Converter

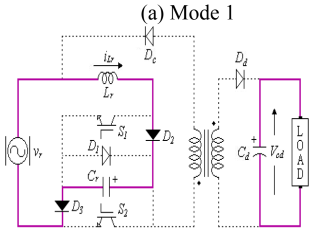
Fig. 3 shows five equivalent circuits for each operational mode in one cycle switching of the proposed converter. At initial condition, the current flowing through inductor L_r is zero. Switches S_1 and S_2 are off-state, and the capacitor C_r



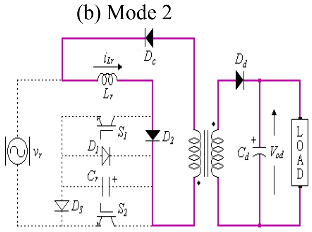
(a) Mode 1



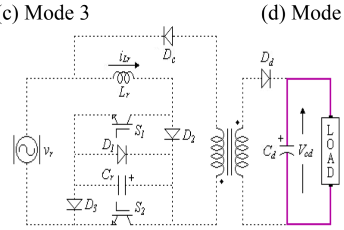
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Fig. 3. Equivalent circuits of each operational mode in one cycle switching.

is charged to the sum of an output voltage v_r of the rectifier and an output dc voltage V_{cd}. It is defined that the input ac voltage of $v_{in} = V_m \sin\omega_s t$, $\omega_s = 2\pi f_s$ and the output voltage from diode rectifier of $v_r = |v_{in}| = |V_m \sin\omega_s t|$.

Mode 1 **(T_1 : $t_0 \sim t_1$)**

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 the form of a series *LC* resonance circuit. The capacitor C_r discharges its electric charge through the inductor L_r. The turn-on of the switching devices occurs at zero current state, namely ZCS. The capacitor voltage v_{cr} and the inductor current i_{Lr} are expressed as follows.

$$v_{cr} = (2v_r + V_{cd})\cos\omega_r(t - t_0) - v_r \quad (1)$$

$$i_{Lr} = \frac{2v_r + V_{cd}}{X}\sin\omega_r(t - t_0) \quad (2)$$

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

This mode ends when $v_{cr} = 0$. The inductor current I_{L1} at the end of this mode is given by

$$I_{L1} = \frac{1}{X}\sqrt{(2v_r + V_{CD})^2 - v_r^2} \quad (3)$$

Mode 2 **(T_2 : $t_1 \sim t_2$)**

Mode 2 begins when the voltage across C_r becomes zero. Then the diode D_1 starts conduction. The inductor current takes a route of S_1-D_1-S_2. The inductor current linearly increases as the following until the switches are turned off.

$$i_{Lr} = \frac{v_r}{L_r}(t - t_1) + I_{L1} \quad (4)$$

This mode ends when both S_1 and S_2 are turned off simultaneously. The inductor current I_{L2} at the end of this mode can be obtained by

$$I_{L2} = I_{L1} + \frac{v_r}{L_r}\left[T_{on} - \sqrt{L_r C_r}\cos^{-1}\left(\frac{v_r}{2v_r + V_{cd}}\right)\right] \quad (5)$$

where T_{on} is a turn-on period of the switches S_1 and S_2.

Mode 3 **(T_3 : $t_2 \sim t_3$)**

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_2-C_r-D_3 and charges C_r. Then this mode takes the form of a series *LC* resonance circuit. The turn-off of S_1 and S_2 occurs at ZVS, because the voltage of C_r is zero. In this mode, the voltage of C_r and the current of L_r are expressed as follows.

$$v_r = v_r + XI_x \sin[\omega_r(t - t_2) + \theta] \quad (6)$$

$$i_{Lr} = I_x \cos[\omega_r(t - t_2) + \theta] \quad (7)$$

where $I_x = \sqrt{\frac{c_r}{L_r}v_r^2 + I_{L2}^2}$, $\theta = \sin^{-1}\left(-\frac{v_r}{\sqrt{v_r^2 + \frac{L_r}{C_r}I_{L2}^2}}\right)$

When the capacitor voltage v_{cr} becomes equal to "$v_r + V_{cd}$" and the diode D_c starts conduction, this mode ends. The inductor current at the end of this mode can be assumed to a constant value I_{L2}, because this mode is very short period.

Mode 4 **(T_4 : $t_3 \sim t_4$)**

By the conducting of the diode D_c, the inductor current i_{Lr} flows through the load side. The inductor current linearly decreases as the next equation.

$$i_{Lr} = -\frac{V_{cd}}{L_r}(t - t_3) + I_{L2} \quad (8)$$

This mode ends when $i_{Lr} = 0$.

Mode 5 **(T_5 : $t_4 \sim t_0$)**

In mode 5, as the inductor current i_{Lr} is zero and S_1, S_2 are off, $v_{cr} = v_r + V_{cd}$, $i_{Lr} = 0$ are kept.

One switching period ends at this time and next cycle begins when switching devices S_1, S_2 are turned on.

4. Computer Simulation and Experimental Results

The proposed converter was analyzed by *PSpice* simulat- ion program. The circuit parameters for the simulation are listed in Table 1. The output voltage V_{cd} of the simulation circuit is regulated at about dc 200V, and the switching frequency is 40kHz. The diodes are ideal, and every switch is replaced by an equivalent circuit consisting of a variable resistance and an ideal diode.

Fig. 4 shows the waveforms of each part in one cycle switching for the proposed converter, in order to verify the quasi-resonant operation and soft switching operation of the control devices.

In Fig. 4, the controlling switches, S_1 and S_2, of duty factor 30% are simultaneously turned on at t_0, and the capaci

Table 1. Circuit parameters

Input voltage, v_{in} (rms)	100V, 60Hz	Smoothing capacitor, C_d	1000μF
Input filter inductor, L_f	2mH	Load resistor, R_L	100Ω
Input filter capacitor, C_f	3μF	Transformer, turns ratio	1 : 1
Resonant inductor, L_r	50μH	Snubber resistor, R_s	50Ω
Resonant capacitor, C_r	50nF	Snubber capacitor, C_s	0.47μF

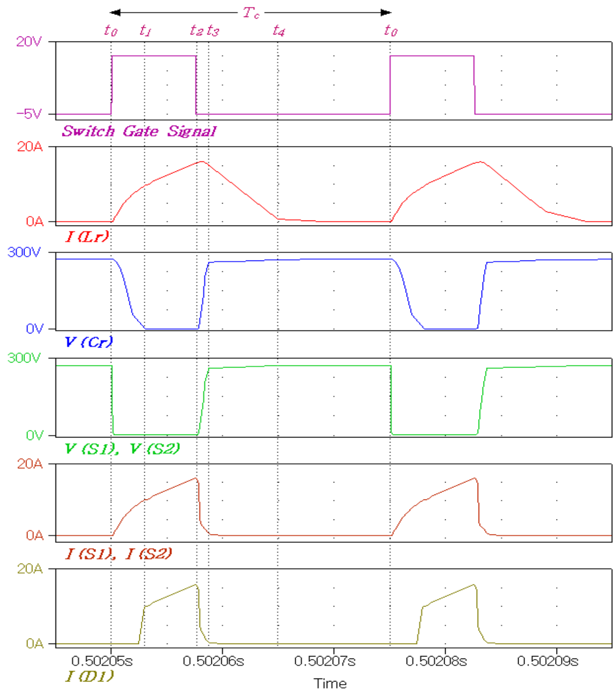


Fig. 4. Simulation waveforms of each part.

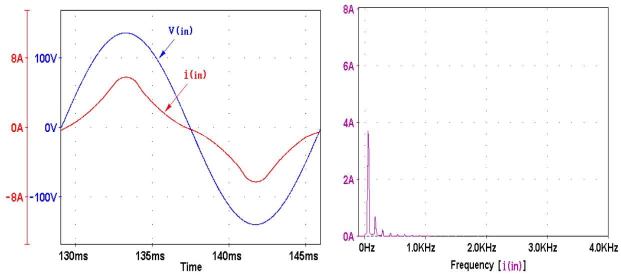
tor C_r begins to discharge. The capacitor voltage v_{cr} becomes zero at t_1. At t_2, the controlling switches are simultaneously turned off and the capacitor C_r is charged by the inductor current i_{Lr}. The voltage of C_r becomes equal to "$v_r + V_{cd}$" at t_3. At t_4, the inductor current i_{Lr} reaches zero and the switches are kept off till the next cycle. The indicated T_c is the period of one cycle of switching operation. In addition, as the current flowing through switches is zero at t_0, the switches are turned on at ZCS. As the voltage across switches is also zero at t_2, the switches are turned off at ZVS. The simulated results confirm the validity of theoretical results for each mode previously stated.

Fig. 5 shows the waveforms of input currents based on an input ac voltage and the frequency spectra of input currents. The amplitude of the input current in the conventional PFC converter is smaller than a sinusoidal waveform around the zero cross point, as shown in Fig. 5(a). Hence the current includes quite a little of the third harmonic component.

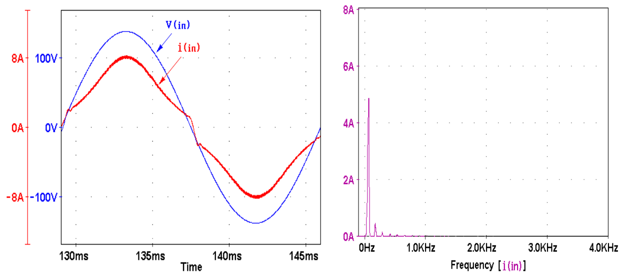
However, in the case of the proposed PFC converter, the amplitude of the input current around the zero cross point shows an upward curve, as shown in Fig. 5(b). The reason is that an accumulated energy in the resonant capacitor C_r regenerates into the input power source by quasi-resonant operation.

Therefore, the input current of the proposed converter is more similar to a sinusoidal waveform, and the frequency spectrum of the input current also shows the reduction of the harmonics in comparison with that of the conventional PFC converter.

In order to confirm the feasibility, the proposed converter was built in the maximum output power of 1.0kW. The principal circuit devices in the proposed converter



(a) Conventional PFC converter



(b) Proposed PFC converter

Fig. 5. Input waveforms, and frequency spectra of input currents.

were designed on the basis of Table 1. The output load was also composed of a variable wiring resistor within the range of 10Ω to 1000Ω of 1.0kW rating. The power switches were implemented by Fuji IGBT series 1MBH40-60 (V_{CE}=600V, I_C=40A, and T_{off}=520ns rated for 40kHz switching frequen-cy operation). The power diodes were used to FRD (fast recovery diode) type.

The control circuit of the converter was built in a Micom. package of Intel 80c196kc processor. The switching signal was controlled with a programmed PWM data function table and a designed voltage-feedback circuit board through the A/D (analog/digital) converting port of the Micom. An experimental photograph of the proposed PFC converter is shown in Fig. 6.

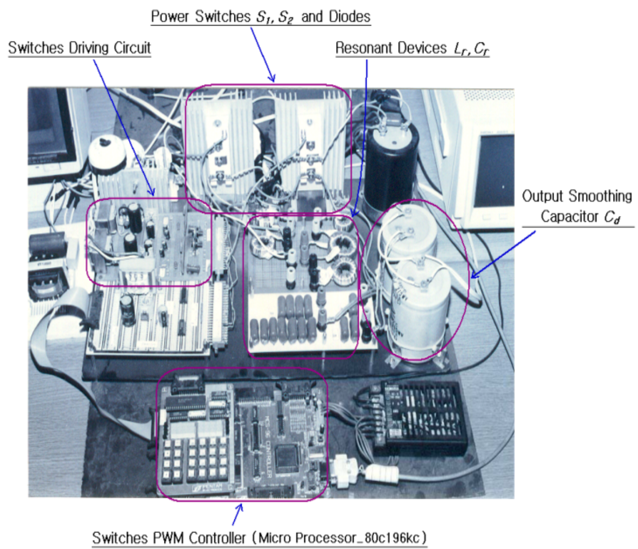


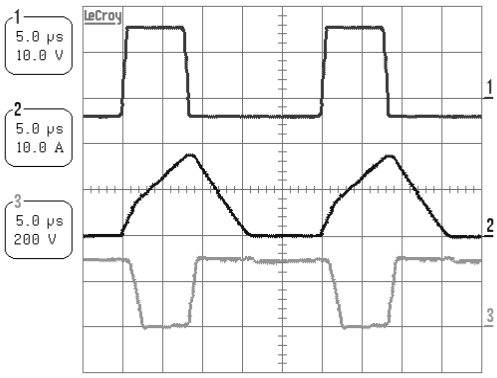
Fig. 6. Experimental photograph of proposed PFC converter.

Fig. 7 shows the waveforms of each part in one cycle switching for the proposed converter, in order to verify the quasi-resonant and soft switching operation of the control devices. Experimental values were obtained in the case of the load resistor $R_L = 100\Omega$ and duty factor $D_c = 30\%$.

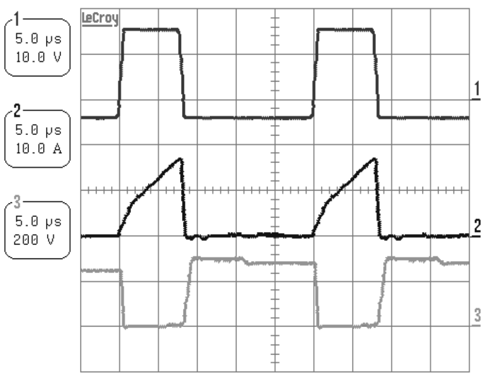
In Fig. 7, the switches used in the converter were operated with the soft switching, namely turn-on at zero current and turn-off at zero voltage, according to quasi- resonant operation. Particularly, the resonant operation of the quasi-resonant circuit was partially enforced at only switching turn-on time and turn-off time. It reduces the losses and stresses of the resonant devices.

To analyze the input currents of the convention PFC converter and proposed PFC converter, Fig. 8 and Fig. 9 show the waveforms of input currents flowing through input LC low pass filter (LPF) based on an input ac voltage and the frequency spectra of input currents. Specially, the third harmonic component generated in the proposed PFC converter is smaller than that of the conventional PFC converter. The above experimental results agree well with computer simulation results previously stated.

Fig. 10 shows the total harmonic distortion (THD) curve of input current waveform according to duty factor. The proposed PFC converter has more low distortion. The relationship between the output dc voltage V_{cd} and duty factor is shown in Fig. 11. The output dc voltage of the proposed converter is higher than that of the conventional converter.

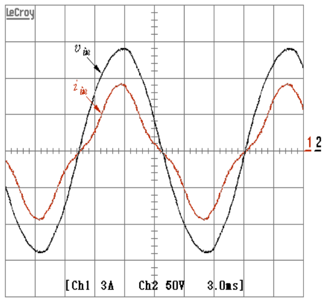


(a) Inductor current i_{Lr} [2] and capacitor voltage v_{cr} [3]

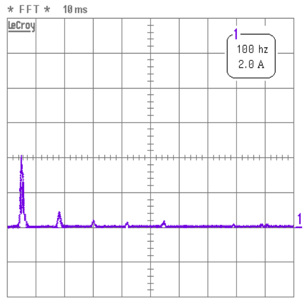


(b) Switch current i_s [2] and voltage v_s [3]

Fig. 7. Experimental waveforms according to switching-signal [1].

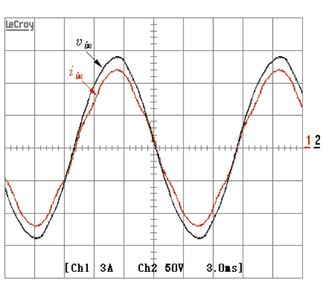


(a) i_{in} [1] and v_{in} [2]

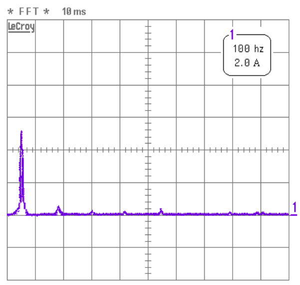


(b) Frequency spectrum of i_{in}

Fig. 8. Analyses of input waveforms in conventional PFC converter.



(a) i_{in} [1] and v_{in} [2]



(b) Frequency spectrum of i_{in}

Fig. 9. Analyses of input waveforms in proposed PFC converter.

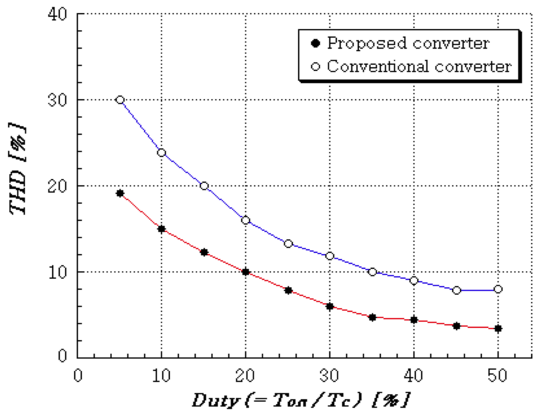


Fig. 10. Relationship between THD and duty factor.

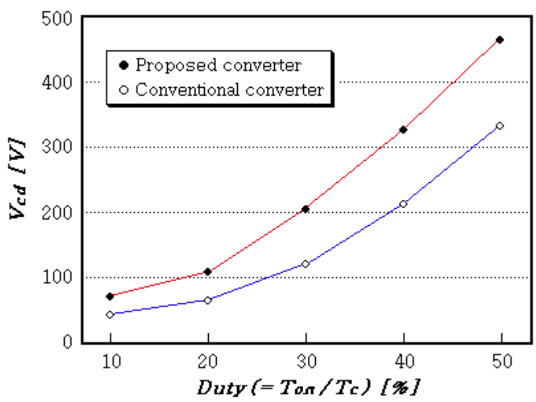


Fig. 11. Relationship between output dc voltage V_{cd} and duty factor.

The relationship between the power factor and duty factor is shown in Fig. 12. The proposed PFC converter maintains high power factor at every measurement range. In order to DCM, each measurement data was accomplished with the range of duty factor D_c = below 50%.

The above superior experiment results of the proposed converter are caused by the charged voltage of the loss-less snubber capacitor, which is added to the rectified input voltage by quasi-resonant operation.

The power losses of main devices in the proposed converter are shown in Fig. 13, respectively. Fig. 14 shows the relation between the system efficiency and output power.

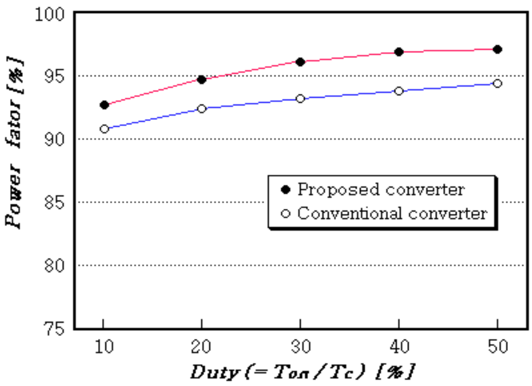


Fig. 12. Relationship between PF and duty factor.

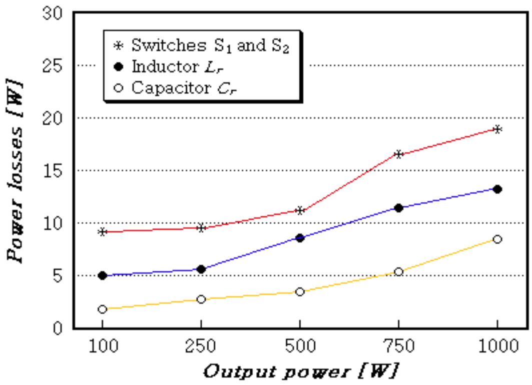


Fig. 13. Power losses of main devices in proposed converter.

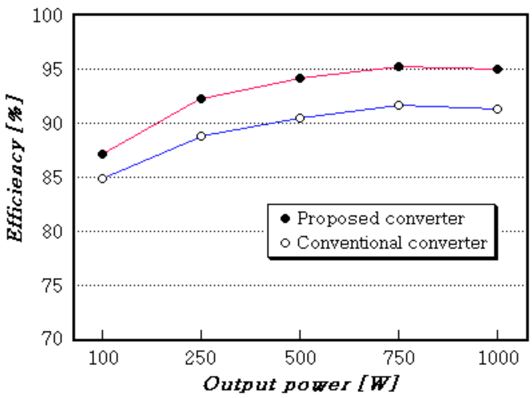


Fig. 14. Relationship between efficiency and output power.

The output power was measured in the adjusted range of the variable resistor with PWM switching control for a fixed output voltage of dc 200V. The snubber circuit in the conventional converter was also composed of a snubber resistor of 50Ω and a snubber capacitor of 0.47μF, which was generally used in hard switching converters. The efficiency of the proposed soft switching converter was increased more than that of the conventional hard switching converter.

5. Conclusion

A novel isolated buck-boost converter for PFC which includes a step up-down chopper and a quasi-resonant circuit has been described in this paper. The switching devices in the proposed converter were operated with soft switching and driven with DCM according to PWM. The quasi-resonant circuit made use of a step up-down inductor and a loss-less snubber capacitor. As a result, the proposed PFC converter obtained that the switching power losses were low and the system efficiency was high. The input ac current waveform in the proposed converter became a quasi sinusoidal waveform in proportion to the magnitude of input ac voltage under constant switching frequency. Moreover, the accumulated energy in the loss-less snubber capacitor was regenerated into the input power source by the quasi-resonant operation. It resulted in not only increasing input power factor due to reducing THD but also elevating output voltage, in comparison with the conventional PFC converter. The proposed converter operating to DCM also simplified the requirement of control circuit. The superior operation performance of the proposed PFC converter was verified by the simulation and experimental results compared with the conventional PFC converter.

References

[1] Garcia, J. A. Cobos, et al., "Single phase power factor correction: A survey", *IEEE Trans. on PE*, Vol. 18, No. 3, pp. 749-755, May 2003.

[2] Y. T. Jang, M. Jovannovic, et al., "High-Power-Factor Soft-Switched Boost Converter", *IEEE Trans. on PE*, Vol. 21, No. 1, pp. 98-104, Jan. 2006.

[3] Q. Zhao, M. Xu, F. C. Lee, and J. Qian, "Single-Switch Parallel Power Factor Correction AC-DC Converters with Inherent Load Current Feedback", *IEEE Trans. on PE*, Vol. 19, No. 4, pp. 928-936, July 2004.

[4] D. Sadarnac, W. Abida, and C. Karimi, "The Double Discontinuous Mode Operation of a Converter: A method for soft switching", *IEEE Trans. on PE*, Vol. 19, No. 2, pp. 453-460, March 2004.

[5] B. Feng, and D. Xu, "1-kW PFC Converter With Compound Active-Clamping", *IEEE Trans. on PE*, Vol. 20, No. 2, pp. 324-331, March 2005.

[6] W. J. Lee, S. W. Choi, C. E. kim, and G. W. Moon, "A new PWM-controlled quasi-resonant converter for a

high efficiency PDP sustaining power module", *Journal of Power Electronics*, Vol. 7, No. 1, pp. 28-37, Jan. 2007.

[7] H. Watanabe and H. Matsuo, "A novel high-efficiency DC-DC converter with 1V/20A DC output", *IEEE INTELEC 2002,* pp. 34-39, Sept.-Oct. 2002.

[8] IEEJ: "Recent development on soft switching", *IEEJ Technical Report*, No. 899, pp. 4-8, Sept. 2002 (in Japanese).

[9] Y. Tsuruta, and A. Kawamura, "A High Efficiency and High Power Chopper Circuit QRAS using Soft Switching under Test Evaluation at 8KW", *Journal of Power Electronics*, Vol. 6, No. 1, pp. 1-7, Jan. 2006.

[10] X. Ruan, Z. Chen, and W. Chen, "Zero-Voltage-Switching PWM Hybrid Full-bridge Three-level Converter", *IEEE Trans. on PE*, Vol. 20, No. 2, pp. 395-404, March 2005.

[11] K. Taniguchi, K. Koh, and H. W. Lee, "Experimental waveforms of single-pulse soft-switching PFC converter", *Journal of Power Electronics*, Vol. 4, No. 1, pp. 56-63, Jan. 2004.

[12] S. K. Chung, and J. G. Lim, "Design of Bootstrap Power Supply for Half-Bridge Circuits using Snubber Energy Regeneration", *Journal of Power Electronics*, Vol. 7, No. 4, pp. 294-300, Oct. 2007.

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