Improvement of Input Current Waveform for Soft-Switching Boost DCM Converter with Unity Power Factor

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ABSTRACT-In this paper, a soft-switching discontinuous mode (DCM) power factor corrected (PFC) converter is analyzed by applying the double Fourier series expansion. It is found that the fundamental component and higher-order harmonics included in the input current waveform are obtained by the Fourier series expansion of the mean value of the inductor current. From the theoretical analysis, a new method removing the distortion of the input current waveform is proposed. In spite of an open loop system, the proposed method makes a great improvement of the total harmonic distortion even if the ratio of output voltage to input voltage is very low.

1. INTRODUCTION

PWM power factor correction (PFC) techniques have received great attention in recent years. In most cases, PWM-PFC converters are constructed by a diode rectifier and an active power circuit such as a boost or a buck-boost chopper [1-2]. In Fig.1, the converter is a discontinuous conduction mode (DCM) operation in order to obtain some merits of simpler control such as fixed switching frequency, without current sensor and synchronization control circuit. The DCM operation provides for a simple control but it must be turned off at the maximum value of the current. The soft switching is promising in the improvement of the turn-off characteristics and stress relief of the components.

We have proposed a soft-switching boost PFC converter as shown in Fig.2 [3]. In the soft-switching converter, the switching device is replaced by the loss-less snubber circuit to achieve the zero voltage switching (ZVS) at the maximum inductor current.

In both converter shown in Fig. 1 of hard-switching converter and in Fig.2 of soft-switching converter, the distortion in the input current increases with the low ratio of output voltage to input voltage. On the other hand, the high ratio of output voltage to input voltage causes the cost up of the converter because of requirement of the high voltage devices.

To improve the input current waveform of the soft-switching converter, a new duty factor control method is proposed in this paper. A soft-switching discontinuous mode (DCM) power factor corrected (PFC) converter is analyzed by applying the double Fourier series expansion. From the theoretical analysis, a new method removing the distortion of the input current waveform is proposed. In spite of an open loop system, the proposed method makes a great improvement of the total harmonic distortion even if the ratio of output voltage to input voltage is very low.

2. OPERATIONAL MODE OF SOFT-SWITCHING PFC CONVERTER

Fig.3 shows an inductor current waveform for one switching cycle. Operation of soft-switching PFC converter consists of 5 modes.

A mode analysis is performed for input AC voltage of

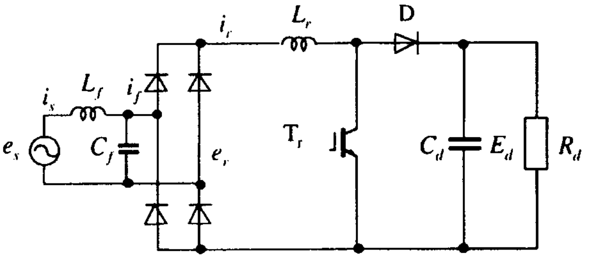


Fig. 1 Conventional hard-switching DCM converter.

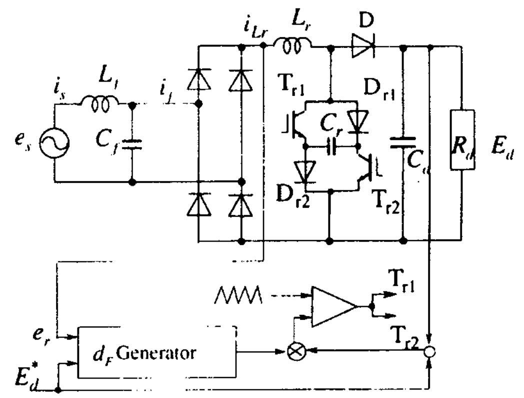


Fig.2 Circuit configuration of soft-switching DCM converter.

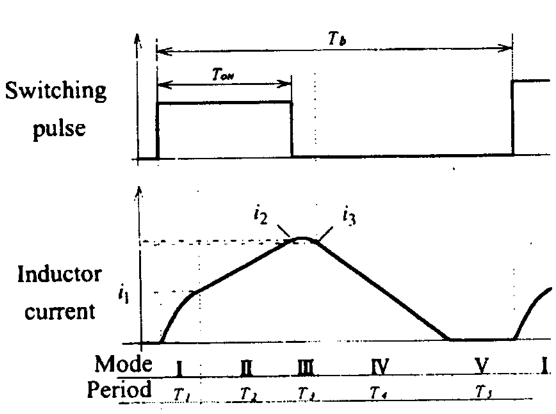


Fig.3 Reactor current waveforms.

$e_s = E_s \sin \omega_s t$, $\omega_s = 2\pi f_s$ and output voltage from diode rectifier of $e_r = |e_s| = |E_s \sin \omega_s t|$. In initial condition, T_{r1}, T_{r2} are off, he inductor current is zero and capacitor C_r is charged to voltage E_d. Analyzed results of the commutation capacitor voltage v_{Cr} and the commutation reactor current i_{Lr} are shown below.

MODE I $(T_1 : t_0 \sim t_1)$

When T_{r1} and T_{r2} are turned on at the same time, the commutation capacitor begins to discharge. Then

$$v_{Cr} = (e_r + E_d)\cos \omega_r t - e_r \qquad ...(1)$$

$$i_{Lr} = \frac{e_r + E_d}{X_r} \sin \omega_r t \qquad ...(2)$$

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

This mode ends when v_{Cr}=0 at time $t = T_1$. Duration of this mode T_1 is nearly equal to $\pi / 2\omega_r$. Then, the commutation reactor current $i_1 = i_{Lr}(T_1)$ is

$$i_1 \cong \frac{e_r + E_d}{X_r} \qquad ...(3)$$

MODE II $(T_2 : t_1 \sim t_2)$

The commutation reactor current i_{Lr} increases linearly as follows,

$$i_{Lr} = (e_r / L_r)t + i_1 \qquad ...(4)$$

In this period, v_{Cr}=0.

Mode II ends when T_{r1} and T_{r2} are turned off at the same time. Then, the duration of this mode T_2 is as follows,

$$T_2 = T_{ON} - T_1 \qquad ...(5)$$

At time $t = T_2$, the commutation reactor current i_2 is as follows,

$$i_2 = \frac{e_r}{L_r} T_2 + i_1 \cong \frac{e_r}{L_r}\left(T_{ON} - \frac{\pi}{2\omega_r}\right) + \frac{e_r + E_d}{X_r} = I_{p2} \quad ..(6)$$

MODE III $(T_3 : t_2 \sim t_3)$

When T_{r1} and T_{r2} are turned off at the same time, the commutation capacitor begins to be charged. Mode III ends when diode D is turned on at $v_{Cr} = E_d$. At time $t = t_3$, the commutation reactor current i_3 is nearly equal to I_{p2}.

MODE IV $(T_4 : t_3 \sim t_4)$

When diode D begins to conduct, the current flowing into the reactor L_r begins to flow load side, then reactor current decreases linearly. In this mode, $v_{Cr} = E_d$ is kept. Mode IV ends when diode D is turned off at i_{Lr}=0.

MODE V $(T_5 : t_4 \sim t_0)$

In mode V, as the reactor current i_{Lr} is zero and T_{r1}, T_{r2} are off, $v_{Cr} = E_d$, i_{Lr} =0 are kept.

One switching period ends at this time and next cycle begin when switching devices T_{r1}, T_{r2} are turned on.

3. ANALYSIS OF INPUT CURRENT WAVEFORM

Since the ratio of an AC source frequency and a switching frequency is generally incommensurable, the PWM input current waveform becomes a non-periodic function. The harmonic analysis of such a waveform can be carried out by using the double Fourier series [4-5]. The input current waveform i_s is given by

$$i_s = \sum_{m=0}^{\pm\infty} \sum_{n=0}^{\pm\infty} K_{mn} e^{j(mx+ny)} \qquad (7)$$

$$K_{mn} = \frac{1}{(2\pi)^2} \int_0^{2\pi} \int_0^{2\pi} i_r(x,y) e^{-j(mx+ny)} dx dy \qquad (8)$$

where i_r is a inductor current, ω_b is a switching angular frequency, ω_s is an AC source angular frequency, $x = \omega_b t$, $y = \omega_s t$, m=0,1,2,..., and n=0,1,2,...

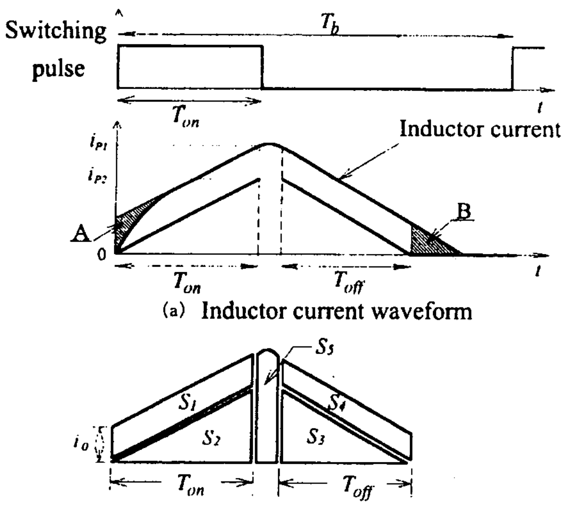
As a result, the frequency components included in the PWM output waveform are a fundamental component higher-order harmonic, and the sidebands of a carrier frequency. If the frequency ratio becomes large, the sidebands move into the high-frequency region apart from the fundamental frequency. Therefore the sidebands can be removed by the input filter easily. The input current waveform without sidebands is given by

$$i_s = \sum_{n=0}^{\pm\infty} K_{0n} e^{jny} \qquad (9)$$

$$K_{0n} = \frac{1}{2\pi} \int_0^{2\pi} \left\{ \frac{1}{2\pi} \int_0^{2\pi} i_r(x,y) dx \right\} e^{-jny} dy$$

$$= \frac{1}{2\pi} \int_0^{2\pi} \{ I_r(y) \} e^{-jny} dy \qquad (10)$$

where $$I_r(y) = \frac{1}{2\pi} \int_0^{2\pi} i_r(x,y) dx \qquad (11)$$



(a) Inductor current waveform

(b) Approximati

Fig.4 Approximation of inductor current waveform.

I_r is the mean value of the inductor current i_r. Eq. (10) indicates that the fundamental component and higher-order harmonics included in the input current waveform are obtained by the Fourier series expansion of the mean value of the inductor current i_r.

Fig. 4 shows an approximation of inductor current waveform shown in Fig.3. An approximation of area A = area B shown in Fig. 4 (a) can be expressed an inductor current waveform as shown in Fig. 4 (b).

Therefore, the mean value I_r of the inductor current i_r is

$$I_r = (S_1 + S_2 + S_3 + S_4 + S_5) / T_b$$

$$= \frac{1}{X_r}\left\{\left(1 - \frac{\pi}{2}\right)d_F + \frac{d_F^2}{2L_r f_b}\right\}\frac{e_r}{1-(e_r / E_d)}$$

$$+ \frac{1}{X_r}(d_F + X_r C_r f_b)\frac{E_d}{1-(e_r / E_d)} \qquad (12)$$

where $i_{P2} = (e_r / L_r)T_{on}$, $i_0 = i_{P1} - i_{P2}$, $T_{on} = \{e_r / (E_d - e_r)\}T_{off}$, $S_5 = C_r E_d$.

4. IMPROVEMENT OF INPUT CURRENT WAVEFORM

If $d_F >> X_r C_r f_b$, then $e_r\{1-(e_r / E_d)\}^{-1} \cong e_r$,

$$\therefore\ I_r \cong \frac{\{1-(\pi/2)\}d_F}{X_r}e_r + \frac{d_F}{X_r\{1-(e_r / E_d)\}}E_d = I_r' \qquad (13)$$

Both eqs (12) and (13) are obtained maximum values at $\omega_s t = \pi / 2$. Fig.5 shows the errors of I_r for I_r' at

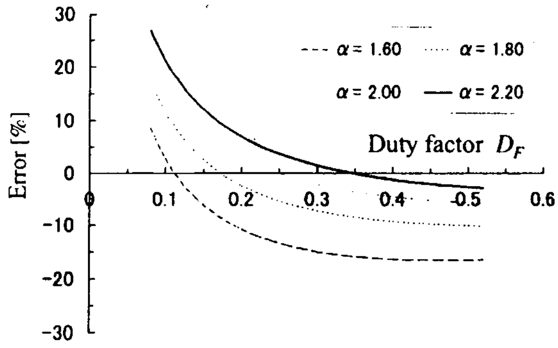


Fig.5 Errors of I_r for I_r' at $\omega_s t = \pi / 2$.

$\omega_s t = \pi / 2$. The errors are small comparatively.

An improvement of the input current waveform can be derived by applying the theoretical results. A fundamental component and higher-order harmonics included in the input current waveform are obtained by the Fourier series expansion of the mean value of the inductor current. Namely, it is implied that the input current becomes pure sinusoidal waveform when the mean value of the inductor current is completely proportional to the input voltage waveform. Therefore,

$$\frac{1}{\pi}\int_0^{\pi}\frac{d_F E_d}{X_r\{1-(e_r / E_d)\}}d\omega_s t \propto \frac{1}{\pi}\int_0^{\pi}\frac{e_r}{X_r}d\omega_s t$$

$$\therefore\ \frac{d_F}{1-(e_r / E_d)} = Ae_r \qquad (14)$$

From (20), duty function d_F can be obtained by

$$d_F = D_F\left(1 - \frac{1}{\alpha}|\sin\omega_s t|\right)|\sin\omega_s t| \qquad (15)$$

where $0 \le (D_F = A) \le 1$ and A is constant.

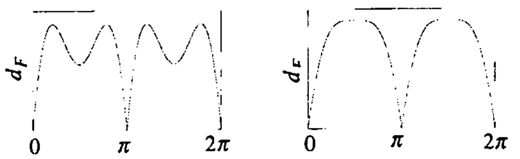
Fig. 6 shows a waveform of d_F from (15). Top area of the inductor current at boost ratio of $\alpha = 2.00$ ($E_d = 565V$) is flatness and the waveform at $\alpha = 1.237$ ($E_d = 350V$) has double peak. The input current waveform is improved by controlling the duty factor according to (15).

5. CHARACTERISTICS OF PROPOSED d_F CONTROL

Principal parameters for simulation are listed in Table 1. Comparison of the *THD* between the conventional constant d_F control, the soft-switching constant d_F control and the proposed soft-switching d_F control are shown in Fig. 7. Input power is 1.2kW. In wide variation of duty factor, the proposed method establishes a great improvement of THD. Many harmonics included in the input current waveform of the proposed method can be decreased.

Table 1 Principal parameters for simulation.

Source Voltage (Max)	E_s	$200\sqrt{2}$ [V]
Source Frequency	f_s	60 [Hz]
Switching Frequency	f_h	20 [kHz]
Smoothing Capacity	C_d	1000 [μF]
Resonant Capacitor	C_r	0.1 [μF]
Resonant Inductor	L_r	100 [μH]



(a) $\alpha = 1.237(E_d = 350V)$ (b) $\alpha = 2.00(E_d = 565V)$

Fig.6 d_F Modulating signal.

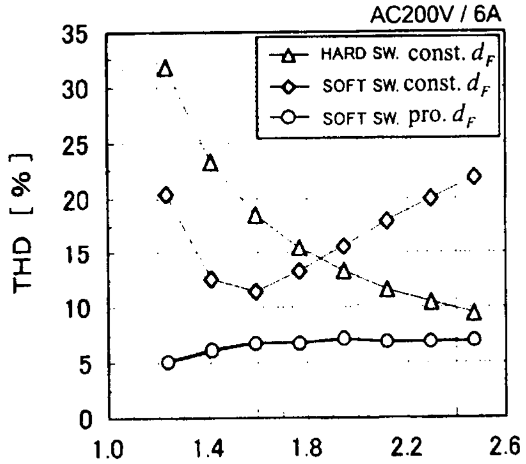


Fig.7 Comparision of THD.

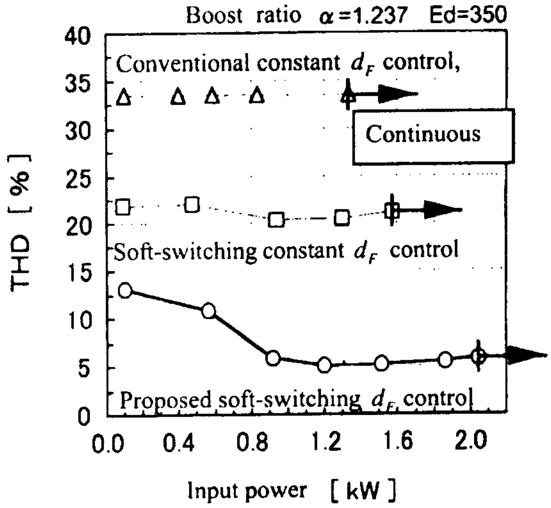
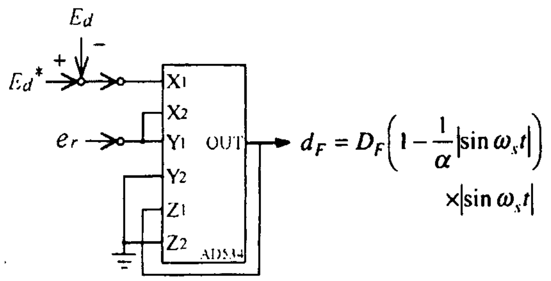
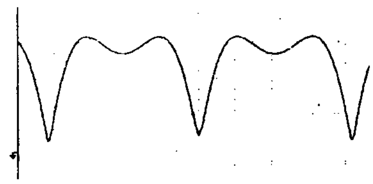


Fig 8 THD vs. input power.



(a) d_F function generator



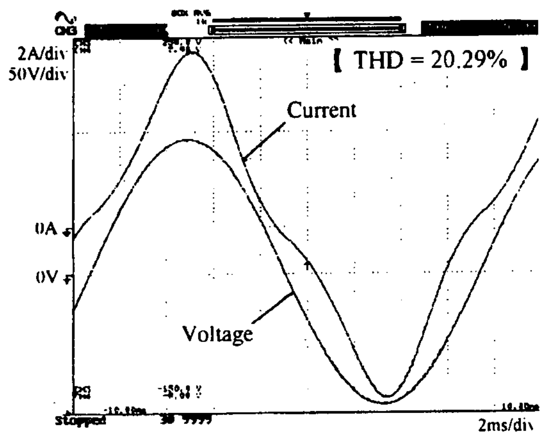
(b) Experimental waveform of d_F.

Fig 9 Generation of d_F modulating signal.

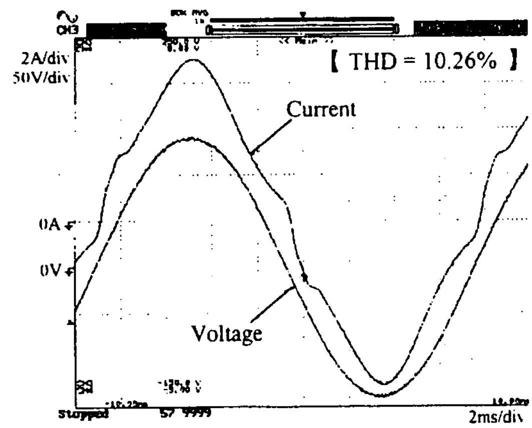
Fig. 8 shows variation of THD for input power at $\alpha = 1.237$ [$E_d = 350V$]. Maximum power is 1.3kW for the conventional, 1.6kW for the soft-switching constant d_F control and 1.9kW for the proposed soft-switching d_F control. The proposed d_F control achieves both improvement of input current waveform and power range.

6. EXPERIMENTAL RESULTS

Many characteristics of the proposed soft-switching PFC converter ware confirmed by experimental results. The input current waveform can be improved by controlling the duty factor according to eq (15) instead of constant d_F control. A circuit to control the duty factor according to Eq. (15) can be



(a) Conventional constant d_F control.



(b) Soft-switching constant d_F control.

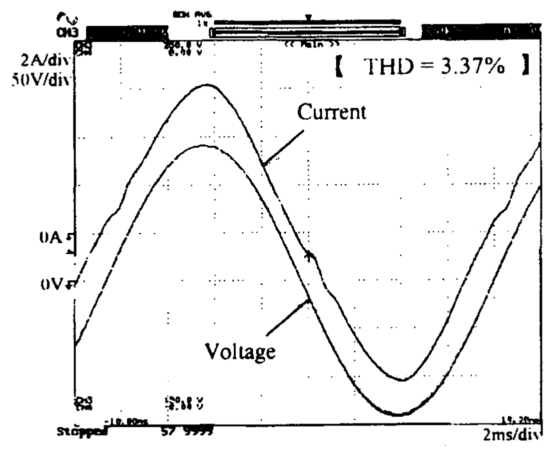


Fig.10 Examples of input voltage and current waveforms ($\alpha = 1.4$).

realized by using one multiplier-divider ICs (AD534). The generation circuit of d_F modulating signal is very simple as shown in Fig.9 (a). Fig.9 (b) shows an experimental waveforms of d_F modulating signal..

Fig. 10 shows an example of the experimental input voltage and current waveforms for the conventional constant d_F control, soft-switching constant d_F control and the proposed d_F control for soft-switching PFC converter. Experimental waveforms are obtained for the case of the input voltage V_S=100V rms, the input frequency f_s =60Hz, switching frequency f_b=20kHz, L_f = 2.42mH, C_f = 9.34μF, L_r = 120μH, C_d = 1mF, R_d = 100Ω and $\alpha = 1.4$. The proposed control method establishes a great improvement of THD in spite of an open loop system.

7. CONCLUSIONS

To improve the input current waveform of the soft-switching converter, a new duty factor control method has been proposed in this paper. A soft-switching discontinuous mode (DCM) power factor corrected (PFC) converter is analyzed by applying the double Fourier series expansion. It is found that the fundamental component and higher-order harmonics included in the input current waveform are obtained by the Fourier series expansion of the mean value of the inductor current. From the theoretical analysis, a new method removing the distortion of the input current waveform is proposed. In spite of an open loop system, the proposed method makes a great improvement of the total harmonic distortion even if the ratio of output voltage to input voltage is very low. Proposed soft-switching boost PFC converter achieves the zero voltage switching (ZVS) at the maximum current.

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