Novel Crest Factor Improvement of Electronic Ballast-Fed Fluorescent Lamp Current Using Pulse Frequency Modulation

Joong-Ho Song, Ick Choy, KIST
and Ju-Yeop Choi, Kwangwoon Univ. Korea

Abstract – In case that electronic ballast employing a valley-fill passive power factor correction (PFC) circuit is used for feeding fluorescent lamps, a new method to reduce crest factor of the lamp current is studied in this paper. In order to reduce crest factor to lower value, a pulse frequency modulation technique based on the waveform of the dc-link voltage which is predetermined by the passive PFC circuit, is taken into the switching control action of the electronic ballast. An equation-based analysis between the crest factor of lamp current and the effect of varying the inverter switching frequency is comprehensively performed.

Key words – Electronic ballast, fluorescent lamps, crest factor, passive power factor correction

I. INTRODUCTION

Recently, electronic ballast has become attractive in light industry since it has good performance such as light weight, high efficiency, good power factor, compared with the magnetic ballast that is bulky, heavy, and inefficient with low power factor [1]. In general, there are two considerations in designing the electronic ballast operating in the high frequency. One is required to comply with power quality standard regarding the input current of the electronic ballast. Although active PFC circuit with boost topology can be entirely satisfactory for the harmonic compliance, a 50% valley-fill PFC circuit also provides a reasonably good power factor above 0.93 [1-2]. The other consideration is crest factor of the fluorescent lamp current, which is generally recommended as a value below 1.7 by lamp manufacturers. When electronic ballast provided with the 50% valley-fill PFC is used for driving fluorescent lamps, the crest factor results in about 1.9 that is not desirable in general applications [2].

This paper aims at reducing the crest factor of fluorescent lamp current driven by electronic ballast with the passive PFC circuit in the input stage. A research on the fluorescent lamp ballast design using the passive PFC and a crest factor control was reported. In the work, crest factor control was performed, based on using current transformer to measure lamp current [2]. On the contrary, a control strategy proposed in this paper is executed by feeding back the valley-fill dc voltage without providing any additional components in the power circuit, except a few control circuit components are employed to handle the feed-backed dc voltage. Parallel-loaded resonant inverter within the electronic ballast is operated in the mode of pule frequency modulation (PFM). An equation-based relationship between the crest factor of lamp current and the variation of the inverter switching frequency is comprehensively investigated, considering the waveform of the dc-link voltage. The basic characteristics of electronic ballast with the proposed PFM control scheme are described in detail, and finally its effectiveness is verified by several simulated and experimental results.

II. OPERATING CHARACTERISTICS OF ELECTRONIC BALLAST

A. Input stage

The input stage with 50% valley-fill passive PFC circuit is shown in Fig. 1, where the circuit block composed of diodes and capacitors in the dc-link improves the input power factor [1-2]. The *LC*-filter between the diode rectifier and the passive PFC circuit filters out the high frequency current ripple generated by the half-bridge inverter switching.

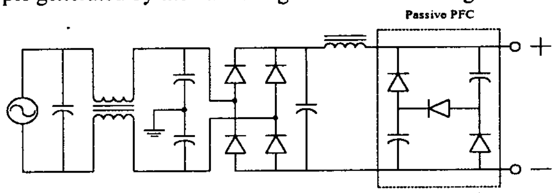


Fig. 1. Input stage with the passive PFC circuit

B. Resonant circuit

Fig. 2 shows the parallel-loaded resonant circuit, which has been widely adopted as the basic circuit topology for the electronic ballast. The steady-state frequency characteristics of this circuit are calculated by using ac circuit analysis technique. In the following calculation, all components are considered to be ideal and the fluorescent lamp can be considered as a resistance. This is a valid model for high frequency operation of the lamp [3]. Note that the fluorescent lamp has negative incremental impedance characteristics under the small-signal perturbation with the lamp voltage and current varied around the operating point [4].

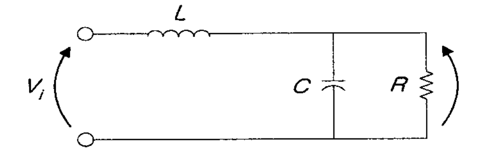


Fig. 2. Parallel-loaded resonant circuit

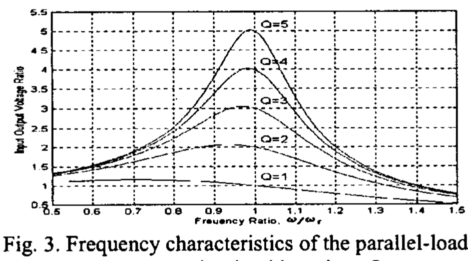


Fig. 3. Frequency characteristics of the parallel-loaded resonant circuit with various Q

The characteristic equation of this circuit is described as

$$\frac{|V_o(j\omega)|}{|V_i(j\omega)|} = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_r}\right)^2\right)^2 + \left(\frac{\omega}{\omega_r Q}\right)^2}} \quad (1)$$

where $\omega_r = 1/\sqrt{LC}$ and $Q = R/(\omega_r L) = \omega_r CR$, and frequency characteristic curves are plotted as shown in Fig. 3. The ballast should be able to supply high-voltage enough to light fluorescent lamps at starting. Moreover, the ballast should be able to supply low voltage enough to keep lighting during running. It can be shown in this figure that the parallel-loaded resonant circuit has such characteristics.

C. Half-bridge inverter and starting scenario

The half-bridge resonant inverter combined with parallel-loaded resonant as shown in Fig. 4 is used for the electronic ballast. When DC voltage is applied to the input-side of the inverter, it is changed into square waveform at the points of *a* and *d* as shown in Fig. 5(a). The square waveform is consequently converted to ac waveform by the blocking capacitor, C_b, as shown in Fig. 5(b). This ac voltage is fed to the resonant circuit and becomes a filtered waveform as shown in Fig. 5(c). Finally, the input stage with the 50% valley-fill PFC circuit of Fig. 1 is connected to the half-bridge inverter with the parallel-loaded resonant circuit of Fig. 4 with the dc-link commonly linked. In this combined circuit, since the 50% valley-fill voltage as shown in Fig. 6(a) is applied to the dc-link of the inverter input stage, the large-scaled contour waveform across the points of *b* and *d* in the inverter output circuit is shown as Fig. 6(b).

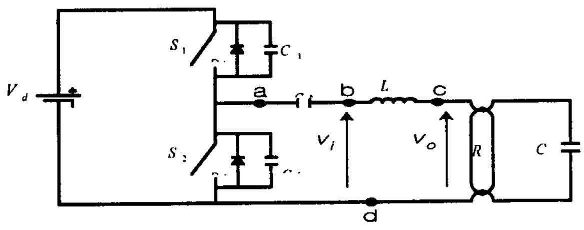
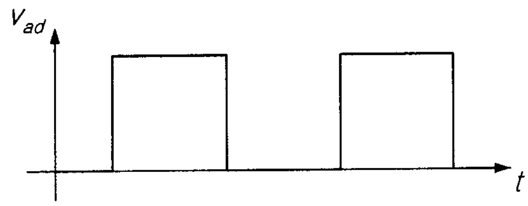
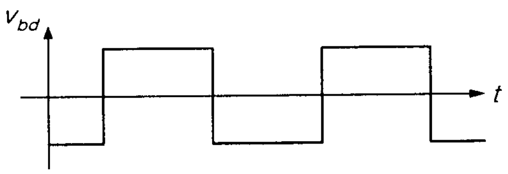


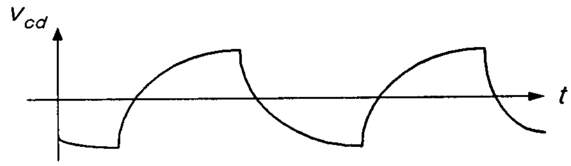
Fig. 4. Half-bridge inverter with the parallel-loaded resonant circuit.



(a) across a-d

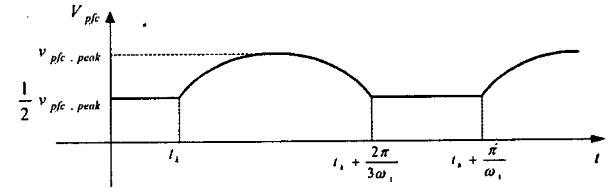


(b) across b-d

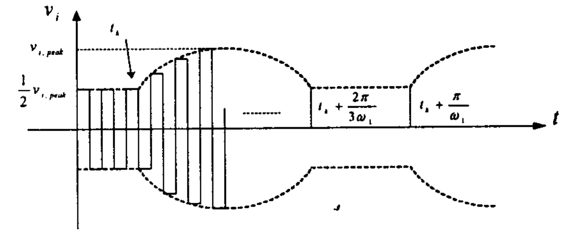


(c) across c-d

Fig. 5. Voltage waveforms of the inverter



(a)



(b)

Fig. 6. (a) 50% valley-fill voltage; (b) Input voltage to the resonant curcuit

The high voltage instantaneously applied to ionize the gas in fluorescent lamp affects the lifetime of the lamp since its filaments are heated up instantaneously. To lessen this effect, starting scenario is needed to be performed, in which very low current flows through the lamp to preheat the filaments, followed by applying higher voltage for ignition, and finally appropriate running power is applied to the lamp. These requirements are satisfied easily by changing the switching frequency along to the predetermined procedure.

The frequency characteristics of the inverter output circuits during the preheat and ignition modes are shown in the upper curve of Fig. 7, where the lamp current flows little since the resistance of the lamp is very high. After sufficient preheat, the applied lamp voltage increases up to high voltage enough to ignite the lamp as the switching frequency decreases. Then, the resistance of the lamp becomes much smaller, thus the lamp current actually flows through the lamp. In this running mode, the respective frequency characteristics are shown in the lower curve of Fig. 7. The switching frequency decreases to obtain the appropriate voltage corresponding to the running state.

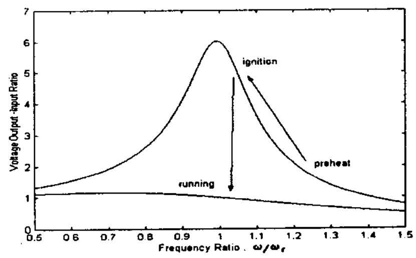


Fig. 7. Frequency characteristics under starting scenario; the upper curve for preheat and ignition, the lower for running.

III. NEW CREST FACTOR CONTROL

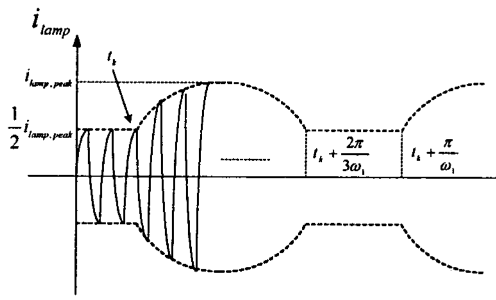
A. Description on the control scheme

For guarantee of the lifetime of a fluorescent lamp, the recommendation that the crest factor of the lamp current is below 1.7 should be satisfied. The crest factor is defined as following equation:

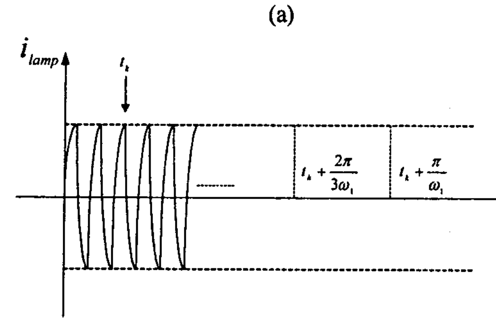
$$CF = \frac{I_{lamp,peak}}{I_{lamp,rms}}. \tag{2}$$

It is seen in Fig. 6(b) and 8(a) that the flowing lamp current shows a waveform contour reflecting the dc-link voltage waveform. Considering equation (2), therefore, the crest factor can be reduced if the contour of the lamp current becomes to be flat.

The proposed method in this paper is to reduce the difference between the peak and rms values of lamp current by decreasing the fluctuation of the contour of the lamp current. In this scheme, a PFM switching technique based on the dc-link voltage waveform is used to reduce the fluctuation difference. When the valley part in the dc-link voltage is applied to the lamp, the switching frequency of the inverter decreases to a preset value to increase the magnitude of the lamp current. Note that such an increase of the supplied lamp current is accomplished by increase of the voltage boost gain in the half-bridge resonant inverter circuit. When the hill part in the dc-link voltage is applied to the lamp, the switching frequency increases with the shape of the voltage up to a preset value and consequently makes the lamp current decrease. The idealized waveform of the lamp current can be changed from the concave contour of Fig. 8(a) to the smoothed contour of Fig. 8(b) with the help of the PFM control action. Therefore, the crest factor of the lamp current becomes smaller. The dc-link voltage waveform can be used as the basic reference waveform for the control input signal of the proposed method.



(a)



(b)

Fig. 8. Idealized lamp current: (a) without PFM; (b) with PFM

Fig. 9 shows the overall block diagram of the ballast control system at running including the proposed control scheme. The required switching frequency is determined from the crest factor reduction block. It is said that $f_{run,min}$ is the minimum running frequency and f_{var} is the variable frequency. A feedforward signal, f_{ff} denotes the remaining signal waveform subtracting the half value of the dc-link peak voltage from the dc-link voltage waveform. This feedforward signal is multiplied by the gain K to determine the width of the varying frequency, and added to $f_{run,min}$ predetermined by the starting scenario and finally produces the switching frequency signal required to achieve the lamp current with a low crest factor. The method to determine the switching frequency explained in the above can be also described in the graphical representation of Fig. 9. The gain K in the crest factor reduction loop adjusts the intensity of control signal to compensate the influence of the concave waveform of the dc-link voltage. In Fig. 10, the loop gain K can be described as

$$K = \frac{f_{run,\max} - f_{run,\min}}{f_{ff,peak}}. \tag{3}$$

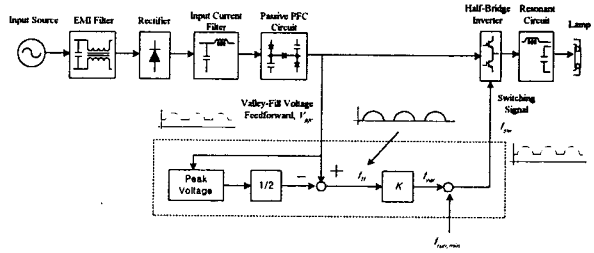


Fig. 9. Overall control block diagram of the electronic ballast during running

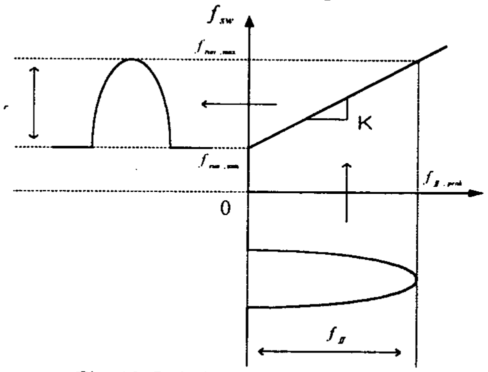


Fig. 10. Relationship between f_{sw} and f_{ff}

B. Crest factor and gain K

When the electronic ballast feeds the fluorescent lamp, a relationship between the crest factor of the lamp current and the loop gain K is calculated in this section. Considering Fig. 9 and 10, the switching frequency of the half-bridge inverter can be described as equation (4).

$$f_{sw}(K,t) = f_{run,\min} + f_{\text{var}} = f_{run,\min} + K(V_{pfc} - V_{valley})$$
$$= \begin{cases} f_{run,\min} + K\dfrac{V_{pfc,peak}}{2}\sin\omega_1\left(t + \dfrac{\pi}{6\omega_1}\right) \\ f_{run,\min} \end{cases}$$

$$t_k \le t < t_k + \frac{2\pi}{3\omega_1} \quad (4)$$

$$t_k + \frac{2\pi}{3\omega_1} \le t < t_k + \frac{\pi}{\omega_1}$$

In this equation, ω_1 denotes the angular velocity of the ac input utility line voltage and t_k means the timing instant at which the sinusoidal waveform block in the dc-link voltage begins, shown in Fig. 6(a).

The output resonant circuit is also dealt with to calculate the lamp current. The circuit of Fig. 4, where V_{bd} and V_{cd} mean the input voltage, v_i, and the output voltage, v_o, respectively, is considered here. The input voltage, v_i, which is a square wave in Fig. 5(b) and shows a contour like the waveform of Fig. 6(a), is described in the following equation (5).

$$v_i(K,t) = \begin{cases} (-1)^{\mathrm{int}(2f_{sw}(K,t)t)} \dfrac{V_{pfc.peak}}{2} \sin \omega_1\left(t + \dfrac{\pi}{6\omega_1}\right) \\ (-1)^{\mathrm{int}(2f_{sw}(K,t)t)} \dfrac{1}{4} V_{pfc.peak} \end{cases} \quad (5)$$

$$t_k \le t < t_k + \frac{2\pi}{3\omega_1}$$

$$t_k + \frac{2\pi}{3\omega_1} \le t < t_k + \frac{\pi}{\omega_1}$$

where the function, int(·) means getting only integer part of its argument. The output voltage, v_o, is also expressed as the following equation (6) [5].

$$v_o(K,t) = -v_i(K,t)e^{-\frac{1}{2RC}t}(\cos\alpha t + \beta \sin \alpha t) + v_i(K,t) \quad (6)$$

where $\alpha = \sqrt{\frac{1}{LC} - \left(\frac{1}{2RC}\right)^2}$ and $\beta = \sqrt{\frac{L}{4R^2C^2 - L}}$.

The lamp current can be calculated as equation (7).

$$i_{lamp}(K,t) = \frac{1}{R}v_o(K,t) = -\frac{1}{R}v_i(K,t)e^{-\frac{1}{2RC}t}(\cos\alpha t + \beta\sin\alpha t) + \frac{1}{R}v_i(K,t) \quad (7)$$

Next, the rms value of the lamp current is calculated as

$$i_{lamp.rms}(K) = \sqrt{\frac{\omega_1}{\pi}\int_{t_k}^{t_k+\pi/\omega_1}\left[-\frac{1}{R}v_i(K,t)e^{-\frac{1}{2RC}t}(\cos\alpha t + \beta\sin\alpha t) + \frac{1}{R}v_i(K,t)\right]^2 dt}$$

$$= \sqrt{\frac{\omega_1}{R\pi} I(K)}, \quad (8)$$

where the integration formula without R is replaced with $I(K)$ for the sake of simplification.

Considering that the voltage gain of equation (1) is also keeping and the peak value of the lamp current appears at the peak of the lamp voltage, the peak value of the lamp current is calculated as

$$i_{lamp.peak}(K) = \max_{t_k \le t < t_k + \frac{\pi}{\omega_1}} \left\{ \frac{V_{pfc.peak}}{R\sqrt{\left(1 - (2\pi f_{sw}(K,t))^2 LC\right)^2 + \left(\frac{L}{R}2\pi f_{sw}(K,t)\right)^2}} \right\} \quad (9)$$

From equations (2), (8) and (9), the crest factor of the lamp current is obtained as the following equation.

$$CF(K) = \frac{V_{pfc.peak}}{\sqrt{\frac{\omega_1}{\pi} I(K) \min_{t_k \le t < t_k + \frac{\pi}{\omega_1}} \left\{ \left(1 - (2\pi f_{sw}(K,t))^2 LC\right)^2 + \left(\frac{L}{R}2\pi f_{sw}(K,t)\right)^2 \right\}}} \quad (10)$$

The crest factor can be plotted in terms of the loop gain K while different values of $f_{run,min}$ are considered as shown in Fig. 11, which is calculated by using the parameters of Table 1 in the section IV. This figure shows that there is a certain value of the loop gain K to make the crest factor be minimized. The minimum point of the crest factor is found at the K value of about 25 on the curve corresponding to the $f_{run,min}$ of 20kHz.

In order to check if the appropriate lamp current flows under condition of the minimum crest factor as shown in Fig.11, the respective peak and rms values are plotted in Fig. 12. In this figure, equations (8) and (9) are used and the lamp current decreases monotonically as K increases. This figure shows that the rms lamp current doesn't increase beyond the nominal value under the minimum crest factor operation. It is noted that the frequency lower than 20kHz cannot guarantee the sufficient margin for the ZVS-on of the switches.

Fig. 13 shows the maximum and minimum running switching frequencies calculated for the PFM with respect to the gain K. It is noted in this figure that the region between the two curves represents the modulation width of the running switching frequency produced by PFM control.

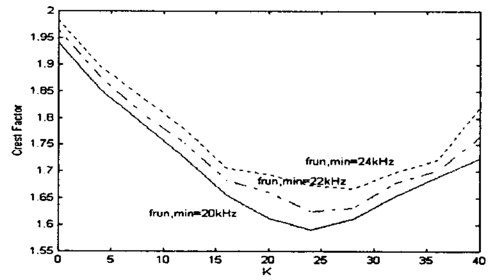


Fig. 11. Crest factor versus the loop gain K

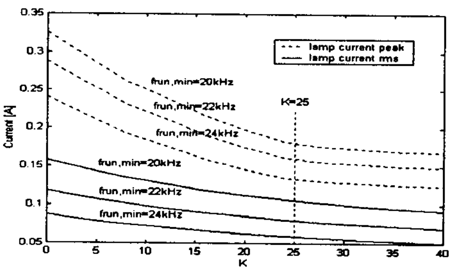


Fig. 12. Peak and rms lamp current in terms of the gain K and $f_{run,min}$

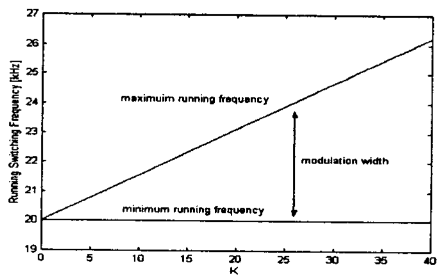


Fig. 13. Maximum and minimum switching frequencies versus the loop gain K

IV. SIMULATION AND EXPERIMENT

A. Simulation

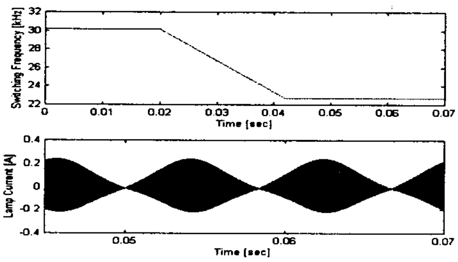
The system parameters and the switching frequencies used in simulations are shown in Table 1 and Table 2 respectively. The impedance of a fluorescent lamp is considered as incremental resistance [4]. It is set to vary at running from 700Ω when the input voltage is on the valley, to 1000Ω when on the hill. Before ignition, it may be assumed as infinite value, but in this simulation as 10MΩ.

The running frequencies are set so that the lamp current and power are on the same level in all cases. And it is assumed for this simulation that the fluorescent lamps are ignited when the switching frequency is 24kHz.

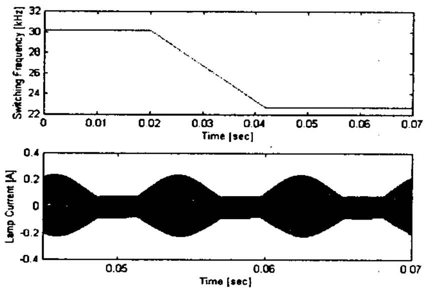
Table 1. System Parameters

Input voltage, V_{in}	$220V_{rms}$
Resonance Inductance, L	3mH
Resonance Capacitance, C	15nF
Blocking capacitance, C_b	$0.2\mu F$

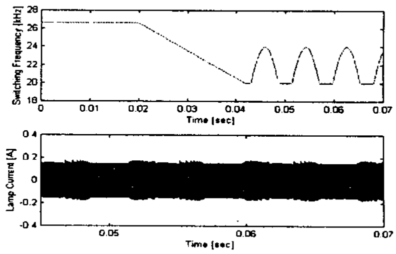
Simulations are performed for three cases. The case 1 shown in Fig. 14(a), where both PFC and PFM are not applied, shows the crest factor of 2.04. The case 2 of Fig. 14(b), which is provided with PFC and without PFM, shows the crest factor of 1.94. In case 3 of Fig. 14(c), where both the PFC and the PFM are used and the loop gain K is 25.7, the crest factor of 1.6 is obtained. It is testified from these results that the proposed method using PFM is relatively effective in reducing the crest factor. Note that two windows of each figure have different time span, or the lower windows show lamp current only when running state. Moreover, it is confirmed from Fig. 15 that soft switching (ZVS-on) is achieved in the whole range of running frequency, where the PFM is applied.



(a) without PFC and PFM

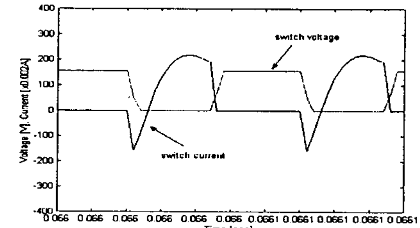


(b) only with PFC

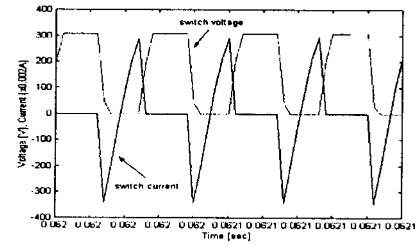


(c) with PFC and PFM

Fig. 14. Switching frequency trajectory and lamp current at running



(a) in low frequency region

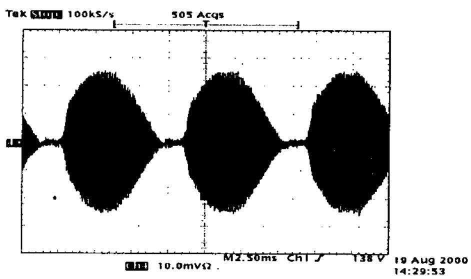


(b) in high frequency region

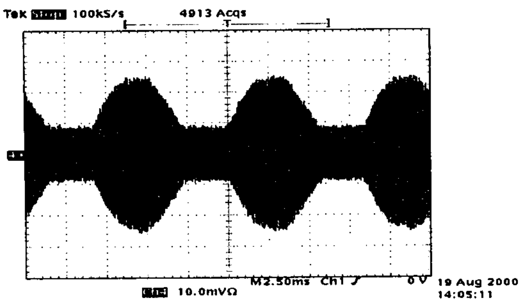
Fig. 15. Switch voltage and current

B. Experiment

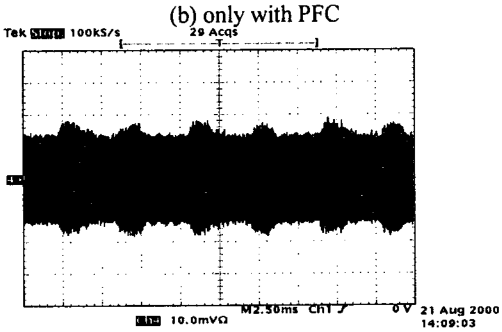
For experiment, 22 fluorescent lamps (40W) are used and KA7540 is employed as the ballast control IC. The PFM control loop is built with analog circuits consisting of op-amps and resistors. The system parameter values are the same as those for the simulation, and the lamp current of each case is on the same level. As shown in simulation section, experiments are performed for three cases. In case 1 of Fig. 16(a), the crest factor of lamp current at running reads about 2.0. In case 2 shown in Fig. 16(b), the crest factor reads about 1.9. The case 3 of Fig. 15(c) shows the crest factor of about 1.5.



(a) without PFC and PFM



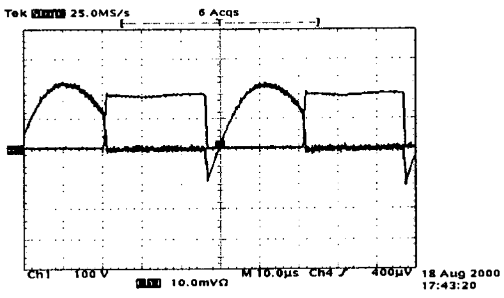
(b) only with PFC



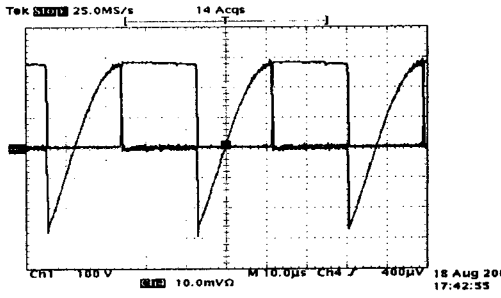
(c) with PFC and PFM

Fig. 16. Lamp current at running (0.1A/div., Time: 2.5ms/div.)

These results asmost coincide with the simulated results. It is seen in these results that the proposed method using PFM is very attractive in reducing the crest factor. Also, Fig. 17 shows that the soft switching (ZVS-on) is guaranteed in the whole range of running frequency. Note that the ZVS behavior is somewhat marginal in low frequency region. It is because the frequency is near to resonant frequency of the resonant circuit. However it does not affects any unexpected operation since the soft switching is always achieved. Additionally, the THD of input current is 35% and power factor is 0.935.



(a) in low frequency region



(b) in high frequency region

Fig. 17. Switch voltage and current (0.2A/div., 100V/div., Time: 10μs/div.)

V. CONCLUSION

When electronic ballasts employing a 50% valley-fill passive PFC circuit are used for feeding fluorescent lamps, a new method to reduce the crest factor of the lamp current is proposed. The 50% valley-fill passive PFC, which is cost-effective and widely used in many lighting applications, results in the undesirable value of the crest factor of the fluorescent lamp current. To reduce crest factor less than 1.7, PFM technique based on the waveform of the dc-link voltage that is obtained by the passive PFC circuit is proposed in this paper. It is confirmed through simulation and experiment that the crest factor of the lamp current is reduced to the value of about 1.5, and the soft switching (ZVS-on) of the inverter is guaranteed in the whole range of running frequency.

REFERENCE

[1] R. R. Verderber, O. C. Morse, W. R. Alling, "Harmonics from Compact Fluorescent Lamps," *IEEE Trans. Ind. Appl., Vol. 29, No. 3*, pp. 670-674, 1993

[2] P. N. Wood, "Fluorescent Ballast Design Using Passive PFC and Crest Factor Control," *IEEE IAS'98*, pp.2076-2081

[3] M. C. Cosby, Jr., R. M. Nelms, "A Resonant Inverter for Electronic Ballast Applications," *IEEE Trans. Ind. Elec., Vol. 41 No. 4*, pp.418-425, Aug. 1994

[4] E. Deng, S. Cuk, "Negative Incremental Impedance and Stability of Fluorescent Lamps," *IEEE APEC'97*, pp. 1050-1056, 1997

[5] L. R. Nerone, "A Mathematical Model of the Class D Converter for Compact Fluorescent Ballasts," *IEEE Trans. Power Elec., Vol. 10, No. 6*, pp. 708-715, 1995

[6] N. Mohan, T. M. Undeland, W. P. Robbins, "*Power Electronics*," 2/e, Wiley, 1995

[7] R. L. Steigerwald, "A Comparison of Half-Bridge Resonant Converter Topologies," *IEEE Trans. Ind. Elec., Vol. 3 No. 2*, pp.174-182, Aug. 1988

[8] M. K. Kazimierczuk, W. Szaraniec, "Class-D zero-voltage-switching inverter with only one shunt capacitor," *IEE Proceeding-B, Vol. 139, No. 5*, pp.449-456, Sep. 1992

[9] Th. J. Ribarich, J. J. Ribarich, "A New Model for High-Frequency Electronic Ballast Design," *IEEE IAS'97*, pp.2334-2339, 1997