Use of Chaotic Switching in Electronic Ballasts

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***Abstract* – This paper investigates the use of chaotic pulse-width modulation (CPWM) scheme for electronic ballasts to eliminate visible striation (appearance of black and white bands along the tube) in fluorescent lamps. The principle is based on the fact that the power spectral density of the lamp current will be rich of low-frequency harmonics in inverters switching with CPWM. Although this phenomenon is undesirable for power supplies requiring high quality output, it provides a favorable means to eliminate striations in this particular application. Most importantly, the lamp life will not be affected with the CPWM, since the lamp current crest factor is found to be similar to the one with standard PWM and the lamp current does not have dc component. The effectiveness of eliminating striations is confirmed experimentally with a T8 36W prototype.**

I. INTRODUCTION

High-frequency electronic ballasts for fluorescent lamps have been popular nowadays. The use of high-frequency ac current may increase the efficacy of the lamp by as much as 20% [1]. Important design considerations of ballasts include high power factor, low total harmonic distortion, low electromagnetic interference (EMI), low lamp current crest factor, and low flickering [2, 3]. In order to comply with some international standards, such as IEC 61000-3-2 Class C appliances [4], many existing electronic ballasts consist of a front stage input power factor corrector and a second stage of high-frequency ballast inverter. The two stages are inter-linked by dc link of fixed voltage, typically at 400V. In practice, boost- and flyback-type pre-regulators are the most popular choices for the front stage, whilst either a voltage-fed or current-fed inverter is usually chosen for the second stage. Among various resonant inverters, the voltage-fed resonant parallel-loaded inverter is the most popular topology. Fig. 1a shows a full-bridge version of the inversion.

Apart from igniting the lamp, electronic ballasts can also provide dimming function. The most common dimming method is to control the switching frequency of the second stage. By adjusting the switching frequency of S_1 to S_4, the reactance of L_r is varied and, thus, the lamp power can be controlled. Many commercially available integrated circuits have been developed for this particular application [5]. However, at low luminous level, the lamp tends to "striate" (appearance of alternating bands of bright and dim areas along the lamp tube [6]). Striations are manifestations of ionization oscillations and waves. This means that periodic changes in electron density are caused not only by redistribution of a fixed number of electrons (as in plasma waves), but by alternation of regions of predominant production and removal of electrons [7]. Striations can be eliminated by providing a small amount of dc current or low-frequency ac current to the electrodes to produce a composite current waveform through the lamp [8, 9]. However, dc current will have adverse effects on the lamp life and the low-frequency ac current requires an extra current injection circuit and introduces low-frequency luminous output variation.

Instead of introducing explicitly, this paper investigates the use of chaotic pulse-width modulation (CPWM) in the output inverter to generate high density of low-frequency components in the lamp current inherently, among all random switching schemes. This phenomenon is sometimes undesirable for power supplies requiring high quality output, but becomes a favorable means to eliminate striations in this particular application [10]. As there is no fixed low-frequency component in the lamp current, the luminous output has no fixed low-frequency variation. Most importantly, the lamp life will not be affected with the CPWM since the lamp current crest factor is similar to the one with standard RPWM and the lamp current does not have dc component. The effectiveness of eliminating striations is confirmed experimentally with a T8 36W prototype.

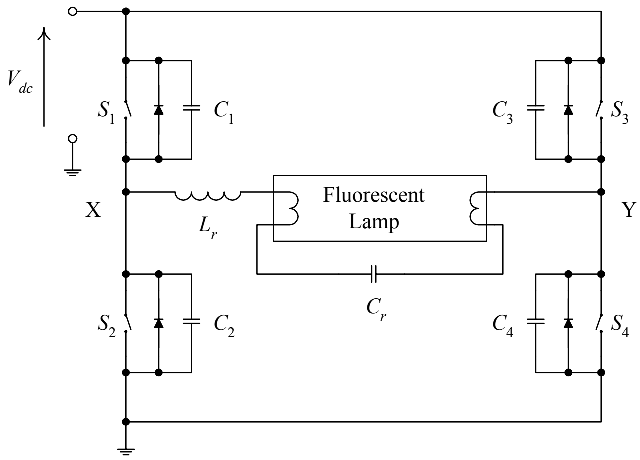
II. OPERATING PRINCIPLES

Fig. 1a shows the typical circuit of electronic ballast for fluorescent lamps using a full-bridge inverter circuit. The dc voltage V_{dc} is converted into an ac voltage across the fluorescent lamp. S_1 is switched in the same phase as S_4,

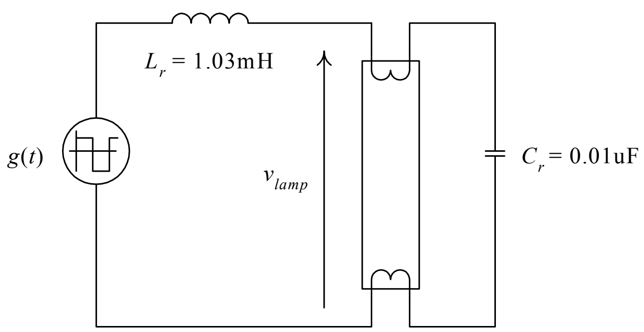
The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. City U 1233 / 02E).

whilst S_2 is switched in the same phase as S_3. The two pairs are switched in anti-phase and their duty cycles are 0.5. Thus, a square-like waveshape will be formed across the two nodes X and Y. The capacitors C_1 - C_4 are used to achieve zero-voltage switching of all switches for minimizing EMI and switching losses.

Fig. 1b shows the ballast-lamp equivalent circuit, in which the ballast is represented by a square-wave voltage source v_S connecting to a resonant tank, formed by L_r - C_r. The lamp tube is connected across C_r. For the sake of investigation, v_S is generated from the full-bridge inverter with S_1 to S_4 driving by a dSPACE digital processing system. Since the resonant tank circuit is usually designed to operate at a high quality factor, the fundamental frequency component of the square wave is the dominant one in the circuit. The fluorescent lamp is modeled by a resistor.



(a) Typical circuit of electronic ballast using full bridge inverter.



(b) Ballast-lamp equivalent circuit.

Fig. 1 Electronic ballast for fluorescent lamps.

A. Characteristics of CPWM scheme

CPWM is similar to conventional PWM with constant switching frequency. v_S is switched between $+V_{dc}$ and $-V_{dc}$. As depicted in Fig. 2, the only difference is that the pulse width is varied randomly between α_1 and α_2 [i.e., $\alpha_k \in [\alpha_1, \alpha_2]$]. Thus, the duty cycle d_k at kth switching cycle lies between d_1 ($= \alpha_1 / T_S$) and d_2 ($= \alpha_2 / T_S$), where T_S is the period of the switching frequency. However, the average duty cycle is kept at 0.5. A randomness level $\Re$ is defined as follows,

$$\Re = \frac{\alpha_2 - \alpha_1}{T_S} = d_2 - d_1 \tag{1}$$

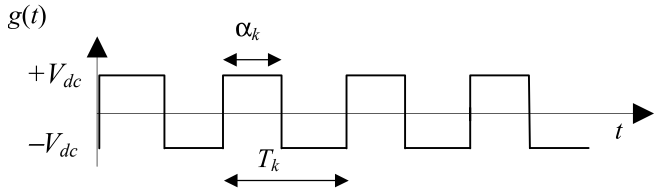


Fig. 2 Waveform of v_S with RPWM.

B. Power Spectral Density (PSD) of v_S

The PSD $S_p(f,\Re)$ of the waveform in Fig. 2 [5] is

$$S_p(f,\Re) = f_S \{E[|V_S(f)|^2] - |E[V_S(f)]|^2 + f_S |E[V_S(f)]|^2 \sum_{k=-\infty}^{\infty} \delta(f - k f_S)\} \tag{2}$$

where f_S is the nominal switching frequency and $V_S(f)$ is the Fourier transform of a cycle of v_S with chaotic level $\Re$. $E[\cdot]$ is the expected value over the whole ensemble. Expression of $V_S(f)$ is as follows,

$$\begin{aligned} V_S(f) &= V_{dc} \int_0^{d_k T_S} e^{-j2\pi f t} dt - V_{dc} \int_{d_k T_S}^{T_S} e^{-j2\pi f t} dt \\ &= \frac{j V_{dc}}{2\pi f} [2\, e^{-j2\pi f d_k T_S} - 1 - e^{-j2\pi f T_S}] \end{aligned} \tag{3}$$

where d_k is considered as a chaotic variable with $P(d_k)$ of uniform distribution. That is,

$$P(d_k) = \frac{1}{d_2 - d_1} = \frac{1}{\Re}. \tag{4}$$

Thus,

$$\begin{aligned} E[|V_S(f)|^2] &= \int_{d_1}^{d_2} P(d_k) V_S(f) V_S^*(f) d\, d_k \\ &= \frac{2 V_{dc}^2}{(2\pi f)^2} \{2 + [\cos(2\pi f T_S) + 1] + \\ &\quad \frac{V_{dc}^2}{\pi f \Re T_S} \{[\sin(2\pi f d_2 T_S) - \sin(2\pi f d_1 T_S)] - \\ &\quad \{\sin[2\pi f(1 - d_2) T_S] - \sin[2\pi f(1 - d_1) T_S]\}\}\} \end{aligned}$$

$$E[V_S(f)] = \int_{d_1}^{d_2} P(d_k) V_S(f)\, d\, d_k \tag{5}$$

$$= \frac{V_{dc}}{\pi f}\Big[\frac{1}{2\pi f \Re T_S}\left(e^{-j2\pi f d_2 T_S} - e^{-j2\pi f d_1 T_S}\right) - j\left(e^{-j2\pi f T_S} + 1\right)\Big]. \tag{6}$$

Compared with standard PWM, $S_p(f,\Re)$ consists of both continuous and discrete components. As the continuous component will spread over the frequency spectrum, the low-frequency component is particularly useful for eliminating striations.

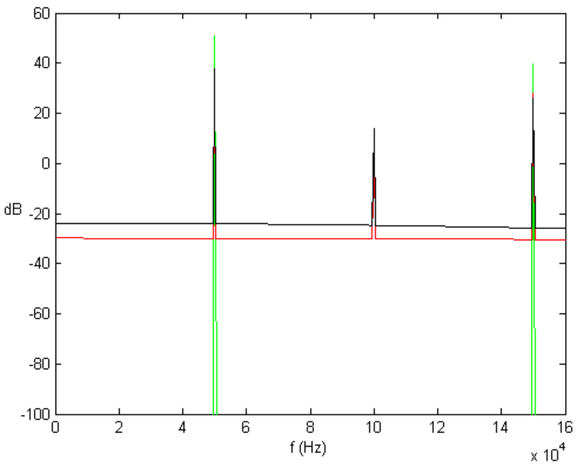


Fig. 3 Comparison of the low-frequency characteristics under different $\Re$.

D. Frequency Characteristics

Let $H(f)$ be the transfer function of the L_r - C_r circuit in Fig. 1. The PSD of the lamp voltage $v_{lamp}(f,\Re)$ of the converter can be shown to be

$$v_{lamp}(f,\Re) = S_p(f,\Re)\,|H(f)|^2 \;,\; f \neq 0\,. \tag{6}$$

where $H(f) = \dfrac{1}{L_r C_r \left[j 2\pi f\left(\dfrac{1}{R_L C_r}\right) - (2\pi f)^2 + \dfrac{1}{L_r C_r}\right]}$

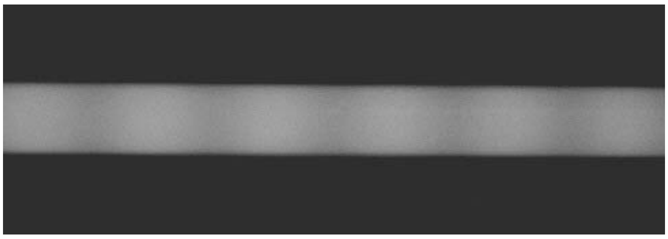
and R_L is the equivalent lamp resistance.

Fig. 3 shows a comparison of the low-frequency characteristics under different $\Re$. The low-frequency components increase with the increase in $\Re$. Most importantly, the dc component is zero, which will not cause adverse effect on the lamp life. The effectiveness of eliminating the striation increases with high $\Re$. However, visible flickers may occur because the variation of the lamp power is large with high $\Re$.

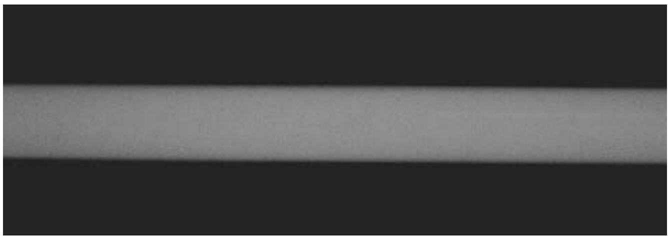
III. EXPERIMENTAL VERIFICATIONS

A T8 36W prototype was built and tested. The driving signals are generated from dSPACE. The components' values are shown in Fig. 1. The switching frequency is 50kHz. With standard PWM, the lamp starts to striate when the lamp power is at 30% of the rated value [Fig. 4(a)]. With RPWM, striation disappears for $\Re$ = 0.1 [Fig. 4(b)]. In particular, the lamp can be dimmed down to 5% without striation. Nevertheless, if $\Re$ is further increased, visible flicker occurs.

Fig. 5 shows the lamp current waveforms with different $\Re$. When $\Re$ = 0 [i.e., Fig. 5(a)], it is same as the standard PWM scheme. When $\Re$ = 0.1 [i.e., Fig. 5(b)], the current waveform or the lamp current crest factor is almost same as Fig. 5(a). However, the striations can be eliminated. If $\Re$ = 0.3 [i.e., Fig. 5(c)], variation of the lamp current (and thus the lamp power) is large and introduces visible lamp flicker, counteracting the advantage of eliminating striations.

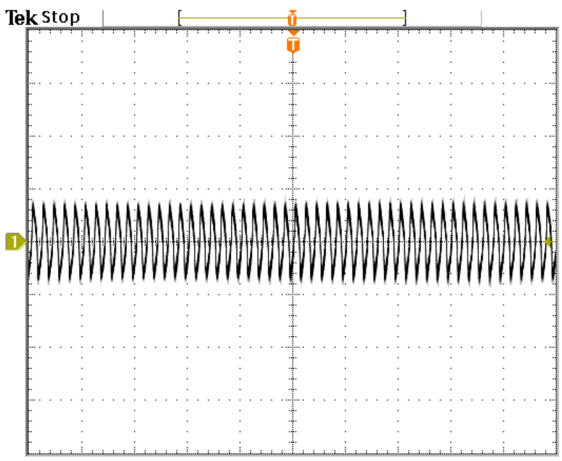


(a) Without CPWM.

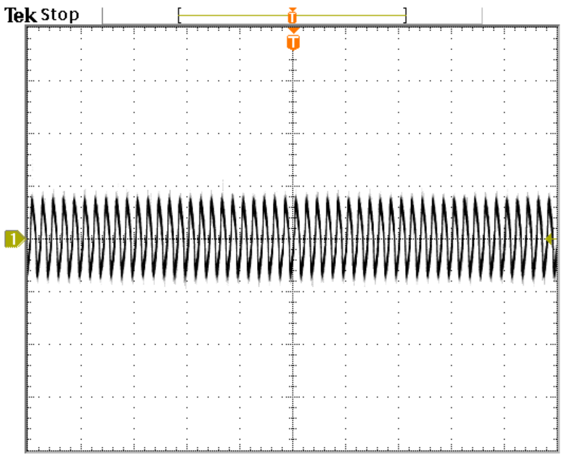


(b) With CPWM ($\Re$ = 0.1).

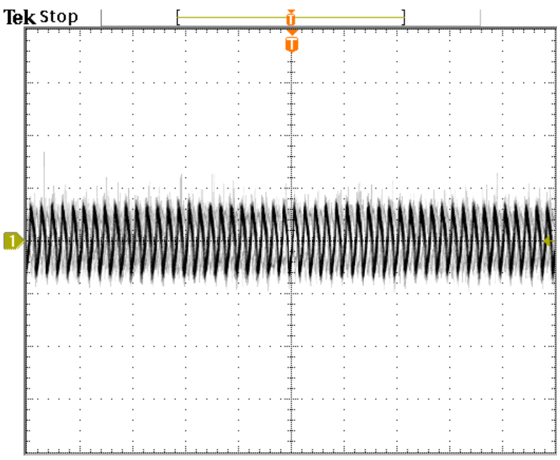
Fig. 4 Appearance of the lamp tube.



(a) $\Re$ = 0 (Standard PWM).



(b) $\Re = 0.1$.



(c) $\Re = 0.3$.

Fig. 5 Lamp current waveforms with different $\Re$.
(Ch1: 0.1A/div. Timebase: 100µs/div)

IV. Conclusions

This paper investigates the use of RPWM scheme for electronic ballasts to eliminate visible striations in fluorescent lamps. Low-frequency harmonics inherently exist at the inverter output with RPWM. Most importantly, the lamp life will not be affected with suitable randomness level since the lamp current crest factor is similar to the one with standard PWM and the lamp current does not have dc component. Compared with some existing techniques, the proposed one does not require extra power circuit modifications, but simply the modulation scheme at the signal level. Its effectiveness has been verified experimentally with a T8 36W prototype.

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