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A novel discrete dimmable electronic ballast

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Abstract: A novel discrete dimmable electronic ballast for a fluorescent lamp without changing the original power wiring system is developed. We propose a new method that detects the number of times the power-switch is pressed to make the electronic ballast generate the corresponding power rating. A dimming module realizes the proposed method and makes the DC-AC inverter in a round-robin manner to output the respective power rating. A prototype of the discrete dimmable electronic ballast for a T5 fluorescent lamp of 28 W under 110 VAC/60 Hz, for generating a four-state power rating is developed to demonstrate the feasibility of this approach.

Keywords: electronic ballast, dimmable, fluorescent lamp, discrete

Classification: Science and engineering for electronics

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1 Introduction

Lighting systems account for about 20% of the total energy consumed worldwide, and using high-frequency electronic ballasts for driving fluorescent lamps can both improve light quality and save energy [1, 2]. In practice, the maximum brightness a lighting device can emit is not always required, which implies a waste of energy. Thus, dimmable electronic ballasts have been developed for commercial lighting applications [1, 2, 3, 4, 5]. Traditionally, dimming controls can be classified into three methods: duty-cycle control [5], varying switching frequency control (VSFC) and varying DC link voltage control [2, 3].

Although the VSFC method is widely used in industry, it delivers continuous dimming, and thus can not be applied directly in a switch-based power wiring system. In this paper we therefore propose a new method for a discrete dimmable electronic ballast which can be applied directly and without changing the original switch-based wiring system. It makes the lighting systems upgrade more effectively from non-dimmable to dimmable ones. Note that this dimming module is just for controlling one lamp, giving it variable power ratings, and it is different from controlling the switching on/off of multiple lamps [4]. A review of the literature did not find any similar studies that sought to dim one fluorescent lamp discretely by an on-off switch without changing the wiring of the power system.

The kernel of the proposed method is a dimming module which consists of a switch detector, a shift register and the control circuit, called ΔR generator, for generating the resistance for each state. We define each state as representing a power rating. There are a finite number of states, and state transitions are triggered by pressing the switch. Hence users can dim the brightness of a fluorescent lamp by pressing the switch. In addition, users can introduce a fluorescent lamp lighting fixture equipped with this new dimming module without changing the original power wiring system.

We implemented the proposed approach for a dimmable electronic ballast that drives a 28 W T5 fluorescent lamp with four power ratings by utilizing four arithmetic sequence frequencies that are selected round-robin when the power switch is pressed.

2 Operation and analysis of the proposed circuit

The proposed dimmable electronic ballast, shown in Fig. 1 (a), consists of a conventional electronic ballast, marked yellow, and the new dimming module, marked green. The former includes the stages of the EMI filter, the rectifier, the PFC controller, and the DC-AC inverter [6]. The latter is composed of a detector, a shift register and the ΔR generator.

2.1 DC-AC inverter

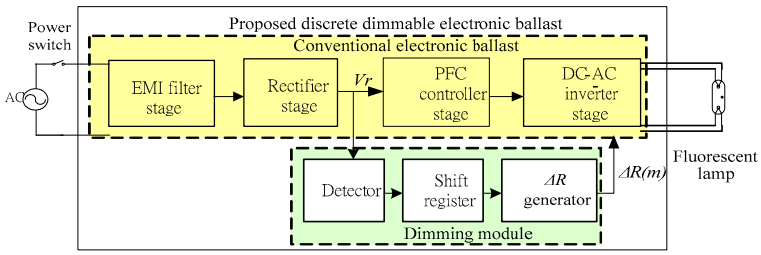
The basic circuit of the half-bridge series resonant (HBSR) DC-AC inverter for the electronic ballast is shown in Fig. 1 (b), while the HBSR DC-AC inverter with the proposed dimming module are shown in Fig. 1 (c). Assuming

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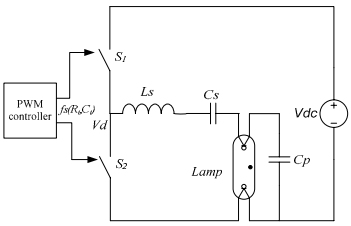
that the series blocking capacitor C_s is much larger than the resonant capacitor C_p, the equivalent circuit of Fig. 1 (b) and Fig. 1 (c) is shown in Fig. 1 (d). The model of the fluorescent lamp can be depicted by the negative resistance characteristics, and expressed as

$$R_{lamp} = \frac{V_{lamp}}{I_{lamp}} = R_S + \frac{V_H}{I_{lamp}} \tag{1}$$

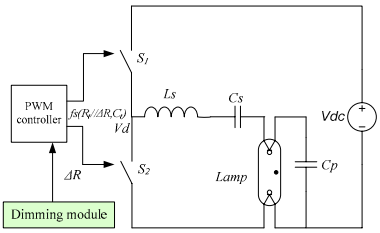
where V_H and R_S are the two parameters of the fluorescent lamp model [7], and V_H and R_S are designated on a conceptual V-I plane of a lamp, as shown in Fig. 1 (e).



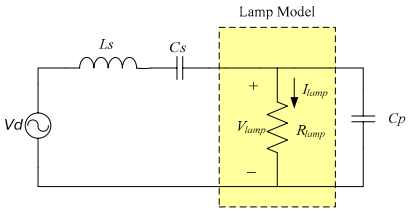
(a) Block diagrams of the proposed discrete dimmable electronic ballast



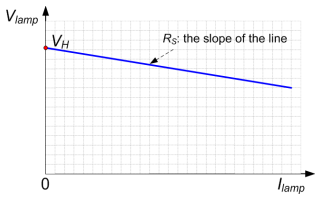
(b) HBSR inverter



(c) HBSR inverter with the dimming module



(d) Equivalent circuit of HBSR inverter



(e) The conceptual V-I plane of a lamp

Fig. 1. The proposed discrete dimmable electronic ballast

The asymmetrical square-wave voltage $V_d(t)$ is applied to the fluorescent lamp through the load resonant circuit. Only the fundamental component $V_1(t)$ of the $V_d(t)$ will be present in the inverter through a high quality factor of the load resonant circuit. With a fundamental approximation of $V_1(t)$ and neglecting the filament resistance, the lamp voltage V_{lamp} can be obtained as

$$V_{lamp}(t) = \frac{V_1(t)}{\sqrt{\left[1-\left(\frac{f_s}{f_o}\right)^2\right]^2 + \left(\frac{f_s Z_o}{f_o R_s}\right)^2 \left(\frac{V_H - V_{lamp}}{V_{lamp}}\right)^2}} \tag{2}$$

where

$$V_1(t) = \frac{\sqrt{2}V_{dc}}{\pi}\sin(2\pi f_s t) \tag{3}$$

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$$Z_o = \sqrt{\frac{L_s}{C_p}} \tag{4}$$

$$f_o = \frac{1}{2\pi\sqrt{L_s C_p}} \tag{5}$$

Z_o and f_o are the characteristic impedance and the resonant frequency of the load resonant circuit. Thus, the lamp power can be obtained as

$$P_{lamp} = \frac{V_{lamp(RMS)}^2}{R_{lamp}} \tag{6}$$

where $V_{lamp(RMS)}$ is the root-mean-square (RMS) value of the lamp voltage $V_{lamp}(t)$ [7]. If the operating frequency f_s is altered, the impedance of the series resonant tank is changed accordingly. Thus, we could get the variable lamp power by varying the switching frequency of the inverter.

2.2 Detector:

The detector generates a one-shot pulse signal when the power switch has an off-on switching. The detector consists of a differential circuit and a one-shot circuit, as shown in Fig. 2. When the switch is turned from off to on, the line rectified voltage (V_r) node rises from 0 to a high DC voltage. Such a change of V_r is passed to the differential circuit to make a differential signal. The differential signal then triggers the one-shot circuit to generate a one-shot pulse signal for the shift register. The number of times the one-shot pulse signals are generated is decided by how many times the differential signals are generated.

2.3 Shift Register

The shift register, shown in Fig. 2, is triggered by the pulse signal. If we require n states, the shift register has n bits. For the n-bit shift register, it outputs signals "$Q_n Q_{(n-1)} \dots Q_2 Q_1$" according to the number of times (m) the one-shot pulse signal generated, as the following equation shows:

$$Q_n Q_{(n-1)} \dots Q_2 Q_1 = \begin{cases} \text{“}00\dots01\text{”} & for\ m = 1 \\ \text{“}00\dots10\text{”} & for\ m = 2 \\ \dots & \dots \\ \text{“}01\dots00\text{”} & for\ m = 3 \\ \text{“}10\dots00\text{”} & for\ m = n \end{cases} \tag{7}$$

If the power switch is turned off for a period of time that is greater than the discharge time of the power supply of the control IC, the shift register will be reset.

2.4 ΔR generator

The function of ΔR generator is that it generates variable resistance, according to the state of the shift register. As shown in Fig. 2, n switches and n resistors are controlled by the shift register to generate an equivalent resistance $\Delta R(m)$, or ΔR in short, where m is defined in Eq. (7). As we

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determine the element parameters of the DC-AC inverter resonant tank, we can get the lamp power ratings P_m under the switching frequency f_m by the VSFC method. The switching frequency of the PWM controller is

$$f_m\left[R_T(m), C_t\right] = k\frac{1}{R_T(m)C_t} \quad for\ m = 1, 2, \ldots, n \tag{8}$$

where k is a constant factor depending on the PWM controller, and $R_T(m)$ and C_t are the frequency parameters. $R_T(m)$ is the total equivalent resistance of $R_t//\Delta R(m)$, where R_t is the original resistance of PWM controller for the conventional electronic ballast and $\Delta R(m)$ is the resistance generated by the dimming module. By Eq. (8), f_m is inversely proportional to $R_T(m)$ when k and C_t are fixed. We define $\Delta f = f_n - f_1$, and $\Delta R_T = R_T(n) - R_T(1)$ can then be obtained. If n states are required, we can evenly partition the frequency into $n-1$ divisions. Hence $R_T(m)$ can be determined as:

$$R_T(m) = R_t - \frac{(m-1)\Delta R_T}{n-1} \quad for\ m = 1, 2, \ldots, n \tag{9}$$

and $\Delta R(m)$ generated by the dimming module can be obtained as

$$\Delta R(m) = \frac{R_t R_T(m)}{R_t - R_T(m)} \quad for\ m = 0, 1, \ldots, (n-1) \tag{10}$$

Through the preliminary digital process (a detector, shift register and ΔR generator), we can determine the resistance $R_T(m)$ to get the required frequencies $f_1, f_2, \ldots$ and f_n. Finally by the VSFC method, we can get the lamp output power ratings P_1 under f_1, P_2 under $f_2 \ldots$ and P_n under f_n as required.

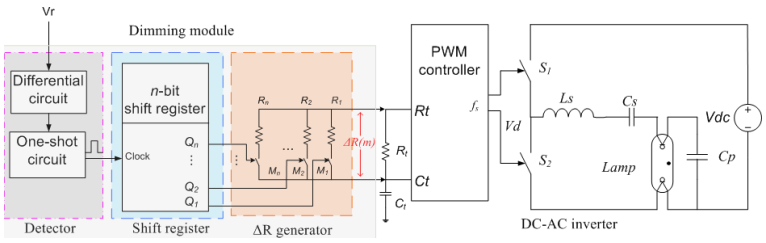


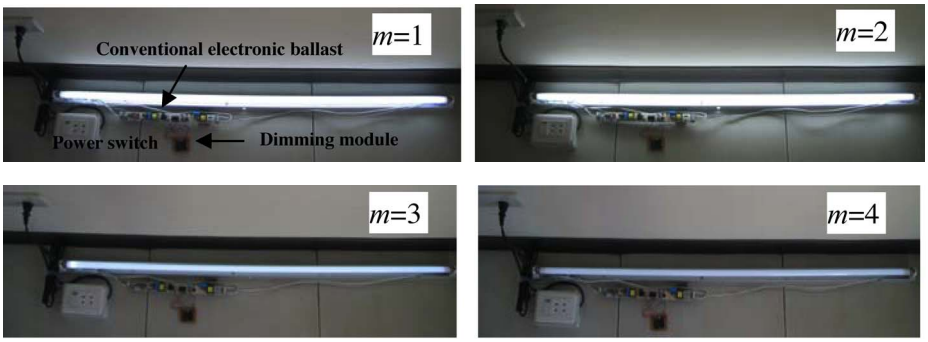
Fig. 2. The circuits of the dimming module

3 Experimental Results

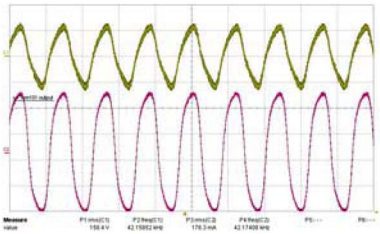
A prototype of the proposed discrete dimmable electronic ballast is shown in Fig. 3 (a) for driving a 28 W T5 fluorescent lamp to have four power ratings ($n = 4$). Referring to Fig. 2, the main specifications and parameters of the system are as follows: (1) the input voltage: 110 VAC 60 Hz; (2) $L_s = 3.5$ mH, $C_s = 1$ uF, $C_p = 2200$ pF; (3) $S_1 = S_2$: N-MOS 600 V 2 A; (4) PWM controller IC: IRS2153D; (5) differential circuit: resistors and capacitors; (6) one-shot circuit: CD4002; (7) shift register: CD4015; (8) $M_1 \sim M_4$: PDTC143ES; (9) $R_t = 12$ k and $C_t = 560$ pF; (10) $\Delta R(m)$: $R_1 = 168\,\text{k}\Omega$, $R_2 = 30.8\,\text{k}\Omega$, $R_3 = 15.8\,\text{k}\Omega$ and $R_4 = 10.2\,\text{k}\Omega$.

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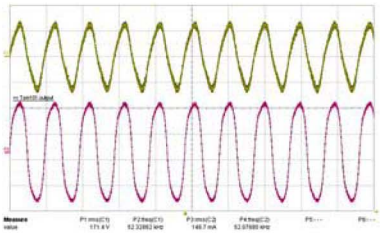
The waveforms of the lamp voltage and current for each state are shown in Fig. 3 (b) to 3 (e), and the experimental data are shown in Fig. 3 (f). Fig. 3 (g) represents the relation of the lamp power versus frequency with the VSFC and the proposed discrete method. In Fig. 3 (h), we show the efficiency of the prototype. On average it is 8% better than the data in [1] and 39% better than the data in [3] when the lamp power ratings are 4 W, 20 W, 25 W and



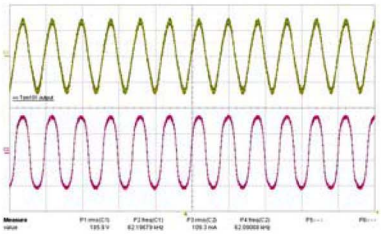
(a) The four states of the prototype, for m = 1 to 4, respectively.



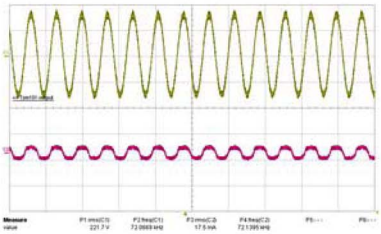
(b) Lamp waveforms for m=1



(c) Lamp waveforms for m=2



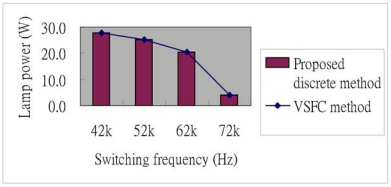
(d) Lamp waveforms for m=3



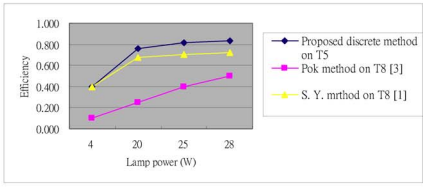
(e) Lamp waveforms for m=4

Shift register output	Input voltage (VAC)	Input current (mA)	Switching frequency f_s (kHz)	Lamp voltage V_{lamp} (V)	Lamp current I_{lamp} (mA)	Lamp power P_{lamp} (W)	Efficiency (%)
"0001"	110	303	42.15	158.4	176.3	27.9	83.8
"0010"	110	280	52.32	171.4	146.7	25.1	81.6
"0100"	110	243	62.19	185.9	109.3	20.3	76.0
"1000"	110	88	72.06	221.7	17.5	3.9	40.1

(f) Experimental data



(g) Lamp power vs. frequency



(h) Efficiency comparison

Fig. 3. The prototype and its experimental results

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28 W. However, [1] and [3] use continuous control methods on T8 fluorescent lamps, while we use T5 fluorescent lamps.

4 Conclusion

A novel discrete dimmable electronic ballast consisting of digital and analog control is proposed, which is capable of saving energy and upgrading effectively in lighting system applications. Our design integrates the detector, shift register and ΔR generator into a dimming module that can be applied readily with existing electronic ballast systems, keeping the original power wiring system. A prototype for driving a 28 W T5 fluorescent lamp was implemented to demonstrate its effectiveness in delivering four power ratings by pressing a power switch serially. In future research, we may achieve greater efficiency by the varying DC link voltage control method.

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