A New HID Lamp Ballast using Internal LC Resonance and Coupled Inductor Filter

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Abstract - This paper proposes a new ballast that is ignited by internal LC resonance of buck converter. In order to cancel the steady state current ripple, the proposed ballast utilizes the coupled inductor filter which minimizes the size and weight of the ballast. The operation mode of the proposed ballast is analyzed and the performance of the new ballast is verified by the experimental results from a 150W prototype ballast for metal halide discharge (MHD) lamp.

I. INTRODUCTION

Among the various kinds of high intensity discharge (HID) lamps, MHD lamps are considered to be one of the most effective light sources since MHD lamps have high electrical-to-lumen efficacy, long life, good color rendition , and good focusing capability, etc.

In spite of these advantages, the mode of operation is quite complex compared to the other lamps [1]. To start the MHD lamp, it is necessary to provide a high ignition voltage between electrodes. The high voltage induces high electric field, which accelerates the electron in the tube. The accelerated electrons are crashed with other molecules, which are ionized. To generate this high voltage pulse without an external ignitor, the internal LC resonance can be used for the breakdown voltage of 2kV for the cold lamp.

After the ignition, the lamp begins to discharge to a glow stage, then reaches through a transition to a thermionic arc, and finally a stable arc discharge. In this state, acoustic resonance may occur if the power provided to lamp is fluctuated at its eigen-frequencies, which are determined by internal lamp temperature and pressure. The acoustic resonance may cause arc instability, fluctuation in light output, and in the worst case, a cracking of tubes. It was reported that the lamp ripple current must be under the 20% of the lamp DC current to prevent the acoustic resonance in a low frequency square wave operation [2].

Fig. 1 shows the ballast using the LCC resonant inverter [3]. In ignition mode, a high ignition voltage is produced by the LC resonance. After the ignition, the square voltage applied to the LCC network is filtered to provide sinusoidal current and voltage to the lamp. This circuit is very simple and easy to control. Furthermore, it needs no external ignitor by the LC resonance and shows the better electrical-to-lumen efficacy than low-frequency square wave operation. However, it is not easy to avoid the acoustic resonance due to the variable frequency control and the widely located acoustic resonance frequency in tens and hundreds kHz.

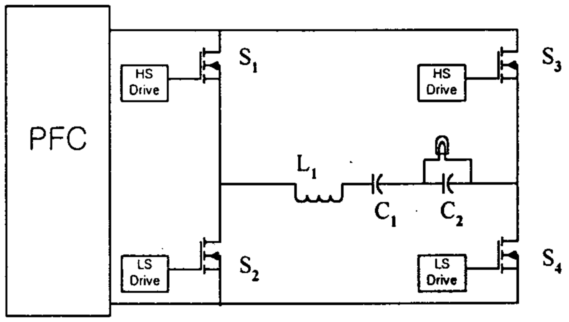

Fig. 1 The ballast using the LCC resonant inverter

Fig. 2 shows the buck type ballast using a 2nd LC stage [4]. In ignition mode, L_1 and L_2 resonate with C_2 to make high ignition voltage using the high Q-factor. After the ignition, it operates as a buck converter of which input voltage is $V_{in}/2$. This circuit has the advantage of eliminating the external ignitor and being able to avoid the acoustic resonance by 2nd stage LC network filtering. However, two separate inductors which increase the size and weight are necessary for sufficient filtering of the lamp current.

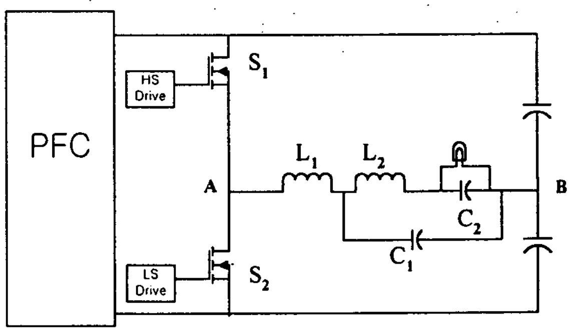

Fig.2 The buck type ballast using 2nd LC stage

In this paper, the ballast with an internal LC resonant ignitor employ a coupled inductor of the buck converter. It minimizes the size and weight of the ballast is used for steady state ripple cancellation . The operation mode of the new ballast is analyzed and the performance is verified by the experimental results from a 150W prototype ballast for MHD lamp.

II. The Proposed Ballast

Fig.3 and Fig.4 show the proposed ballast and gating waveform, respectively. The proposed ballast is ignited by the internal LC resonance. However, this LC network of the ballast cannot filter sufficiently the steady state ripple due to the small capacitive value. Therefore, the coupled inductor filter is applied for steady state ripple cancellation.

A. Ignition phase analysis

In the ignition mode, the square voltage is applied to the LC resonant network by the full-bridge switching action. Fig.5 shows the equivalent circuit at the ignition mode.

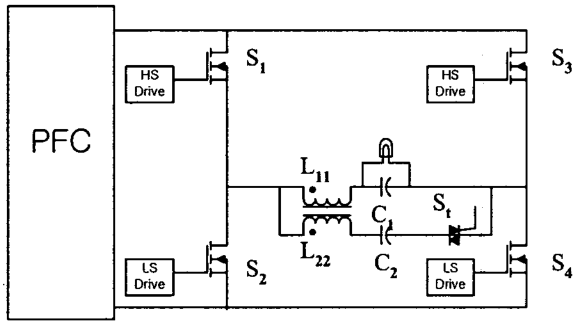

Fig.3 The Proposed Ballast

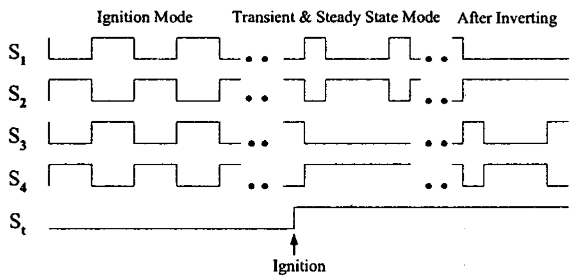

Fig.4 Timing chart of S1, S2, S3, S4 and St

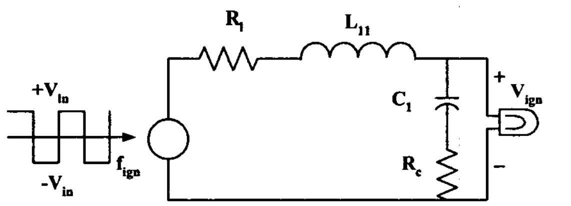

Fig.5 The equivalent circuit of the ignition mode

The input peak current and ignition voltage are given by (1) and (2).

$$I_{in,pk} = \frac{V_{in,pk}}{Z} \qquad \text{where} \quad Z = \sqrt{\frac{L_{11}}{C_1}} \tag{1}$$

$$V_{ign} = \frac{4}{\pi} V_{in} \left| \frac{\frac{1}{SC_1} + R_c}{SL_{11} + R_l + \frac{1}{SC_1} + R_c} \right|_{S=j2\pi f_{ig}}$$

$$\cong \frac{1}{R_l + R_C} \sqrt{\frac{L_{11}}{C_1}} \tag{2}$$

In (2), f_{ig} is the switching frequency at the ignition mode, which is near the resonant frequency.

B. Steady state ripple cancellation analysis

After the ignition, the triac(St) is connected to operate the coupled inductor filter. Fig.6 shows the equivalent circuit after the ignition. This circuit is the conventional buck converter with an added coupled inductor filter.

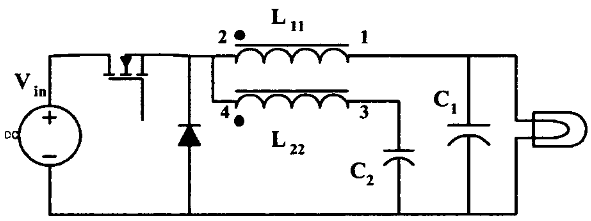

Fig.6 The equivalent circuit after ignition; L_{11}: Primary-side inductance, L_{22}: Secondary-side Inductance

In order to simplify the analysis of the steady state operation, it is assumed that all switching devices are ideal and the ESR of the coupled inductor is zero. Under these assumptions, fig.6 can be converted to the fig.7 by replacing the coupled inductor with T equivalent circuit.

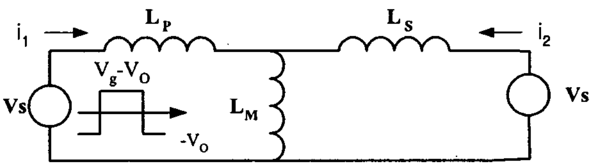

Fig.7 The converted circuit of the proposed ballast in steady state; L_p, L_s = leakage inductance, L_M =Mutual Inductance

The circuit equations of fig.7 are given as follows.

$$(L_P + L_M)\frac{di_1}{dt} + L_M \frac{di_2}{dt} = V_S \tag{3}$$

$$L_M \frac{di_1}{dt} + (L_S + L_M)\frac{di_2}{dt} = V_S \tag{4}$$

L_{efp} and L_{efs} are defined as the effective inductance of the primary side and the effective inductance of the secondary side, respectively. The followings are easily obtained by the calculation from (3) and (4) [5].

$$L_{efp} = L_{11}\frac{1-k^2}{1-kn} \quad (5)$$

$$L_{efs} = L_{22}\frac{1-k^2}{1-\frac{k}{n}} \quad (6)$$

where $k = \frac{L_M}{\sqrt{L_{11}L_{22}}}$ $\quad n = \sqrt{\frac{L_{11}}{L_{22}}}$

From the plot of (5) and (6) in fig.8, the effective inductance can be modulated by the change of the effective turns ratio. This transfers the ripple current from one side to other, resulting in ripple cancellation.

In this circuit, the lamp ripple current flowing through the L_{11} should be damped to avoid the acoustic resonance. Therefore, n must be nearly equal to 1/k making the L_{efp}/L_{11} approach to infinity. This makes the lamp ripple current nearly equal to zero.

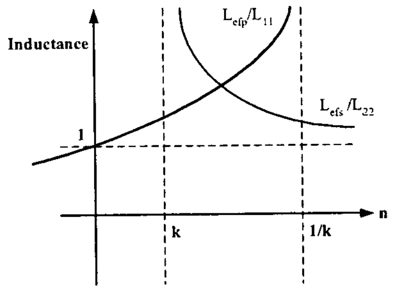

Fig. 8 The plot of the equation (5) and (6)

III. EXPERIMENTAL RESULTS

A 150W, 50kHz prototype has been built and tested to verify the performance of the proposed ballast. It's main components values are given as follows;

$$L_{11} \cong L_{22} = 1.5mH$$

$$C_1 = 10nF$$

$$C_2 = 0.1uF$$

Fig.9 shows the ignition voltage of the MHD lamp (CDM-TD/150W/Philips). The ignition voltage is measured to be 1.25kV, of which value is small compared to that of the ballast using the external ignitor due to the longer period of the ignition pulse.

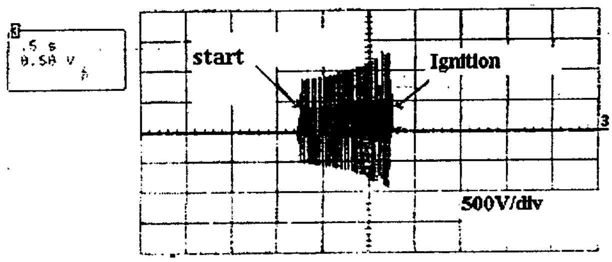

Fig. 9 The Ignition Voltage (500V/div) of a 150W MHD lamp

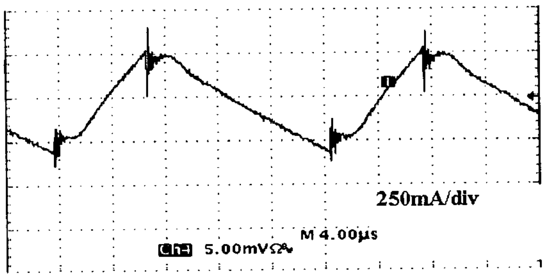

Fig. 10. The load ripple current before using the coupled inductor filter with a steady state resistive load

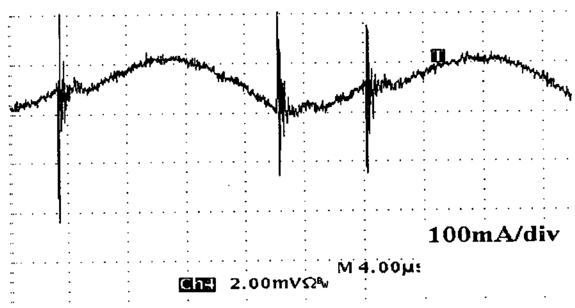

Fig. 11. The load ripple current after coupled inductor filter with a steady state resistive load

Fig. 11 and Fig. 12 compare the load ripple current with and without the coupled inductor filter. These waveforms are obtained by the experiment with a steady state resistive load. In the fig.10, the ripple current is 500mA, which exceeds the 20% of the DC lamp current. Meanwhile, when the coupled inductor filter is used, the load ripple current in fig.11 is much reduced. Fig. 12 and Fig. 13 show the steady state inverting lamp current and voltage respectively, which is experimented with a 150W MHD lamp. The ballast operates with no acoustic resonance at steady state and the reignition voltage of the lamp is identified in fig.13.

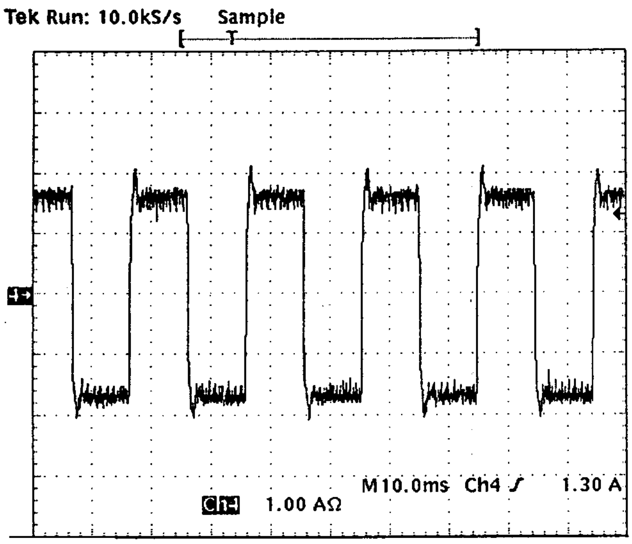

Fig. 12. The Lamp current at steady state which is experimented with 150W MHD lamp (1A/div)

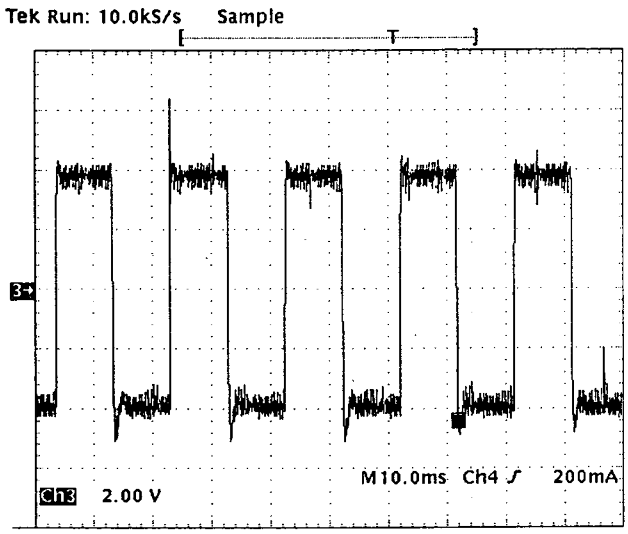

Fig. 13. The Lamp voltage at steady state which is experimented with 150W MHD lamp (40V/div)

IV. CONCLUSIONS

In this paper, the new ballast with an internal ignitor which lowers the cost and reduces the size is proposed. The internal LC resonance of buck converter and coupled inductor filter is used for steady state ripple cancellation. The operation modes of the ballast were analyzed and the performance was verified by the experiment with the 150W MHD lamp.

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