Electronic Ballast with Modified Valley Fill and Charge Pump Capacitor for Prolonged Filaments Preheating and Power Factor Correction

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Abstract – A new circuit, modified valley fill (MVF) combined with resonant inductor of the self-excited resonant inverter and Charge Pump Capacitors (CPCs), is presented to achieve high PF electronic ballast providing sufficient preheat current to lamp filaments for soft start maintaining low DC bus voltage. The MVF can adjust the valley voltage higher than half the peak line voltage. The CPCs draw the current from the input line to make up the current waveform during the valley interval. The measured PF and THD are 0.99 and 12%, respectively. The lamp current CF is also acceptable in the proposed circuit. The proposed circuit is suitable for implementing cost-effective electronic ballast.

1. Introduction

The fluorescent lamp is today's one of the most popular lighting system because of its higher luminous efficacy (lm/W) which is the energy conversion efficiency of the lamp. A ballast is needed for fluorescent lamps or gaseous discharge lamps because these have negative resistance characteristic in the desired region of operation [1,4]. Usually, in combination with capacitor, a lossless inductor or high-leakage transformer is used to compensate the characteristic of the fluorescent lamps. The electronic ballast plays the important roles of providing sufficiently high starting voltage, current limiting after starting, high input power factor, and reducing input line current harmonics.

Typical electronic ballasts have a bridge rectifier followed by an electrolytic energy storage capacitor to provide a nearly constant dc voltage to the subsequent high frequency resonant inverter driving the lamps. The resultant high frequency lamp current has low double line frequency modulation and has a current crest factor (CF) of about 1.5, which meets the traditionally acceptance limit of 1.7. However, this comes at the expenses of very low power factor (PF<0.6) and very high line current harmonic distortion (THD>130%) [1,5]. To obtain a unity power factor, low THD of the line current, and cost-effectiveness, a simple boost-type power factor corrector with a self-excited half-bridge type series resonant inverter is often used in the electronic ballast for fluorescent lamps [1,2,6]. However, the boost converter circuit increases the voltage stress to main device and is lossy and not cost-effective as they operate with high peak triangular shape current with additional power device, passive components and control circuit.

A circuit, referred to as valley charge pumping (VCP), was proposed to solve the drawbacks of the passive PFC method mentioned above and active circuit such as boost converter [7]. The proposed PFC circuit in [7] can control the valley voltage above half the peak line voltage by adjusting the value of reactor connected to the resonant inverter, preventing the pulsating line current around the peak and lowering double line frequency modulation of lamp current. For unity PF, charge pump capacitors are connected to the resonant inverter to draw the input line current during the valley interval. The proposed ballast in [7] has good PFC ability and simple configuration resulting in cost-effectiveness. However, in spite of the improvement of such a power factor corrector, the ballast presses high voltage stress to the lamp at start up. The reason is because the voltage across the lamp during the start-up operation is increased abruptly by the resonance between the inductor and small equivalent capacitor of the resonant inverter, which shortens the preheating time of filaments and the life of the lamp.

In this paper, a new circuit, modified valley fill (MVF) combined with resonant inductor of the self-excited resonant inverter and a charge pump capacitor (CPC), is presented to achieve high PF electronic ballast providing sufficient preheat current for lamp filaments maintaining low DC bus voltage. The MVF can adjust the valley voltage higher than half the peak line voltage, resulting in low CF of lamp current. The CPCs draw the current from the input line to make up the current waveform during the valley interval..

2. Proposed high PF Electronic Ballast

Fig.1 shows the electronic ballast with the proposed high PFC circuit which is composed of a charge pump capacitor(C_p) and a modified valley fill DC-link combined with the inductor (L_r) of the resonant inverter. Unlike the conventional VF circuit, the MVF DC-link has one electrolytic capacitor and five fast diodes ($D_1 \sim D_4$, D_v). To charge the MVF DC-link capacitor C_{dc}, the secondary turn of the inductor/transformer (L_r) is connected through the

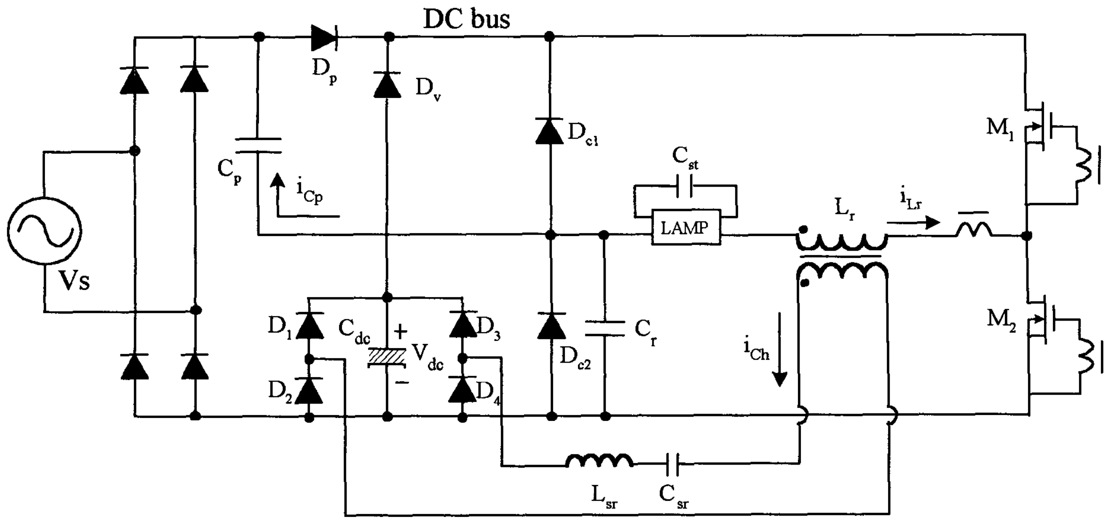

Fig. 1 Proposed high PF Electronic Ballast

L-C series resonant circuit and diode bridge pairs(D_1 ~ D_4). The inductor/transformer (L_r) operates as an inductor during the entire switching period except the transient interval. When the switching action occurs by the self-excited gate driving, the voltage across the resonant inductor/transformer (L_r) becomes larger than the DC-link capacitor voltage during a short transient interval, which results in abrupt voltage change across the L_{sr}-C_{sr} resonant tank in the secondary-side of the transformer(L_r). As a result, the resonant inverter has a short super-resonant charging interval in which the resonant elements are composed of the equivalent capacitance of series-connected C_{sr} and C_r and the inductance L_{sr} under the assumptions that the capacitances C_{st} and C_{sr} and inductance L_{sr} are much smaller than the resonant capacitance C_r and the magnetizing inductance of transformer L_r. The charging operation of DC-link capacitor C_{dc} mainly happens in the direct region when the line voltage is higher than the voltage across C_{dc} because of the exciting voltage to L_{sr}-C_{sr} resonant tank. The valley voltage can be adjusted properly above half of the peak line voltage by setting the values of L_{sr} and C_{sr} and turn ratio(n) of inductor/transformer L_r. The super-resonant frequency $\omega_{sr}(\approx 1/\sqrt{L_{sr}C_{sr}})$ must be determined considering the relationships among the valley voltage, lamp current CF, PF, and preheat time of lamp filaments, etc, which must be traded off for acceptable ballast characteristics. The proposed ballast with the resonant inductor/transformer L_r connected to the DC-link capacitor as shown in Fig. 1 has an ability to limit the lamp starting voltage and dc bus voltage V_{dc} inherently. If the L_{sr} of super-resonant tank is removed, the current flowing through the power MOSFET and charging the DC-link capacitor have pulsating waveform with high amplitude during the switching transient interval, which results in the increased loss of the switches and the reduced life of the electrolytic capacitor. The super-resonant frequency ω_{sr} must be located nearly around the lamp starting frequency to maintain enough preheating time. However, to obtain low current CF of lamp, the super-resonant frequency ω_{sr} should be set near the resonant frequency $\omega_o(\approx 1/\sqrt{L_rC_r})$ of the resonant inverter. In order to obtain acceptable ballast characteristic, the super-resonant frequency ω_{sr} can be roughly decided by the equation followed as

$$\omega_{sr} \approx \sqrt{\omega_o \omega_p}, \quad \omega_p \approx 1/\sqrt{L_{sr}C_{eq}}$$

$$C_{eq} \approx C_r // C_{st} // C_{sr}. \quad (1)$$

3. Steady State Operations

The operations of the proposed electronic ballast shown in Fig. 1 can be explained with two operation regions of direct and valley regions. The direct region is the period which the line source supplies the load power to the lamps through the rectifier diode bridge and the energy of DC link capacitor is charged by the super-resonant tank. When the line source voltage is lower than the DC-link voltage, which is called valley region, the load power is mainly provided by the DC-link capacitor and additionally by the charge pump PFC capacitor(CPC) from the input source.

a) Direct Region

Mode A1 [t0, t1] : The load power is transferred through the bride diode. The CPC operates as a resonance element with C_r. The sum of the voltages across the C_p. and C_r is equal to the line source voltage V_s.

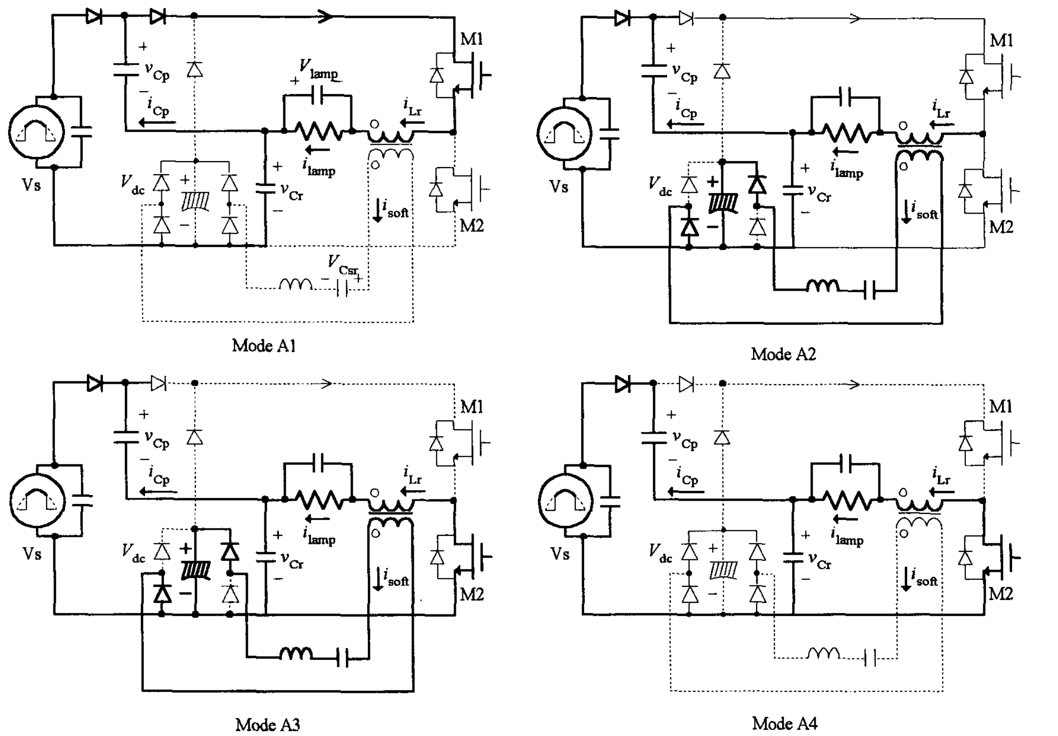

Fig. 2 Mode diagrams during direct region

Mode A2 [t1, t2] : When switching action is occurred, the inductor/transformer L_r is operated as transformer. The DC-link capacitor begins to be charged by the resonant current i_{soft} which is produced by the resonant actions between L_{sr} and the equivalent capacitance C_{eq} shown in the primary –side of the transformer L_r. The mode is changed when direction of the current i_{cp}, i_{cr} is reversed and the voltage across the switch is completely changed.

Mode A3 [t2, t3] : After the switching transition operation, charging operation of the DC-link capacitor by the super-resonance is occurred. The super-resonance frequency is followed as :

$$f_{super} = \frac{1}{2\pi\sqrt{L_{sr}C_{eq}}}$$

$$C_{eq} = [C_{sr} // (C_p + C_r) // C_{st}]$$

The input current is flowed through the CPC. The mode is changed when the voltage condition (2) is met.

$$V_{C_{sr}} + V_{dc} = V_{cr} - V_{lamp} \qquad (2)$$

Mode A4 [t3, t4] : When the half period of the super-resonance is over, the charging action of the DC-link capacitor is stopped. The load is driven by the series-resonance action between the L_r and equivalent capacitance composed of C_p. and C_r. The C_r draws some load powers from the input line.

The operations of the Mode A5 and Mode A6 are the same with those of the Mode A1 and Mode A2. In this operation region, the DC-link capacitor is charged with sufficient energy by the super-resonance to provide load power during the valley region, which results in reducing the lamp current crest factor. Fig. 3 shows the operation waveforms of the ballast during the direct region.

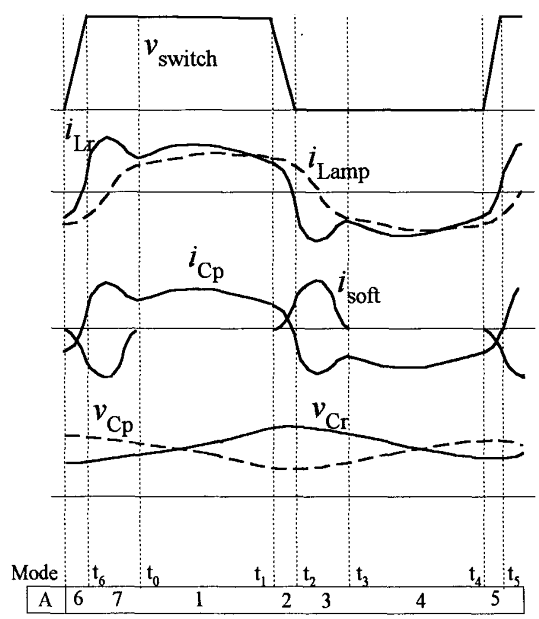

Fig. 3 Operation waveforms during the direct region

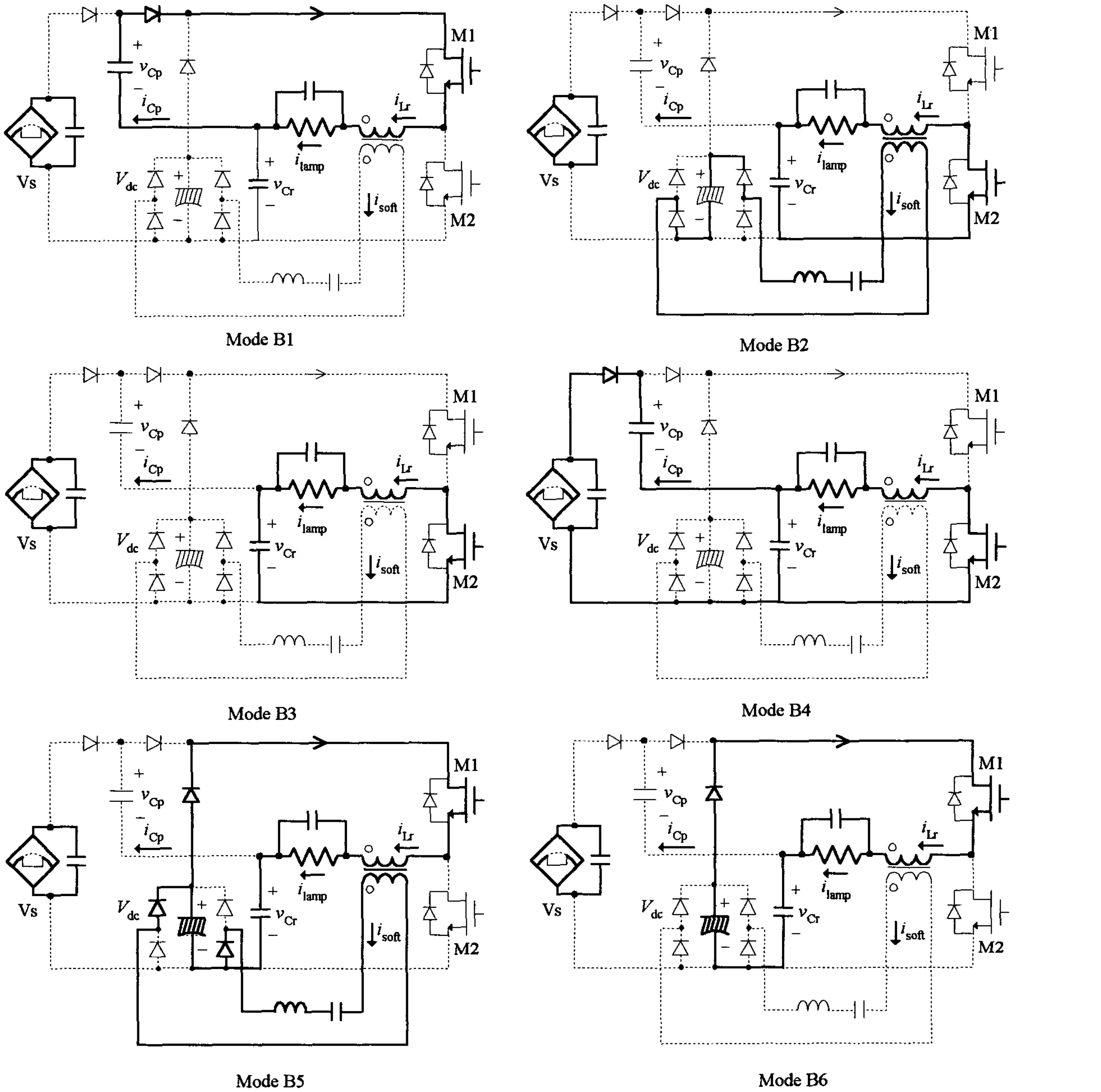

Fig. 4 Mode diagrams during the valley region

b) Valley Region

Mode B1 [t0, t1] : When we use the CPC C_p larger than the resonant capacitor C_r for acceptable PF, the equivalent resonant capacitance in this mode is nearly CPC. The voltage variation across C_r is larger than that of across CPC. For smooth switching action and resonance, a DC-link high frequency filter across the half-bridge is needed.

Mode B2 [t1, t2] : When the switching is occurred, L_r is operated like as transformer because the large voltage variation across the primary-side of L_r make a path for super-resonant current flowing the resonant tank L_{ch}-C_{ch}. The charging resonant current for DC-link capacitor is very smaller than the case of direct region operations.

Mode B3 [t2, t3] : If the super-resonance transient operation is over, a series-resonance between Lr and Cr is performed until the sum of voltages across C_p and C_r is smaller than the line source voltage V_s.

Mode B4 [t3, t4] : When $V_s > V_{c_p} + V_{c_r}$, the bridge diode is conducted, resulting in charge pumping operation to draw the input line current. If the sum of voltages across C_p and C_r is smaller than the DC-link voltage V_{dc}, the bridge diode and D_p is blocked.

Mode B5 [t4, t5] : When the next switching action is occurred, the load power is transferred from DC-link capacitor. In this mode, the Lr operates as transformer.

Mode B6 [t5, t6] : After the transition super-resonance, the lamp is driven by the series-resonance of C_r-L_r-lamp. The load power is continuously transferred from C_{dc}.

Fig. 4 shows the mode diagrams during the valley region explained above. The operation waveforms of the ballast in the valley region is shown in Fig. 5.

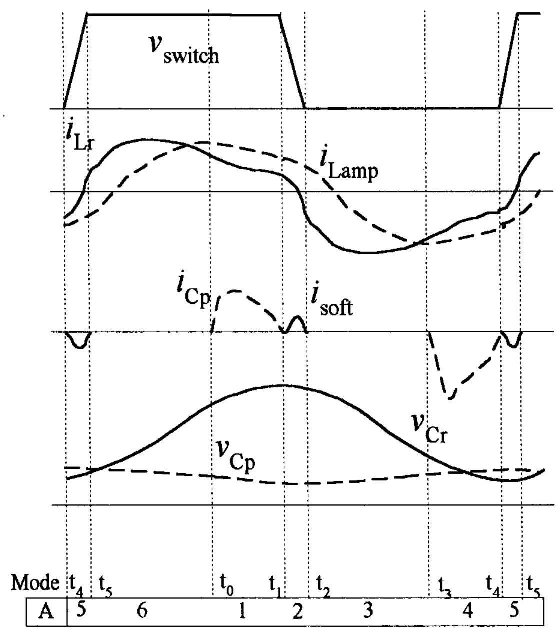

Fig. 5 Operation waveforms during the valley interval

The charge pump capacitor C_p can also be located in the input filter site for two fluorescent lamps removing the blocking diodes (D_{p1}, D_{p2}) and the freewheeling/clamping diodes(D_{c1}, D_{c2}) of Fig. 1. The overall configuration of the electronic ballast with the proposed PFC circuit is shown in Fig. 6. The ballast uses self-excited half-bridge parallel-loaded series resonant inverter for fluorescent lamps with a simple over-current and temperature protection circuit. The protection circuit senses the over-current and over-temperature information with a sense resistor R_{sense} and base-emitter junction voltage of Q_2 attached to the heat-sink of power MOSFET M_2.

4. Experimental results

The proposed electronic ballast in Fig.6 is constructed and tested in the laboratory. One F40T12 fluorescent lamps is used. The line voltage is 220Vac and two MOSFETs IRF740 are used. The components values are chosen as:

C_r = 15nF, C_{st} = 8.2nF, C_{sr} = 10nF
C_p = 82nF, L_{sr} = 400uH
Inductor/transformer(L_r) : primary inductance=1mH, turn-ratio = 1:1

We confirmed that the MVF with the charge pump capacitor operated to the desired results. Fig.7 shows the measured input line voltage and current waveforms. The input current has low harmonic distortion of 12% and measured input power factor of 0.99. Fig. 8 shows the DC bus voltage, current i_{ch}, and i_{cp} to verify the PFC and charging operations of DC-link capacitor. The valley voltage is higher than 200V in 300V_{peak} of line, which results in acceptable lamp current CF of 1.6. Fig. 9 shows the preheating operation of the proposed ballast for soft start. The preheating time for a given ballast is set to about 450msec with DC-link voltage of 380V_{max} at starting. Fig. 10 shows the magnified oscillogram of Fig. 8 in the peak region. In Fig. 10, we confirms the charging operation of auxiliary resonant circuit to electrolytic capacitor C_{dc}.

5. Conclusions

A novel low-cost, high power factor electronic ballast is presented. The proposed ballast employs modified valley fill (MVF) circuit combined with charge pump capacitors having enhanced valley voltage instead of using the boost converter for shaping the input current. The MVF connected with the inductor/transformer of the resonant inverter through the auxiliary resonant circuit can control the valley voltage above half the peak line voltage as well as the preheating time of lamp filaments, resulting in increased lamp life and efficiency. The experimental results prove that the prototype ballast successfully meets the IEC1000-3-2 requirements for luminaries and is suitable for low cost illumination systems.

References

[1] Y. S. Youn, G. Chae, and G. H. Cho, "A unity power factor electronic ballast for fluorescent lamp having improved valley fill and valley boost converter", IEEE PESC97 Record, pp. 53-59, 1997

[2] Y. R. Yang and C. L. Chen, "A self-excited half-bridge series-resonant ballast with automatic input current shaping", IEEE PESC Record, pp. 881-886, 1996

[3] J. Spangler, B. Hussain, and A. K. Behera, "Electronic ballast using power factor correction techniques for loads greater than 300watts, IEEE APEC91 Record, pp. 393-399, 1991

[4] W. J. Roche and H. W. Milke, "Fluorescent lamp starting aids how and why they work," *J. Illuminating Engineering Society*, pp. 29-37, Oct. 1974.

[5] M. H. Kheraluwala and S. A. El-Hamamsy, "Modified Valley Fill High Power Factor Electronic Ballast for Compact Fluorescent Lamps," *IEEE PESC 95*, pp. 10-14, 1995.

[6] R. R. Verdeber, O. C. Morse and W. R. Alling, "Harmonics from compact fluorescent lamps," *IEEE Trans. Industry Applications*, vol. 29, no. 3, pp. 670-674, May/June, 1993.

[7] G. Chae, Y.S. Youn and G.H. Cho, "High Power factor Correction Circuit using Valley Charge-Pumping Circuit for Low-Cost Electronic Ballasts" *PESC 98*, pp. 2003-2008, 1998.

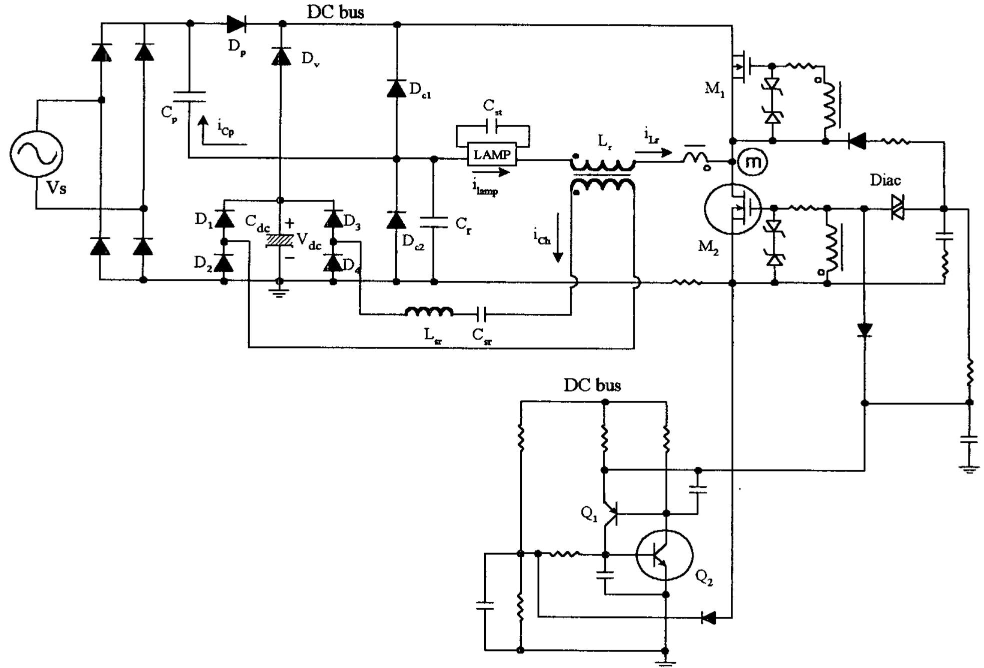

Fig. 6 Overall configuration of prototype electronic ballast for one fluorescent lamp

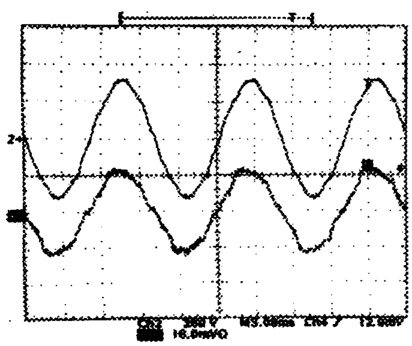

Fig. 7 Input voltage and current for the proposed ballast (200V/div, 0.2A/div, 5ms/div)

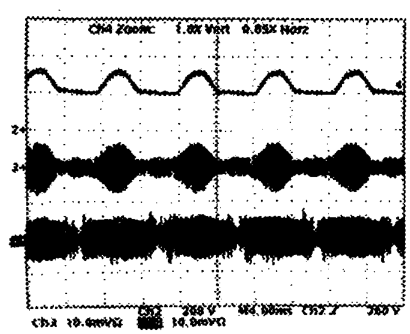

Fig. 8 Experimental results of the DC bus voltage, i_{ch} and i_{cp}, respectively (200V/div, 1A/div, 4ms/div)

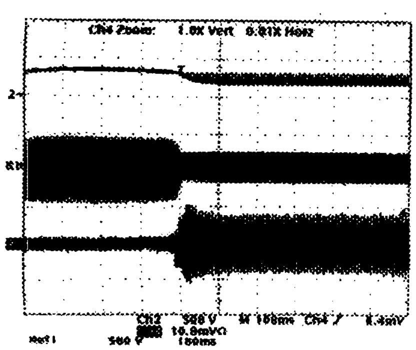

Fig. 9 DC bus voltage, lamp voltage and lamp current during the preheat interval (500V/div, 0.5A/div, 100ms/div)

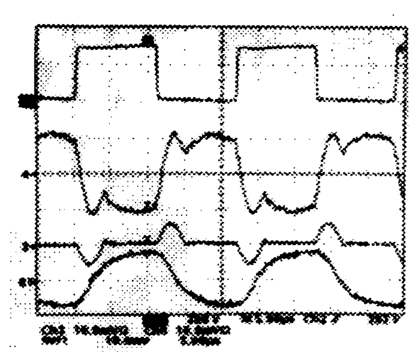

Fig. 10 Experimental results of V_m, $-i_{Lr}$, i_{ch} and lamp current i_{lamp} (200V/div, 0.5A/div, 1A/div, 0.5A/div)