Voltage Multiplier Integrated HID Ballast and the Application of Triple Insulated Wire in the Design of Igniter Transformer

B.P. Divakar, K.W.E.Cheng,
Power Electronics Research Centre, Department of Electrical Engineering
The Hong Kong Polytechnic University

Abstract—**The application of HID lamps in automobiles is gaining popularity owing to the color of the light as well as high lumen/watt ratio from the lamp. In the present paper a voltage multiplier integrated with the secondary winding of the DC converter transformer generates the required voltage to be applied to the igniter. The proposed method not only eliminates one auxiliary winding but also reduces the voltage across the switch on the primary side and consequently the rating of the switch is reduced. The use of triple insulated wire on an RM core in the design of the high voltage igniter is also presented in the paper. A brief review of the HID circuits is done and compared with the proposed circuit. Experimental results from the prototype are presented.**

Key word: **Converter; Inverter; Igniter; HID lamp**

I. INTRODUCTION

HID lamps render almost white light and have better lumen to watt ratio than the halogen lamps. Paper[1] proposes a new chip to control the HID lamp. The chip incorporates a temperature compensation feature to modulate the light output so as to comply with the SAE J2009 standard, In paper [2], a dc-ac class E resonant converter is employed to achieve soft switching, however the maximum peak current of the switch is about 2.8 times the peak input current. In paper [3], a flyback converter with two winding transformer is employed to generate the high voltage for the igniter. The second winding mainly works during start-up to apply the voltage to a spark gap. The two winding transformer reduces the dc link voltage by half and thereby permits the selection of low rating switches. Paper [4] proposes a method in which the voltage doubler is connected on the inverter side and thereby eliminates the auxiliary winding as in [3]. In paper [5], the requirements of an HID igniter are presented and a new design procedure is presented to reduce the overall dimension of the igniter transformer.

In the present work, a new circuit is presented to drive the HID lamp. A multiplier circuit is connected on the dc converter side to obtain the required voltage to apply for the spark gap. The use of voltage multiplier actually lowers the voltage level across the dc converter and thereby permits the selection of components with lower ratings when compared to the circuits in [3 & 4]. The present paper discusses the use of high voltage triple insulated wire in the design of the igniter on an RM core. The solenoid is the usual option in designing the high voltage igniter and the windings consists of windings with a turns ratio of 1:150 using magnet wires. As the number of turns of the secondary is very large, the secondary consists of many layers with proper insulation provided by 5 layers of tapes between the windings [4]. In addition to this the solenoid must be housed in a package to minimize the EMI problem. In order to improve the reliability of the transformer, the igniter used in the present work is wound with triple insulated wire having a breakdown voltage of 10 kV on an RM core. The core does not present EMI problem as the fluxes are confined within the core and helps in lowering the turns ratio.

. A brief review of the HID ballast circuits is presented in section II, operation of the new circuit along with the new ignition transformer is discussed in III, and experimental results are presented in IV followed by concluding remarks.

II. REVIEW OF HID BALLAST CIRCUITS

A. Components of a typical HID ballast circuit

1) DC-DC Converter

The dc-dc converter applies the necessary high voltage at the igniter in order to initiate a spark across the lamp electrodes and then controls the power fed to the lamp upon ignition. Flyback, Sepic and resonant converters are some of the topologies which can be used. The flyback converter has the minimum part count but suffers from high peak input current and therefore, an input filter is required to attenuate the noise. The average magnetizing current in the sepic converter is only 50% of that in a flyback converter resulting in reduction of losses in the transformer.

However, the sepic converter needs additional capacitor and an input inductor compared with the flyback converter.

2) *Igniter*

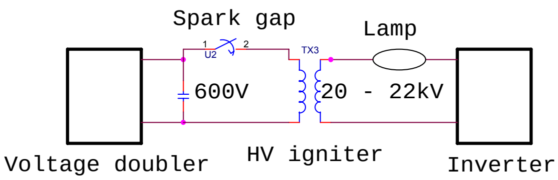

Fig. 1 connection of HV igniter

The igniter is a high voltage transformer which converts the low voltage from the dc converter into a high-voltage pulse of 10 – 22kV magnitude for initiating an arc across the lamp electrodes. The voltage from the voltage doubler is applied to the primary of the igniter through a capacitor and a spark gap arrangement.

3) *Inverter*

The inverter is used to provide an alternating square pulses to the lamp upon ignition.

4) *Controller*

The most important and the complex part of the HID ballast is the controller which controls and dictates the mode of operation depending on the stages from start-up to steady state. The lamp exhibits negative resistance characteristics and therefore, the controller is designed to work in the constant power mode in steady state. The operating mode of the controller changes from constant current mode at start-up to constant power mode after the lamp voltage begins to increase. In order to satisfy the standards, the lamp is driven at twice the rated power at start-up but with the maximum load current limited to around 2.5 A.

B. *HID lamp circuit*

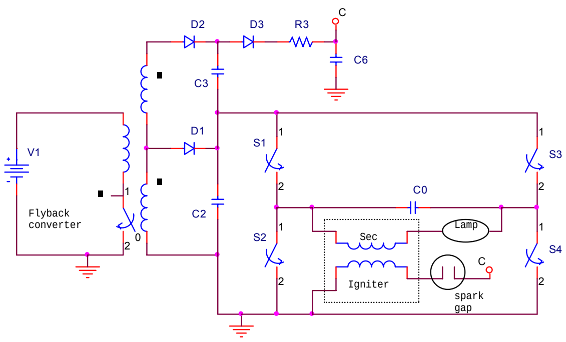

Fig. 2 DC converter-fed voltage doubler

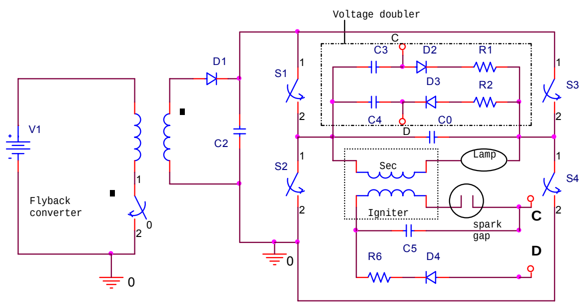

Fig. 3 Inverter-fed voltage doubler

C. *Analysis of the circuit.*

1) *DC converter-fed voltage doubler*

Figure 3 shows the schematic diagram of the circuit containing front-end Sepic dc-dc converter with two secondary windings, a full-bridge inverter circuit and an igniter with spark gap assembly. The capacitors C_2 (charged by the main winding) and C_3 (charged by the auxiliary winding) charge C_6 to about 600 V, which is the breakdown voltage of the spark gap. When the voltage across C_6 (which is connected to one end of the spark gap at the point “c”) reaches the break down voltage of the spark gap, C_6 discharges into the primary of the igniter generating a high voltage pulse across the lamp connected to the secondary winding of the igniter.

2) *(Inverter-fed voltage doubler)*

Figure 4 shows the schematic diagram of the inverter fed voltage doubler circuit. The main transformer in this circuit has only one winding and the voltage doubler circuit formed by diodes and capacitors is connected across the inverter output terminals. As the inverter drives the voltage doubler, this circuit is called as inverter-fed voltage doubler. The operating principle of this circuit is explained with the aid of equivalent circuits in figures 5a and 5b.

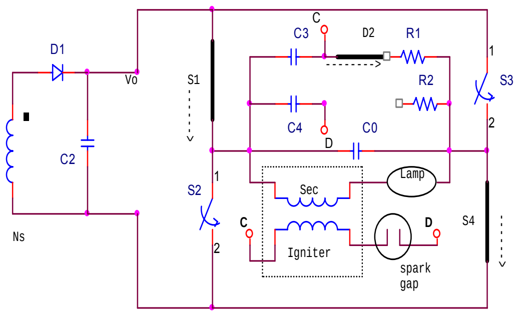

Fig. 4a Mode 1 of the voltage doubler

Stage 1: The capacitor C_3 is charged to the input voltage when S_1 and S_4 are turned on. If the voltage drop across R_1 is neglected the point "C" (the right hand side of C_3) is now at ground potential while the left hand side of C_3 is at a potential equal to the secondary voltage of the Sepic converter.

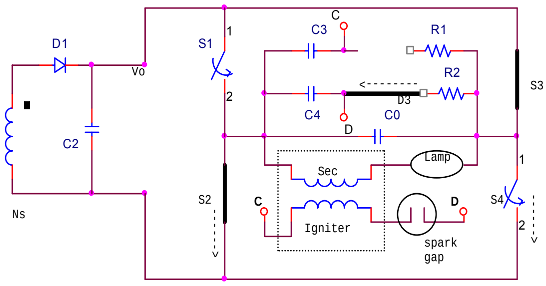

Fig. 4b Mode 2 of the voltage doubler

Stage 2: The mode 2 begins by turning on S_2 and S_3 to charge C_4 to the secondary voltage with point "D" being positive. At the same time, in order to maintain the initial potential difference across C_3, the potential at point "C" is raised (from zero to $-V_{C3}$). The voltage input to the spark gap assembly is $V_{CD} = V_C - V_D$ and the spark gap will breakdown when V_{CD} exceeds its break down voltage resulting in a high voltage pulse across the lamp.

III. OPERATION OF THE PROPOSED HID BALLAST WITH VOLTAGE MULTIPLIER

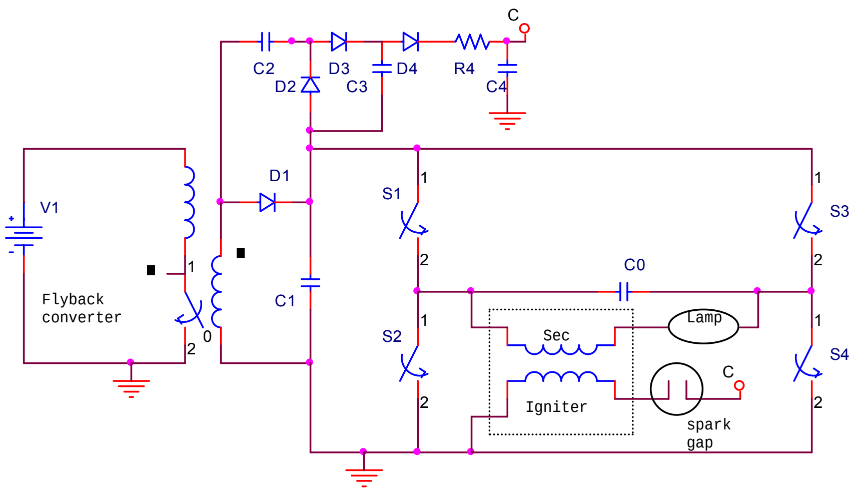

Fig. 5 The proposed HID ballast with multiplier circuit

A. *Operating modes of the new ballast.*

The dc converter fed voltage doubler in figure 4 has one additional winding having the same number of turns as the main winding while the inverter fed voltage doubler in circuit in figure 5 has only one winding but with additional diode and capacitor pair. However, The maximum voltage of the dc converter, just before the ignition, is the same at 300V in both the circuits. As a result the voltage ratings of the components of the DC converter must be greater than 300V in both the circuits. In order to reduce the voltage across the DC converter at start-up, a voltage multiplier circuit constituted by D_2, C_2, D_3 and C_3 is adopted in the proposed new circuit as in figure 6. The operating principle of the voltage multiplier is best understood by considering the equivalent circuit shown in figure 7 in which the secondary voltage across the secondary winding is represented as an ac source.

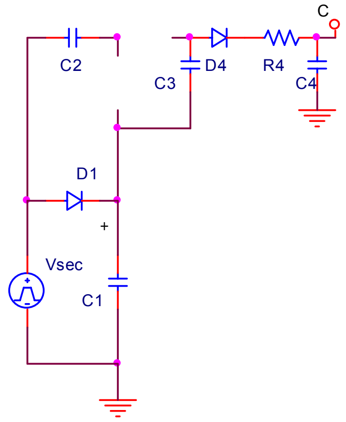

Figure 6a Stage 1: C_1 charging state

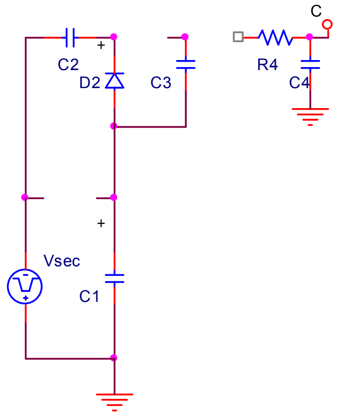

Figure 6b Stage 2: C_2 charging state

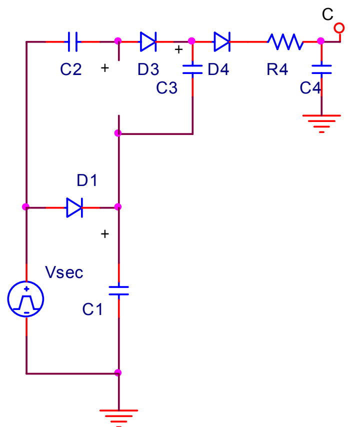

Figure 6c Stage 3: C_1 and C_2 charging state

Stage 1: In this stage the secondary voltage is positive and the equivalent circuit is as shown in figure 6a. The main capacitor C_1 is charged to the secondary voltage.

Stage 2: In the switching cycle, the secondary voltage is reversed and C_2 will be charge to $V_{sec} + V_{C1}$.

Stage 3: C_1 and C_2 charging state: In the next switching cycle, the secondary voltage is positive and as a result D_3 is forward biased by the polarity of C_2 resulting in charging of C_3 to V_{C2}. In the subsequent positive half cycles C_1 and C_3 get charged and in the negative half cycles C_2 gets charged.

After few cycles, the voltage across C_4 is given by

$$V_{C4} = V_{C1} + V_{C3} = V_{C1} + V_{C2} \qquad (1)$$

As the duty cycle of the switch is continuously varying, the positive and negative voltages appearing across the secondary are not equal and hence it is very difficult to predict the instantaneous voltages across C_1 and C_2 on a cycle to cycle basis.

When the voltage across V_{C4} exceeds the breakdown voltage of the spark gap, a high voltage pulse is produced across the secondary of the igniter transformer. The oscillograms in figures show the voltages across C1 and C2 and it can be observed that C1 is charged to 250V as against 300V in circuits presented in [4] . The reduction in the voltage across the converter is useful and permits the selection of components of lower rating. A reduction of voltage by few tens of voltage is always beneficial in any flyback converter where in the leakage inductance has a tendency to add the turn-off spike to the voltage across the MOSFET during turn-off.

B. Design of the igniter transformer using triple insulated wire on an RM core.

The design of the high voltage igniter is very crucial for generating a voltage of 20-22kV required for hot re-strike condition. The insulation and the parasitic parameters of the transformer influence the output voltage. The usual practice is to use a solenoid as the core for the igniter transformer and to house it in a special package to minimize the EMI from it. The turns ratio required to generate the voltage required for hot re-strike with such solenoid will be 1:150 [4] owing to the low permeability of the solenoid resulting in many layers of secondary turns and many layers of insulation tapes between the windings. For example, the igniter transformer used in paper [4] has a turns ratio of 1:200 on a solenoid of diameter = 0.8cm and length = 3cm. The secondary winding has 150 turns wound in 5 layers with five layers of insulation tape of (0.1mm) between the layers. The equivalent circuit of the transformer wound on the solenoid is shown in appendix along with the expressions for the magnetizing and leakage inductances [6].

In a high voltage transformer, the leakage inductance and parasitic output capacitance have to be minimized but any attempt in minimizing one will have an opposite effect on the other and hence the design of the transformer will appear complex for a new designer. A simple method of designing the high voltage transformer is to keep to the fundamentals of magnetics through our intuition i.e. reduce the leakage inductance by winding the primary and secondary such that the area spanned by primary should be complimented by that of secondary. If this condition were to be satisfied with a solenoid, the length of the solenoid has to be very small because of the small winding span of the primary owing to one turn. However, the number of layers for the secondary winding is inversely proportional to the length of the core resulting in higher leakage inductance for cores with smaller lengths. Moreover, the solenoid presents EMI problem as the flux are free to radiate into the surroundings and hence it must be housed in a special package. In order to address all the problems the igniter for this project was designed with a triple insulated wire having 10kV breakdown voltage is wound on an RM-10 core. The number of turns for the secondary to achieve hot re-strike voltage is just 45 turns as compared to 150 turns with the magnet wire on a solenoid. The secondary has just 2 layers with only one layer of insulation tape separating the two secondary layers. The smaller dimension and high permeability of the RM core resulted in increased coupling leading to high voltage generation with fewer turns.

The equivalent circuit of the igniter using RM core can be represented as shown in the appendix.

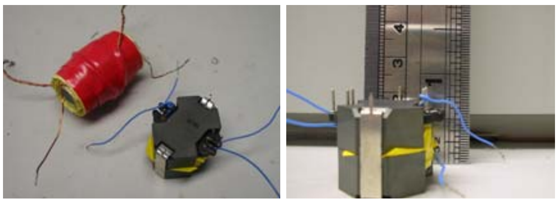

Figure 7 Igniter with solenoid and RM-10 core

IV. EXPERIMENTAL RESULTS

A prototype of the new topology was built in the laboratory and tested on 35 W D2S type of lamp. The specifications of the topologies are as follows:

a) *V_{in}: 9 to 13V*
b) *Nominal Power output: 35 W*
c) *Flyback Transformer turns ratio: 1:10*
d) *Igniter turns ratio: 1:45 on an RM-10 core*

The experimental waveforms are shown below:

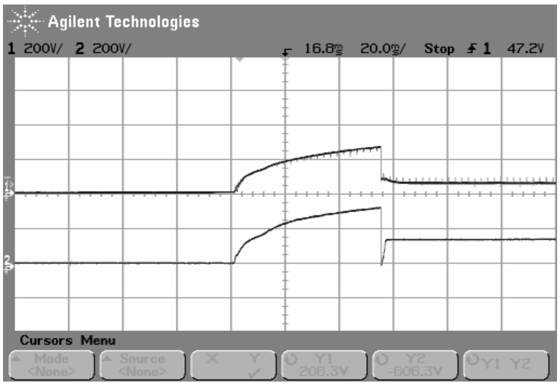

Figure 8 1st trace: Voltage across C_1; 2nd trace: Voltage across C_2.
Scale: 200V/div; 20ms/div

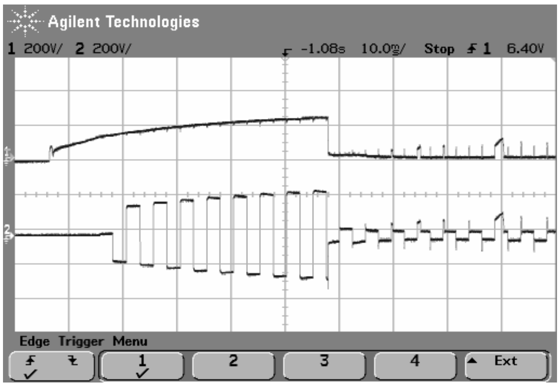

Figure 9 1st trace: DC output Voltage across; 2nd trace: Inverter output Voltage.
Scale: 200V/div; 10ms/div

The experimental results in figure 8 show the voltage across C_1 and C_2 with the peak values just prior to the ignition are 255V and 345V respectively. The voltage across C_1 in the present paper has decreased by about 45V compared to the voltage present in the circuits of papers [3&4]. The voltage across C_1 can be further reduced by choosing lower values for C_2 and C_3 that will enable C2 and C_3 charge to a higher value. Further work is in progress to optimize the design of the circuit to reduce the voltage across C_1 further thereby the the reflected voltage onto the primary side is reduced permitting the selection of the switch with lower rating. The second part of the paper is concerned with the use of triple insulated wire in the design of the igniter to address the insulation issue as well as the EMI problem in the solenoid type of core. Although the size of the igniter designed on an RM-10 core is same as the size of the igniter designed using a solenoid [6], the number of turns in the new design is reduced by about 70% compared to the number of turns required for a solenoid. The diameter of the core of the TEFZEL wire is 0.3mm while the diameter of the entire wire is 0.7mm. The leakage inductance in the RM core was 2.3uH while that in the solenoid of [4] is 1.6uH. The performance of the two cores as far as the generation of the pulse is similar except for the number of turns and the number of insulation layers between the layers.

V. CONCLUDING REMARKS

The main objective of the present work was to decrease the rating of the switch used in the HID ballast and this was achieved by integrating a voltage multiplier circuit to the secondary of the flyback transformer. Compared to the other circuits there was a reduction of about 45V across the secondary as a result of the multiplier circuit. The other aspect of the work was to look into the possibility of using a triple insulated wire on an RM core with a view to minimize the EMI problem and also to minimize the number of turns and the insulation between the layers. The triple insulated wire performed very well on account of its high dielectric strength compared to the laminated magnet wire and therefore the design with it is highly reliable.

VI. FUTURE WORK

The future work will look into reduce the voltage of the switches further by optimizing the design of the components in the multiplier circuit. Cost analysis along with EMI testing will be carried out to compare the various designs using the triple insulated wire on other cores.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of the Innovation and Technology support programme of the Guangdong-Hong Kong Technology Cooperation Funding Scheme, Innovation and Technology Fund under the project GHS/073/04. Authors thank P. Leo & Co., LTD for the samples of TEFZEL wires used in the transformer.

VII. REFERENCES

[1] Ron Fiorello, "powering a 35W DC metal halide HID lamp using the UCC3305 HID lamp controller", Unitrode application note U-161

[2] Alberto Reatti, "Low-cost high power-density electronic ballast for automotive HID lamp", *IEEE transaction on Power Electronics*, pp. 361-368, vol. 15, no. 2, March 2000

[3] Kyu-Chan Lee, Bo Hyung Cho, " Design and analysis of automotive high intensity discharge lamp ballast using microcontroller unit", *IEEE transaction on Power Electronics*, pp. 1356-1364, vol. 18, no 6, Nov 2003

[4] B.P. Divakar, K.W.E. Cheng, D.H. Wang, P. Dong, " Examination of the power conditioning driving circuit for automotive HID lamp", *APSCOM, 2006 accepted.*

[5] W.S. Kim, B.H. Cho and K.C. Lee, "Design and analysis of High-Voltage transformer for HID lamp igniter", APEC 2005, pp. 1043-1047, vol 2, march 2005

[6] D. Abraham Arnold, "Modeling and estimation of leakage phenomenon in magnetic circuits", Ph.D. Theses, CIT, 1986

VIII. APPENDIX

Details of modeling of leakage parameters are dealt in [6]. A part of which is given to supplement the presentation.

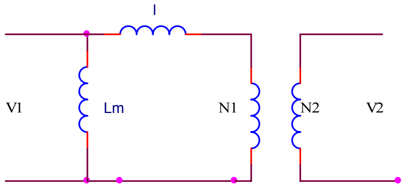

Fig A1 Equivalent circuit of the solenoid transformer

The total leakage inductance is given by [6]

$$l = \frac{2}{3}\frac{N_1^2 \pi \mu_o}{l_m}\left[h_1\left(r_o + \frac{3h_1}{4}\right) + h_2\left(r_o + h_1 + \frac{h_2}{4}\right)\right]$$

The magnetic inductance Lm is given by:

$$L_m = \frac{N_1^2 \mu A}{l_m}$$

Where, lm = length of the winding;
h_1, h_2 = width of pri and sec windings;
r_o = radius of the core

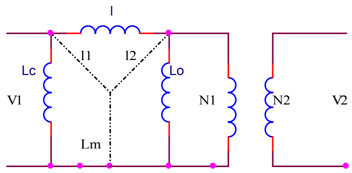

Fig A2 Equivalent circuit of the solenoid transformer

The leakage inductance in the RM core can be approximated as [6]

$$l = \frac{2\pi\mu_o N_1^2}{b}\left[h_1\left(\frac{r_o}{3} + \frac{h_1}{4}\right) + h_2\left(\frac{r_o + h_1}{3} + \frac{h_2}{12}\right)\right]$$

$$L_C = \frac{N_1^2 \mu_o A_C}{l_g} \qquad L_o = \frac{N_1^2 \mu_o A_o}{l_g}$$

Where b = length of the winding
The delta connected network can be converted into star network to determine the magnetizing inductance Lm and the leakage inductances l_1 and l_2.

The voltage conversion ratio is given as:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}\frac{L_o + l}{L_o}$$