

Implementation of a Voltage Multiplier Integrated HID Ballast Circuit With Dimming Control for Automotive Application

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Abstract—High-intensity discharge (HID) lamps are becoming popular substitutes for halogen lamps in automotive headlamps because of the high lumen/watt ratio and the color of the light. In this paper, a ballast (integrated with a voltage multiplier circuit in the secondary winding of the dc converter transformer) with dimming control is presented. The proposed circuit not only eliminates one auxiliary winding but also reduces the voltage across the switch on the primary side and consequently permits the selection of switches with a lower rating. A brief review of the HID circuits is done and compared with the proposed circuit. Experimental results from the prototype are presented. This paper also presents different methods of dimming the automotive HID lamps based on analog and digital control and discusses the relative merits of each of the methods. The dimming control is implemented using both the methods, and experimental results are presented. It is envisaged that the dimming control will provide some flexibility to drivers in the control of HID lamps to suit the driving conditions in the modern cities that are very well lit at night. This paper investigates the merits of each method and discusses the practical issues for implementing such controls.

Index Terms—Constant power, dimming control, high-intensity discharge (HID) ballast.

I. INTRODUCTION

HEADLIGHTS have become an integral part of all vehicles to assist drivers on roads which are not well illuminated and which compromise the safety of other users of the road during night and foggy conditions. Traditional headlights use lamps with filaments made of tungsten and other lead wires made of steel coated with copper. The tungsten filament emits light when its temperature is raised to the level at which incandescence occurs after current is passed through it. The melting point of tungsten being 3370 °C which is nearly double

that of iron, the tungsten can reach a very high temperature and, in fact, generates more heat than it does light. As more energy is consumed in generating heat than what is used to produce light, the lamp has to consume higher power in order to generate enough light to suit the night-driving conditions. The filament lamp consumes more power and, in doing so, dissipates more heat. Therefore, housing a higher wattage lamp in a casing would naturally call for efficient thermal management, resulting in complicated and bulkier lamp casing designs [1]. Light is generated as a result of the emission of electrons from the surface of the filament, and during this process, the surface of the filament is gradually eroded due to the loss of atoms and the evaporation of the tungsten material. The evaporated tungsten gets deposited on the inner lining of the glass bulb, resulting in gradual erosion of the filament. At some point in time, the filament becomes too fragile and breaks [1]. In automobiles, the bulbs are replaced before the natural end of the life of lamps due to safety considerations. Standards do not specify the ageing of lamps but specify the test to determine the ageing, and this is called flux maintaining in the terminology of the standard. The useful life of a lamp may be defined as the number of hours during which the lamp can maintain 70% of its rated light output. In the case of filament lamps, the gradual evaporation of tungsten leads to the appearance of black spots, on the glass tube, which grow in size over a period of time, resulting in the blocking of light. Thus, the ageing of a lamp is artificially accelerated due to the blackening of the bulb although the filament is capable of sustaining the light output [1]. In order to increase the life of the filament lamp, manufacturers filled the bulb with heavy gases which help in slowing down the erosion of the tungsten material. Some of the gases used are Argon, Krypton, and Xenon, with Xenon being the heaviest of the three gases. These lamps came to be known as halogen lamps, referring to the halogen gases used in the lamp [1]. The gas helps the filament to operate at a higher temperature and generate a higher light output. This is achieved by the action of heavier gaseous atoms on the evaporated tungsten atoms. The escaped tungsten atom is captured and brought near the surface of the filament by the heavier halogen atom. The combined atoms, when they come very close to the hot filament, break apart with the tungsten atom being returned to the place where it came from and the halogen atom being freed to repeat its capturing action once again [1]. The application of halogen gas improved the performance of filament lamps to a great extent. Philips, in 1988, introduced a new lamp without any filament based

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on gas discharge principle. The lamp, which is now known as the high-intensity discharge (HID) lamp, does not contain any filaments except for two electrodes in a tube filled with a mixture of Xenon gas and metal halides. The light in such a lamp is generated by striking an arc of several kilovolts between the two electrodes. HID lamps deliver high output compared with halogen lamps but with a relatively low consumption of power. The improved performance of the HID lamp comes at the cost of added complexity in the design of its ballast which is required to control the operation of the lamp from the start to steady state.

HID lamps deliver high output compared with halogen lamps but with a relatively low consumption of power. For example, the light output from a 60-W halogen lamp is about 1200 lm compared with 2600 lm from a HID lamp operating at 35 W. HID lamps are operated at 70 W during startup to meet the SAE J2009 standard and at 35 W at steady state. HID lamps are being fitted in high beam, low beam, and both and are operated at the same rated power of 35 W for both high- and low-beam fittings. As the light in a high-beam position is to be projected far away from the car, the lamp has to be driven to develop maximum light output. However, when the same lamp is fitted in a low-beam position, the light is focused on an area closer to the vehicle, making the surface of the road appear bright. While the purpose of operating the lamp at its maximum power in the high-beam position can be justified because of the visibility requirement in high-beam driving condition, one can question the requirement to drive the lamp at the rated power for driving in a low-beam position, particularly in environments where the roads are very well lit. Majority of the modern cities around the world present such good night-driving conditions that the use of headlamps may seem redundant. Moreover, HID lamps develop twice as much light from the traditional filament lamps, and therefore, it is reasonable to argue that HID lamps in the low-beam position can be driven at lower power and still be made to develop more light than the filament lamp (halogen lamp) operating at 60 W. The aforementioned arguments therefore present a case for an investigation into dimming control with a view to saving energy.

II. LITERATURE REVIEW

Fiorello [2] proposed a new chip to control an HID lamp and makes use of the Sepic converter as the dc–dc converter. The chip provides all the functions necessary for controlling a HID lamp. The chip can be programmed such that the pulsewidth of the gate signal is adjusted from startup to the steady state. Therefore, this action assists in generating a high voltage prior to ignition and in limiting the lamp current within a safe value upon ignition. After the lamp is ignited, it is controlled in constant-current mode to generate twice the rated power in order to satisfy the SAE2009 standard. The controller then enters the constant-power mode in which the lamp is driven at a constant power of 35 W. During this mode, the lamp current gradually decreases while the lamp voltage increases until the lamp reaches its steady state. The time taken by the lamp to reach its steady state is indirectly proportional to the lamp temperature, and as a result, the time taken by a cold lamp

to reach the steady state is relatively longer than that by a hot lamp. This property of the lamp calls for the modulation of the timing of various stages from ignition to steady state. Therefore, the chip provides the necessary temperature compensation by monitoring the voltage across a capacitor whose voltage is an indication of the temperature of the lamp. The chip provides the gating signals not only to the dc–dc converter but also to the switches in the inverter. It is important to prevent the inverter from switching for few milliseconds upon ignition for successful operation. This is implemented by means of an RC combination in the chip which freezes the gate signal to the inverter switches, resulting in a steady emission of electrons from the electrode. This action is termed as dc operation which prevents the lamp from extinguishing after ignition due to the switching of the inverter. In [3], a dc–ac class E resonant converter is employed to achieve soft switching. A voltage doubler is used to apply the high voltage to the igniter at startup. The class E resonant inverter is operated in 100 kHz while the square-wave inverter supplying the lamp is operated at 400 Hz. In [4], a flyback converter with a two-winding transformer is employed to generate the high voltage for the igniter. The second winding mainly works during startup to charge a capacitor, which, along with the capacitor at the main secondary, is discharged in series to apply the voltage to a spark gap. The two-winding transformer halves the dc link voltage and thereby permits the selection of low rating switches. Zhao *et al.* [5] proposes a passive clamped buck–boost converter, which is a nonisolated version of the flyback converter. The operation is similar to the active clamped flyback converter but with an advantage of not using an active switch. The circulating energy present in the active clamp circuit is minimized in this circuit. In [6], the requirements of an HID igniter are presented, and a new design procedure is presented to reduce the overall dimension of the igniter transformer. HID lamps, if driven at frequencies higher than 10 kHz, suffer from “acoustic resonance,” a phenomenon which results in arc extinguishing, flickering, and unstable operation [4]. Several papers [7]–[16] discuss methods to detect and overcome acoustic resonance in HID metal halide lamps other than those used in automobiles. The ballast working in the megahertz range is proposed in [17], resulting in smaller size ballasts. A single-stage HID ballast with frequency modulation is discussed in [23] for commercial application. The dimming control of high-power metal halide lamps have been discussed in [18]–[20], and [26]. In [18], the dimming operation and the influence of the topology on dimming performance are discussed. The dimming operation at low frequency is implemented in [19] and [20]. The dimming control based on voltage and frequency control is discussed in [21], [22], and [26]. However, the aforementioned papers on dimming control are not referred to automotive application. Divakar and Cheng [24] introduce dimming control methods for automotive application using analog methods. An analog interfacing circuit to transfer the dimming control signal to a processor for dimming a high pressure sodium lamp is presented in [26]. A topology of low component count with two high-frequency dc–dc converters and a low-frequency inverter is presented in [27] with the limitation of increased losses due to two high-frequency converter switches.

A. Objectives

In this paper, a ballast without an auxiliary winding on the converter transformer that reduces the voltage across the secondary (hence, primary) is presented. The circuit consists of a voltage multiplier integrated to the secondary winding of the dc converter. The use of a voltage multiplier actually lowers the voltage level across the dc converter and thereby permits the selection of components with lower ratings when compared with the circuits in [4] and [25]. The circuit aids in the generation of the required voltage to the spark-gap and igniter assembly without the additional secondary winding.

The second objective of this paper is to implement dimming control using analog (summation of lamp current and lamp voltage) and digital control (product of lamp voltage and control) and to study the effectiveness of the two dimming control techniques. The main motivation of the work is to study the means to save energy in lamps fitted in low beam by operating the lamp at lower power.

B. Organization of the Paper

This paper is organized as follows. The building blocks of a ballast circuit are introduced in Section III, the proposed topology of the multiplier integrated ballast is presented in Section IV, the theoretical analysis of the power control is discussed in Section V, various dimming methods are introduced in Section VI, practical considerations are discussed in Section VII, and experimental results are presented in Section VIII followed by concluding remarks in Section IX.

III. HID CIRCUIT TOPOLOGIES

As the automotive environment requires a low voltage which is 12, 24, or 42 V for different vehicles and the striking voltage required by HID lamps is of several K_v , the low battery voltage from the vehicle has to be stepped up to a high voltage for the ignition circuit to produce a pulse. The following are the typical components of HID ballasts.

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 a 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 the reduction of losses in the transformer. However, the Sepic converter needs an additional capacitor and an input inductor, resulting in a higher part count.

Igniter: The igniter is a high-voltage transformer which converts the low voltage from the dc converter into a high-voltage pulse of 10–22-kV magnitude for initiating an arc across the lamp electrodes (Fig. 1). The voltage from the voltage doubler is applied to the primary of the igniter through

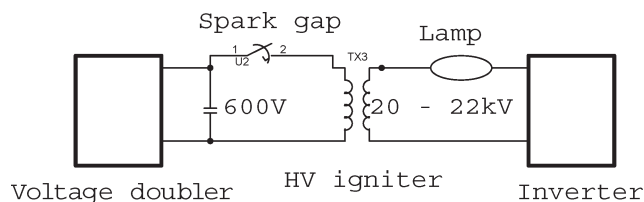


Fig. 1. Connection of HV igniter.

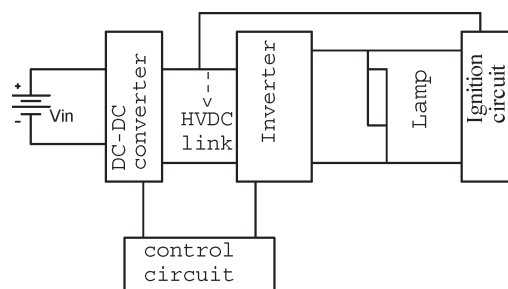


Fig. 2. Connection of ballast with HVDC link.

a capacitor and a spark-gap arrangement. The capacitor discharges its energy through the spark gap into the primary when the breakdown of the spark gap occurs. This discharge pulse in the primary is amplified by the secondary winding and applied across the lamp.

2) *Inverter*: The inverter is mainly used to provide alternating square pulses to the lamp upon ignition. The inverter actually has no active role in the control of power to the lamp other than providing ac pulses to the lamp.

3) *Controller*: The most important and the complex part of any HID ballast is the controller which controls and dictates the mode of operation depending on the stages from startup to steady state. The operating mode of the controller changes from constant-current mode at startup 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 startup but with the maximum load current limited to around 2.5 A.

B. Classification of HID Ballast

The HID ballast circuit can be classified into three main types depending on the method of generating the required high-voltage pulse to the lamp at startup, and they are the following.

1) *Ballast With HVDC Link*: The circuit, as shown in Fig. 2, is simple but requires high-voltage power devices. As the striking voltage is higher with higher power of lamps, it is difficult to use the circuit in practice because of the cost and the reliability.

2) *Ballast With Low-Voltage DC-Link-Fed Voltage Doubler [4]*: A voltage doubler is used in the circuit to provide a higher voltage to an ignition pulse transformer at startup, as shown in Fig. 3(a). The drawback is that an additional transformer winding on the dc converter is needed to provide a voltage to the voltage doubler.

Fig. 3(b) shows the schematic diagram of the circuit with a front-end Sepic dc–dc converter having two secondary windings, a full-bridge inverter circuit and an igniter with

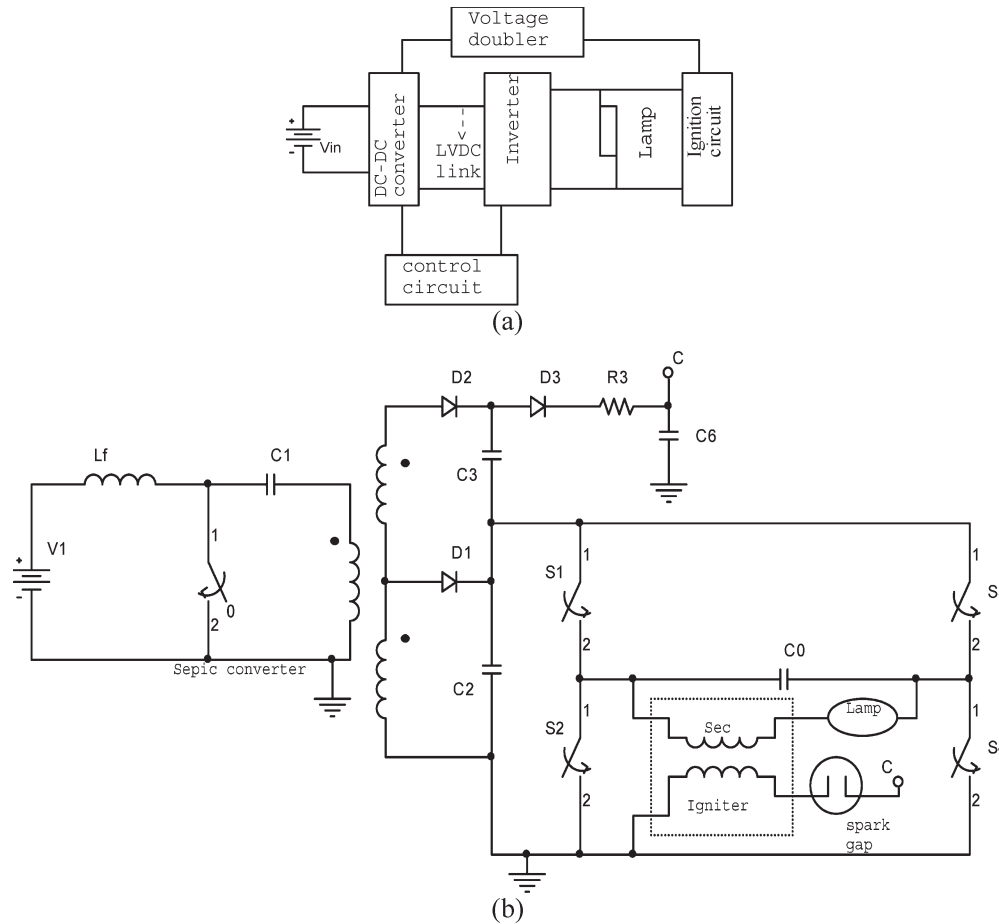


Fig. 3. (a) Schematic of ballast with dc-link-fed voltage doubler. (b) Circuit of the ballast with dc-link-fed voltage doubler.

spark-gap assembly. This is the Sepic version of the dc–dc converter (flyback) presented in [2]. 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 point “C”) reaches the breakdown voltage of the spark gap, the spark gap breaks down and causes C_6 to discharge into the primary of the igniter, thereby generating a high-voltage pulse across the lamp connected to the secondary winding of the igniter.

3) *Ballast With Inverter-Fed Voltage Doubler* [24]: The auxiliary winding can be eliminated by arranging the voltage-doubler circuit and feeding it from the inverter side, as in Fig. 4(a). The operation of the circuit can be explained with the help of the equivalent circuits in Fig. 4(c) and (d).

- 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, point “C” (the right-hand side of C_3) is now at the ground potential while the left-hand side of C_3 is at a potential equal to the secondary voltage of the converter.
- Stage 2) Mode 2 begins by turning on S_2 and S_3 to charge C_4 to the secondary voltage with a positive potential on point “D.” 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 $-V_{C_3}$). As a result, the voltage input to the spark-gap assembly now is $V_{CD} = V_C - V_D$. The spark gap will breakdown when V_{CD} exceeds its breakdown voltage, resulting in a high-voltage pulse across the lamp. The control circuit will then regulate the dc output voltage after the lamp is ignited as in any other topology.

IV. OPERATION OF THE PROPOSED BALLAST

The circuits in Figs. 3 and 4 differ in the way the voltage that is applied to the igniter is developed. In the first circuit, an auxiliary winding is used in the dc–dc converter transformer to form a voltage-doubler circuit with a diode–capacitor combination. In the circuit of Fig. 4, the voltage doubler is fed from the inverter side, and as a result, the auxiliary winding shown in Fig. 3 is absent. However, the maximum voltage of the dc converter, just before the ignition, is the same at 300 V in both the circuits. As a result, the voltage ratings of the components of the dc converter must be greater than 300 V in both the circuits. In order to reduce the voltage across the dc converter at startup, a voltage multiplier circuit constituted by D_2 , C_2 , D_3 , and C_3 is adopted in the proposed new circuit as in Fig. 5. The idea of including this multiplier came from the circuit in Fig. 3(b), in which two series capacitors are charged

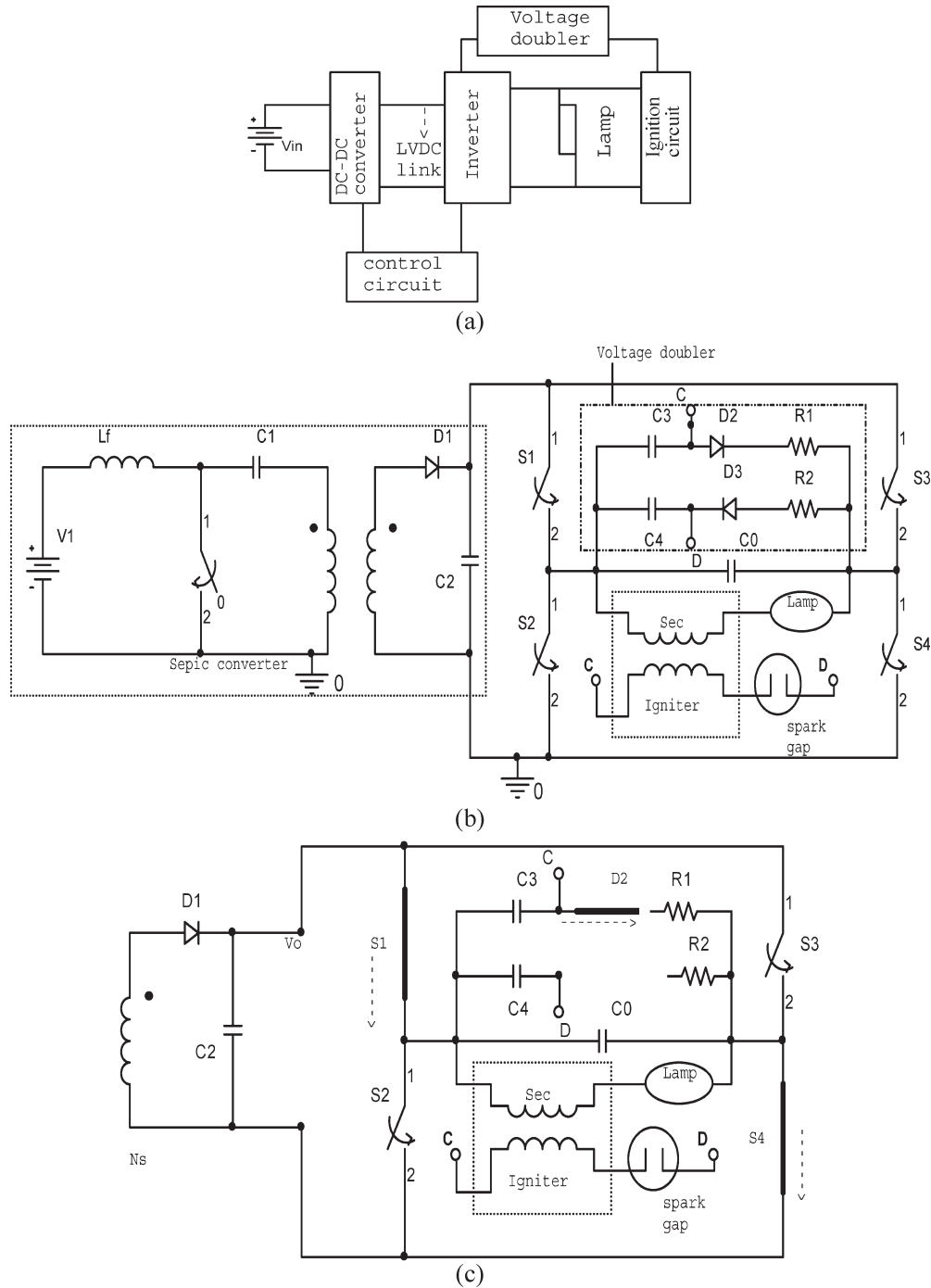


Fig. 4. (a) Schematic of ballast with inverter-fed voltage doubler. (b) Circuit of the ballast with inverter-fed voltage doubler. (c) Mode 1 of the voltage-doubler operation.

separately (using two windings) and then their voltages are summed to generate the required voltage for the igniter. The present circuit is the logical development of that circuit but without the second transformer winding. The authors thank an anonymous reviewer for suggesting a further literature search in the patents, and owing to this, the authors stumbled upon [28], in which a voltage multiplier circuit similar to the one presented here is used. The minor difference between the two is the way the total voltage for the igniter circuit is obtained; in the current work, the total voltage is doubled by the series combination of C_1 and C_3 (with the same polarity), whereas in [28], the

voltage is doubled from the two capacitors that are charged with opposite polarities and not by discharging the two in series as in this paper. Thus, it can be said that the voltage doubling action of the multiplier in this paper is similar to the one in Fig. 3(b), while the voltage doubling action of the multiplier in [28] is similar to the one in Fig. 4(b).

A. Operating Stages of the Proposed Ballast

The operating principle of the voltage multiplier is best understood by considering the equivalent circuits shown in

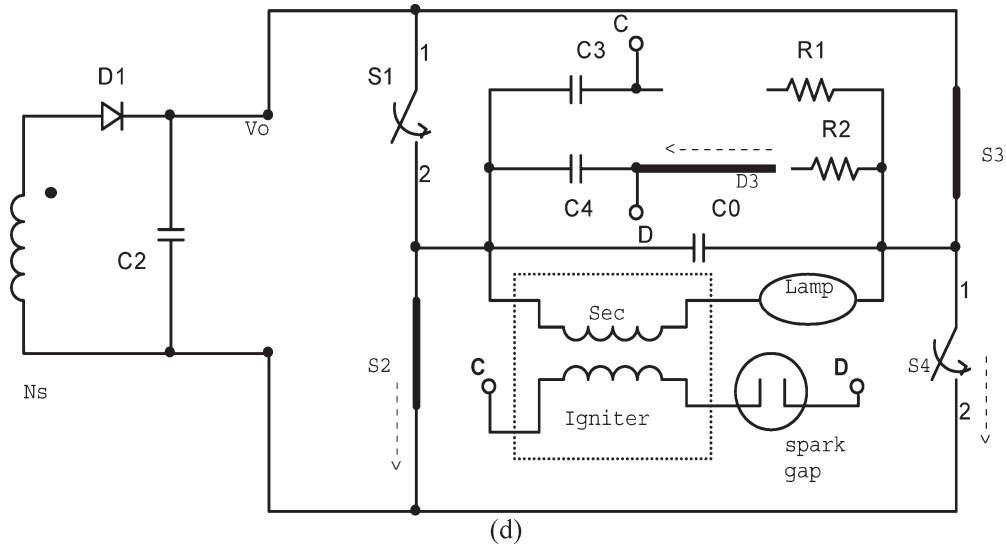


Fig. 4. (Continued.) (d) Mode 2 of the voltage-doubler operation.

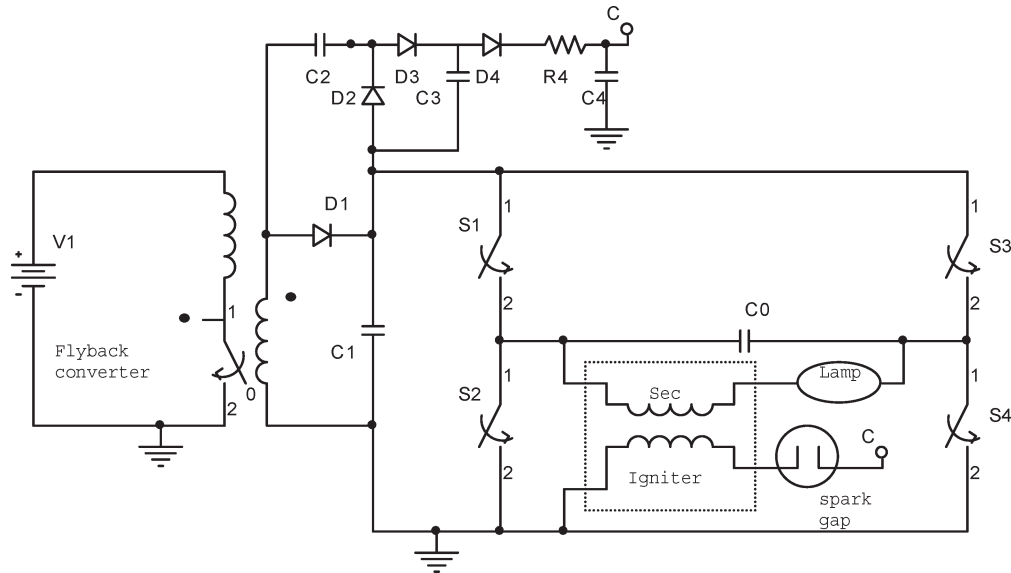


Fig. 5. Proposed HID ballast with multiplier circuit.

Fig. 6(a)–(c) in which the secondary voltage across the secondary winding is represented as an ac source.

After a few cycles, the voltage across C4 is given by

$$V_{C4} = V_{C1} + V_{C3} = V_{C1} + V_{C2}.$$

- Stage 1) In this stage, the secondary voltage is positive with the equivalent circuit, as shown in Fig. 6(a). The main capacitor C1 is now charged to the secondary voltage.
- Stage 2) In this switching cycle, the secondary voltage is reversed, and C2 will be charged to $V_{sec} + V_{C1}$.
- Stage 3) C1 and C2 charging state: In the next switching cycle, the secondary voltage is positive, and as a result, D3 is forward biased by the polarity of C2, resulting in the charging of C3 to V_{C2} . In the subsequent positive half cycles, C1 and C3 get charged, whereas in the negative half cycles, C2 gets charged.

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 C1 and C2 on a cycle-to-cycle basis. V_{C4} is connected to the input of the spark gap, and 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 Fig. 7 show the voltages across C1 and C2, and it can be observed that C1 is charged to about 250 V as against 300 V in the circuits presented in [4] and [25]. The reduction in the voltage across the converter permits the

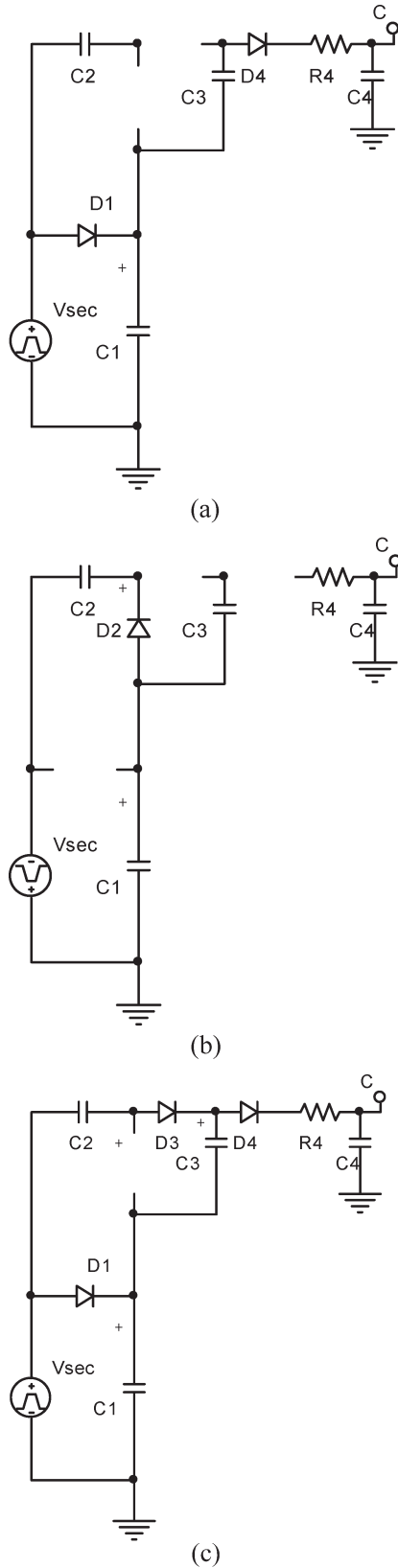


Fig. 6. (a) Stage 1: C1 charging state. (b) Stage 2: C2 charging state. (c) Stage 3: C1 and C2 charging states.

selection of components with lower rating. A reduction of voltage by few tens of voltage is always beneficial in any flyback converter wherein the leakage inductance has a tendency to add

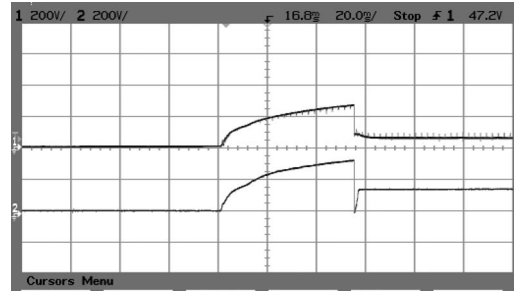


Fig. 7. First trace: voltage across C1. Second trace: voltage across C2. Scale: 200 V/div; 20 ms/div.

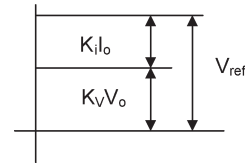


Fig. 8. Representation of constant-power algorithm.

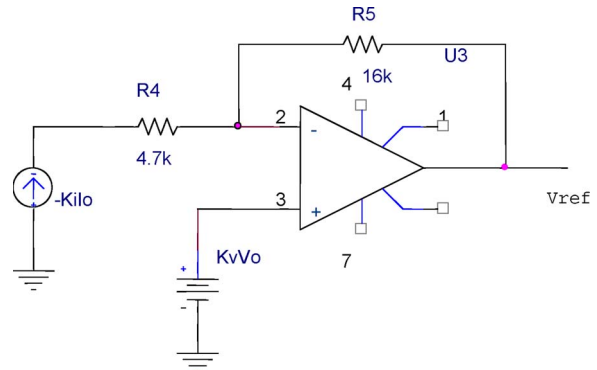


Fig. 9. Op-amp implementation.

the turn-off spike to the voltage across the MOSFET during turn-off.

V. THEORETICAL ANALYSIS OF CONTROL OF POWER [2]

As the HID lamps exhibit negative resistance characteristics, the lamps are driven in constant-power mode in steady state. The following section gives the principle behind the constant-power control operation of the lamp and the steps that lead to the identification of methods to achieve dimming control.

The principle of a constant-power algorithm can be best understood from Fig. 8, where $K_v V_o$, $K_i I_o$, and V_{ref} are the sensed voltage, load current, and the reference signals. The voltage gain K_v and the current gain K_i can be computed to achieve constant power control. The sensed voltage and current signals are summed in an op-amp, as shown in Fig. 9, such that the summed value is equal to V_{ref} which determines the power output of the lamp. As the sum of the sensed signals is equal to the reference voltage and, thus, to the reference power, any change in one will cause a corresponding change in the other so as to maintain the sum at the reference value. Thus, the power of the lamp is controlled to be a constant for changes in the lamp voltage.

From Fig. 9, the following equations can be written in terms of I_o [2]:

$$I_o = \frac{V_{ref}}{G * K_i} - \frac{K_v V_o}{G * K_i} (1 + G) \tag{1}$$

$$P_o = \left[\frac{V_{ref}}{G * K_i} - \frac{K_v V_o}{G * K_i} (1 + G) \right] V_o \tag{2}$$

where $V_{ref} = 2.5$ V, $G = R5/R4 = 3.4$, and P_o is the lamp power.

The voltage and current gains can be computed by considering the linear relation between the load current and the lamp voltage as in the aforementioned equation. By approximating the plot of I_o and V_o as linear within a range of the output voltage, it is possible to determine the gains K_i and K_v .

From (1),

$$m = \frac{-K_v(1 + G)}{G * K_i} \tag{3}$$

The slope is also expressed as

$$m = \frac{C - I_{max}}{-V_{min}} \tag{4}$$

From the aforementioned expressions, one can find the current gain as

$$K_i = \frac{V_{ref}}{G(I_{max} - m * V_{min})} \tag{5}$$

From (1)–(5), one chooses proper values for gains G (op-amp gain), K_v (voltage gain), and K_i (current gain) to achieve constant power control at any desired value. The factors in the aforementioned equation form the basis of the control techniques to achieve dimming control which is explained in the next section.

VI. METHODS OF DIMMING CONTROL

A. Analog Control or Summation Method

A set of curves can be obtained by plotting the power P from (2) against the output voltage by varying other parameters in the equation, and by doing so, the following three methods, which can control the power, can be identified:

- 1) current gain control (K_i);
- 2) voltage gain control (K_v);
- 3) op-amp gain control (G).

1) *Current Gain Control (K_i):* The power can be adjusted by controlling the gain K_i , and a set of plots are obtained for the power with “ K_v ” and “ G ” as parameters. The plots [using (2)] in Fig. 10(a), show the variation of the power output against the lamp voltage and the gain K_i . As K_i increases, the rate of fall of power decreases.

The power regulation curve for a constant K_i exhibits a parabola against the variation of the lamp voltage. It can also be seen from the plots that, for a given K_i , the lamp power does not change appreciably with the lamp voltage, and this observation is useful in regulating the power as the lamp ages.

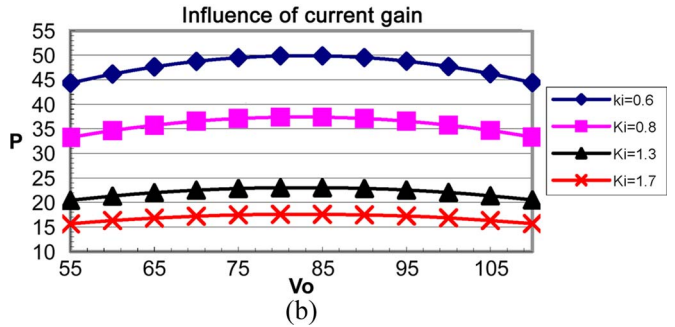
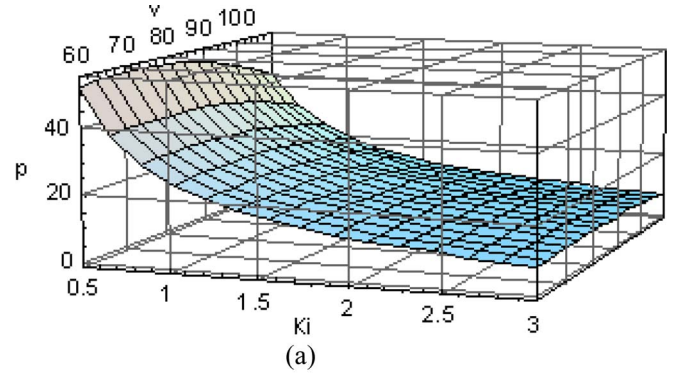


Fig. 10. (a) Plots for current gain control with $K_v = 0.0038$. (b) Two-dimensional plots for current gain control with $G = 3.45$ and $K_v = 0.0034$.

Suppose that the brightness of the lamp is low on account of ageing; it is possible to drive the lamp at a lower current gain setting in order to increase the power and thereby compensate the loss of intensity due to ageing.

Fig. 10(b) shows the power regulation capability of the current gain control which helps in achieving $\pm 5\%$ regulation for a wide change in the lamp voltage.

2) *Voltage Gain Control (K_v):* A set of plots are obtained from (2) by keeping K_i and G constant and varying K_v , as shown in Fig. 11(a) and (b). It can be seen from the plots that satisfactory power regulation is achieved only within a narrow band of change in K_v , and therefore, this method is inferior to the current-gain control method. Therefore, this method was not considered for implementation.

3) *Op-amp Gain (G) Control:* The last method is the op-amp gain control method in which the gain of the op-amp is adjusted to generate the plots in Fig. 12(a) and (b) using (2) for constant values of K_v and K_i . It can be inferred that the selection of the op-amp gain (G) is not possible to achieve good power regulation within $\pm 5\%$.

The plots in Fig. 12(b) show that this method has a poor power regulation like the voltage gain control method; hence, this was also not considered for implementation.

B. Digital Method of Dimming (Product Method)

The analog control method calls for the manual adjustment of the gain G to change the reference power setting to implement the dimming control. Thus, the implementation of this type of control requires changing the value of a resistor to change the gain. For example, in the current gain adjustment method, the current gain, which is the value of the current sense resistor,

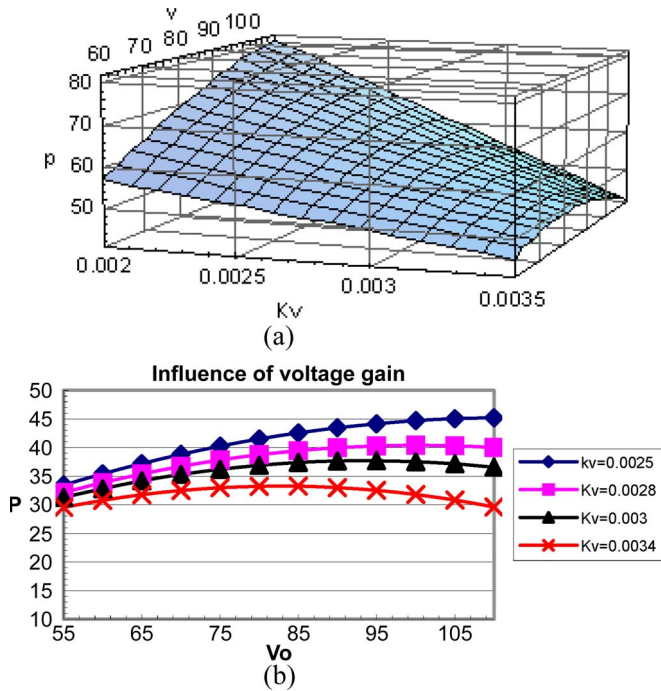


Fig. 11. (a) Plots for voltage gain control with $K_i = 0.6$. (b) Two-dimensional plots for voltage gain control with $G = 3.45$ and $K_i = 0.9$. Amplifier gain (G) control.

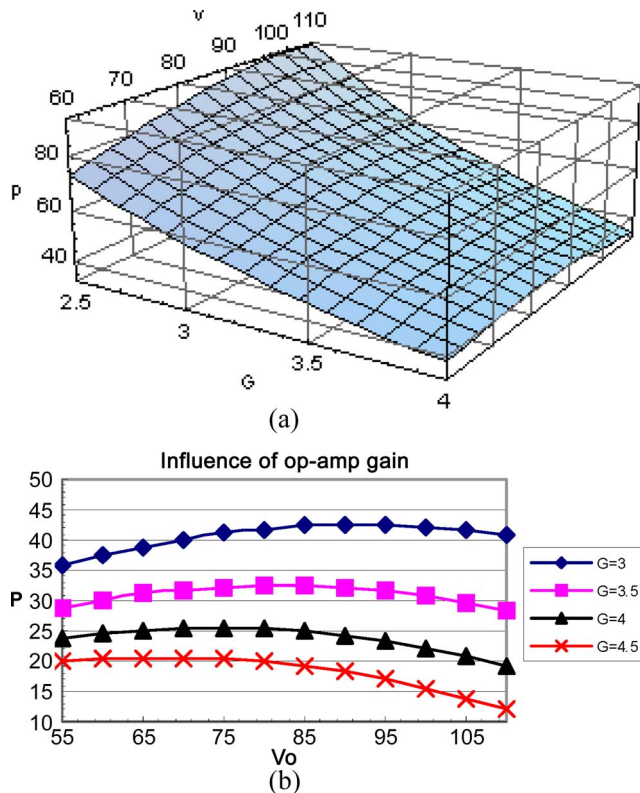


Fig. 12. (a) Plots for op-amp gain control with $K_i = 0.6$ and $K_v = 0.0032$. (b) Two-dimensional plots for op-amp gain control with $K_i = 0.9$ and $K_v = 0.0032$.

is increased to dim the lamp. The manual adjustment of the current sense resistor is, however, difficult to implement in a ballast which is to be fitted in a car. This limitation of the

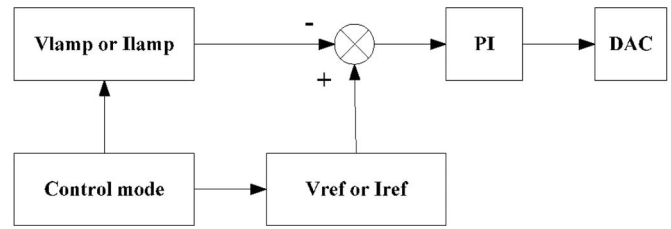


Fig. 13. Block diagram of digital power control.

analog control has motivated us to implement dimming using digital control in which constant power control is achieved by the voltage and current product.

1) *Principle of Digital Dimming or Product Control:* The block diagram representation of the control loop is shown in Fig. 13, in which the voltage and current of the lamp is sensed and compared with a suitable reference, and the error signal is passed through a PI controller which generates a reference signal for controlling the input current of the dc–dc converter. The block representing the control mode will decide the exact mode of operation, depending on the transition stage in which the ballast is in operation at the moment. The low resolution of the microprocessor (8 b) and the analog–digital converter (32 b) does not permit the efficient implementation of the constant power algorithm based on voltage and current product. Another approach that is simple and that permits less memory usage is therefore used in the present work. Accordingly, a lookup table consisting of reference current signals is created, and the appropriate reference value is selected to drive the lamp according to the sensed lamp voltage. The controller, in effect, selects a suitable reference value to drive the lamp based on the required power setting.

The principle involved in the dimming control is to operate the lamp at a lower power than the normal operation by lowering the reference power setting which is used in the computation of the new reference current. This is done by preloading the value of the dimming power in a register and selecting it for computing the value of the reference current when a dimming request is made. There are many ways to initiate dimming. For example, the dimming request can be either manual (by the driver) or automatic (responding to surrounding light using light sensor or responding to speed using signals from tachometer). In the present work, the simple user-prompted dimming control is implemented first to gain understanding of the dimming operation. In this method, the microprocessor detects the command from the user based on the status of an external switch and then operates the lamp at the desired power by loading the stored reference value. The software is designed to accept the dimming request only after the lamp has attained its steady state in about 150 s. This feature is to prevent the switching on of the lamp under dimming conditions (Fig. 14).

The experimental results of dimming from the analog and digital methods are presented and compared in Section VIII.

VII. PRACTICAL CONSIDERATIONS

An HID lamp is a very complex load to drive. The impedance of an HID lamp will drop drastically to about 30Ω from

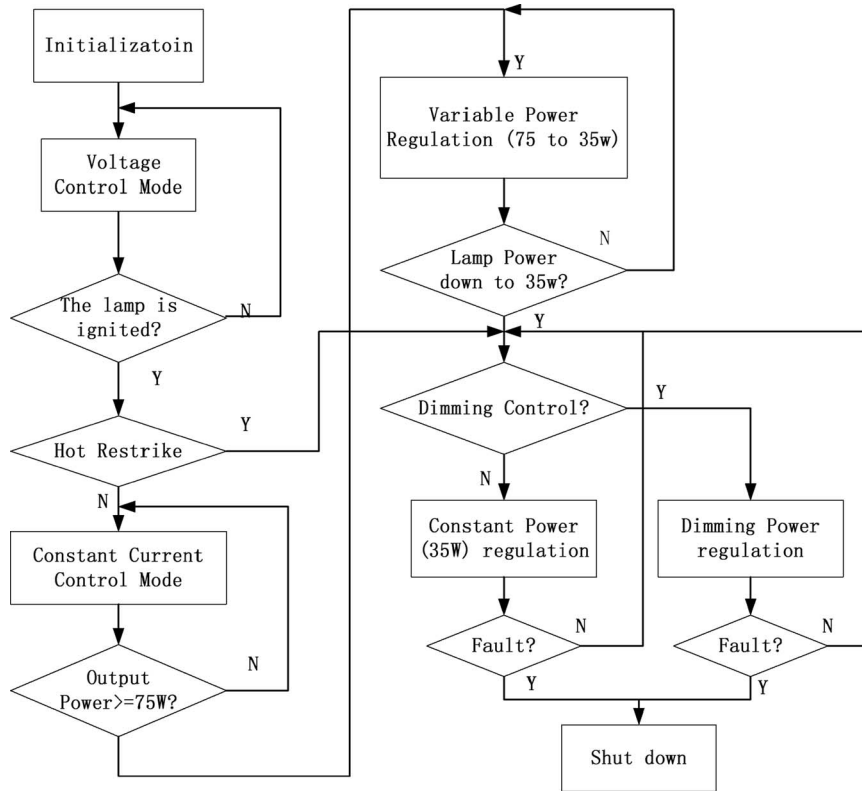


Fig. 14. Flowchart of the dimming algorithm.

infinity when ignited by a high-voltage pulse, and thereafter, the impedance gradually reaches a value of about 200 ohms in the steady state. Therefore, the transitions between each stage should be properly controlled by the HID controller; otherwise, the HID lamp may only be ignited but cannot be lit up. Therefore, there are some factors to be considered in order that the HID lamp will be successfully lighted.

A. DC Operation

The function of the inverter is to apply low-frequency ac signals to the lamp for normal operation. However, for the successful operation of the lamp, the inverter must not change its polarity for a predetermined time upon ignition. This is achieved by freezing the gate signals to the switches of the inverter, and in doing so, the lamp is driven on dc current for a predetermined time which is a function of the temperature of the lamp [2]. The control circuit should be able to determine the optimum duration and govern the dc operation of the lamp upon ignition to prevent the electrodes from being damaged.

B. Takeover Current

As mentioned in the previous paragraph, the HID lamp requires enough takeover current to sustain the arc immediately upon ignition. The required energy is supplied in two short stages [23], one from the small-value polypropylene capacitor ($0.47 \mu\text{F}$) connected across the secondary winding and the second from the larger electrolytic capacitor ($4.7 \mu\text{F}$) connected in parallel with it. The polypropylene capacitor with its relatively



Fig. 15. Bobbin for the igniter transformer.

smaller equivalent series resistance (ESR) is able to supply the initial burst of energy to strike an arc but cannot supply enough energy to sustain the arc. Therefore, a large electrolytic capacitor is needed to store much energy to supply the takeover current for the lamp after the ignition.

C. Insulation

For the igniter transformer, the key issue is to prevent a short circuit between windings. Inadequate insulation can result in serious problems due to insulation breakdown. The igniter transformer should have the capability of generating high-voltage pulses ($> 20 \text{ kV}$) to realize hot restrike.

In order to reduce the cost, the design was finalized using the rod type of core. The winding of a large number of secondary turns was very difficult on the solenoid; hence, a special bobbin consisting of many sections as shown in Fig. 15 was made for the final prototype. The winding arrangement is shown in Fig. 16.

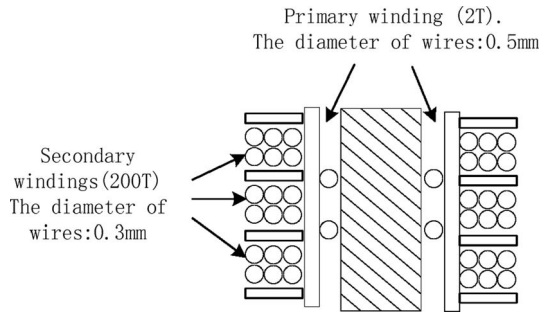


Fig. 16. Igniter transformer winding arrangement.

VIII. EXPERIMENTAL RESULTS

Two prototypes of the new topology were built in the laboratory and tested on a 35-W D2S-type lamp. One was controlled by an analog control while the other was controlled by a digital controller. The specifications of the topology were as follows:

V_{in}	9–13 V;
nominal power output	35 W;
flyback transformer turns ratio	7:70;
core	RM10;
air gap	0.3 mm;
primary wire	diameter: 0.1 mm and number of strands: 60;
secondary wire	diameter: 0.2 mm and number of strands: 3;
capacitors C1 to C4	0.47 μ F;
igniter transformer	2:200;
core	rod type; length: 25 mm; diameter: 6 mm;
primary wire	diameter: 0.5 mm;
secondary wire	diameter: 0.3 mm;
magnetizing inductance	1.58 μ H;
leakage inductance	0.7 μ H;
DC converter frequency	100 kHz;
inverter switching frequency	400 Hz.

A. Result From the Proposed Voltage Multiplier Integrated Ballast

The voltage output of the multiplier shown in Fig. 17 is fed to the input of the spark gap in the igniter. The spark gap conducts when its breakdown voltage exceeds 600 V, thereby causing a charge transfer from the multiplier to the primary of the igniter transformer. The secondary of the igniter transformer, due to its large number of turns, generates a high-voltage pulse as shown in Fig. 18.

The other experimental results recorded from the prototype are shown in Figs. 19 and 20. To start with, the lamp acts as an open circuit; hence, the inverter output voltage (across the lamp plus the secondary of the igniter) before the ignition is high as shown in Fig. 19. After the ignition, the lamp's resistance falls and so does the lamp's voltage. Thereafter, the lamp's resistance gradually increases until the lamp reaches its steady state in about 150 s while the lamp's voltage settles down to its steady value as shown in Fig. 19(a).

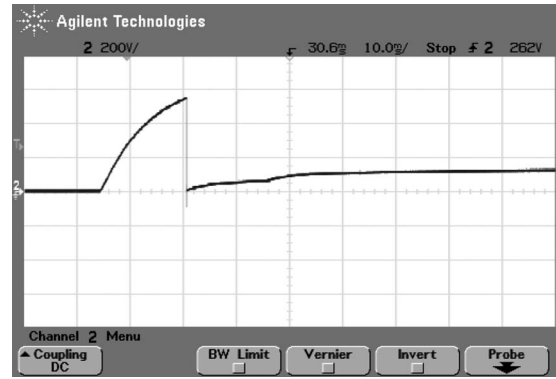


Fig. 17. Output of the multiplier scale: 200 V/div and 20 ms/div.

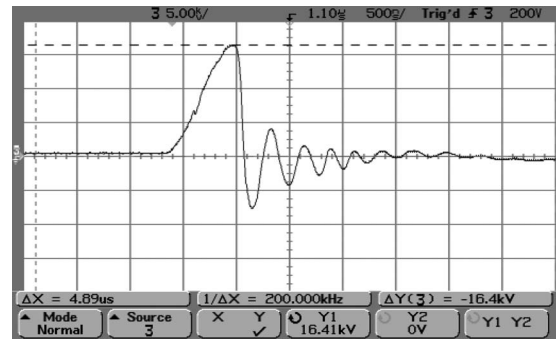


Fig. 18. Output of the igniter scale: 5 kV/div and 500 ns/div.

The inverter output voltage under a warm start is shown in Fig. 19(b) in which it can be seen that the lamp's voltage is in steady-state value immediately upon ignition, indicating a successful warm restrike ability of the ballast. The waveforms of the lamp current under cold and warm start conditions are shown in Fig. 20(a) and (b), respectively. As mentioned in Section IV, the advantage of this multiplier-integrated ballast is that the voltage across the secondary and, hence, the primary of the dc converter transformer sees a reduction of about 50 V (shown in Fig. 7) compared with other topologies. The same is observed from the multiplier arrangement presented in [28].

B. Result From the Analog Dimming Control

The analysis in Section VI revealed that the current gain control is superior to the voltage gain and op-amp gain control methods, and hence, the current gain control was selected for analog dimming control implementation. The ballast was first operated to drive a D2S-type lamp at the rated power until the steady state was reached, and then, the current gain was adjusted manually to reduce the lamp power to about 23 W. The experimental results were compared with the theoretical predictions, and the results are tabulated in Table I.

C. Result From the Digital Dimming Control Method

The same lamp was now driven with the analog controller replaced by a microcontroller. A new printed circuit board was developed using surface-mounted components to achieve higher power density. The microcontroller operates the lamp

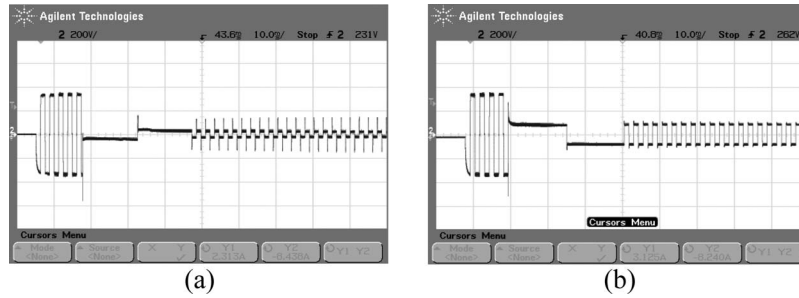


Fig. 19. Inverter output voltage (a) under cold start and (b) under warm start. Scale: 200 V/div and 10 ms/div.

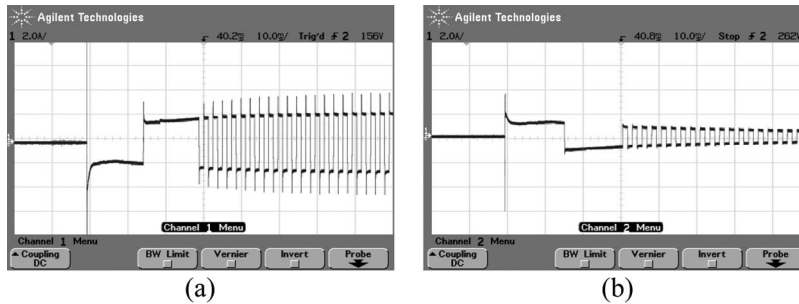


Fig. 20. Lamp current (a) under cold start and (b) under warm start. Scale: 2 A/div and 10 ms/div.

TABLE I
EXPERIMENTAL AND THEORETICAL DIMMING RESULTS

K_i Theoretical	K_i Expt.	Power theoretical	Power Expt
1.4	1.4	21.4 W	23.1 W
0.8	0.75	37.4 W	36.5 W

at its rated power under normal condition and drives the lamp at low power whenever a dimming request is made. The microcontroller calculates the new lamp current by multiplying voltage and current signals as discussed, and hence, this method is called the product method as compared with the summation method of the analog control. The lamp power was reduced from the rated 34–27.5 W using this method. The measurement of its light output was carried out in an integrated sphere under normal and dimming modes, and the corresponding measured values were 2462 and 1672 lm, respectively.

D. Comparison of Dimming Results Between Analog and Digital Control

The minimum power obtained using the analog control was 23 W as compared with 28 W using the digital control. The analog control was implemented by summing the lamp voltage and the current while the digital control was implemented using the product of voltage and current. The current gain K_i in the analog control had to be adjusted to reduce the lamp power while the new reference value was calculated according to the preloaded dimming power in the digital method to initiate the dimming control automatically by the controller, thereby eliminating the limitation of the manual adjustment in the analog control. In the analog control, the current gain K_i acts as a linear scaling factor, thereby resulting in a linear and greater dimming range. On the other hand, the algorithm for digital

TABLE II
ANALOG DIMMING RESULTS

Lamp power	Lamp voltage	lamp current	efficiency
36.5 W	85.8 V	0.425 A	79.8%
23.1 W	84.3 V	0.275 A	78.3%

TABLE III
DIGITAL DIMMING RESULTS

Lamp power	Lamp voltage	lamp current	efficiency
34 W	81 V	0.42 A	80.2%
28 W	78.3	0.277 A	81%

control is implemented using the voltage and current product which results in a highly nonlinear function as far as dimming reference is concerned, resulting in a smaller range of dimming power control. Tables II and III tabulate the results from the analog and the digital dimming methods.

Tables II and III show that the lamp current changes by a wider margin than the lamp voltage in the methods. This is expected because of the nature of the control in which the control variable is the lamp current.

E. Comparison of HID Lamp Under Dimming and Halogen Lamp Under Normal Operation

In order to justify the dimming operation of HID lamps, measurements were also made on a 12-V 60-W Philips H4-type halogen lamp. This lamp develops 1113 lm at 60 W compared with 1672 lm from the HID lamp at 27.5 W with the digital dimming control. The experiment reveals that the brightness of a dimmed HID lamp is nearly 50% more than that of a halogen lamp operating at the rated power, and therefore, there is no compromise on safety on the account of dimming.

IX. CONCLUDING REMARKS

A review of some of the topologies for driving HID lamps in automobiles has been carried out. A circuit integrated with a voltage multiplier without an auxiliary winding has been presented and analyzed. The circuit has a lower voltage across the secondary compared with other topologies and consequently permits parts with lower voltage rating. Any voltage reduction is a desirable feature in a flyback converter which experiences voltage spikes during the turn-off period. The circuit differs from the one presented in [28] in the way that the total multiplier voltage is applied to the igniter circuit. In the present circuit, the total multiplier voltage is due to the series combination of the two capacitors while it is due to the potential difference between the plates of oppositely charged capacitors in [28]. This paper also explored different dimming control methods and analyzed their relative merits. In the analog control method, the current gain control, because of its superior power regulation capability, stands out among the three methods. Although, the analog control provides a better dimming range, it is difficult to implement in practice as it calls for the adjustment of the current sense resistor (current gain K_i). On the other hand, the digital dimming control based on the voltage and current product has the advantage of being more practical as the software calculates the new reference power for driving the lamp upon receiving the request for dimming. The main limitation of the product control is the limited dimming range due to its nonlinear nature when compared with the linear analog control. The preliminary works using the two dimming methods reveal the feasibility of dimming control for automotive applications in order to save energy under driving conditions where there is sufficient ambient light for the driver to dim the lamp. The dimming control provides an opportunity for saving energy without sacrificing safety. It is clear from the discussion that there is a need for a new dimming method that has the advantages but without the limitations of the analog and digital method of control. The future work will look into the implementation of such a scheme using an intelligent digital control that will adjust the brightness of the lamp according to the ambient conditions. For example, the control could include a feature to dim when the car is stopped at signal junctions or when it senses an oncoming vehicle.

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REFERENCES

- [1] *An Introduction to Automotive Lighting*. [Online]. Available: www.autolamps-online.com
- [2] R. Fiorello, "Powering a 35W DC metal halide HID lamp using the UCC3305 HID lamp controller," Unitrode Corp., Merrimack, NH, Unitrode Appl. Note U-161, 1999.
- [3] A. Reatti, "Low-cost high power-density electronic ballast for automotive HID lamp," *IEEE Trans. Power Electron.*, vol. 15, no. 2, pp. 361–368, Mar. 2000.
- [4] K.-C. Lee and B. H. Cho, "Design and analysis of automotive high intensity discharge lamp ballast using microcontroller unit," *IEEE Trans. Power Electron.*, vol. 18, no. 6, pp. 1356–1364, Nov. 2003.
- [5] Q. Zhao, Y. Hu, F. C. Lee, J. A. Sabate, and F. Li, "A high efficiency DC/DC converter as the front-end stage of high intensity discharge lamp ballasts for automobiles," in *Proc. PIEMC*, Aug. 2000, vol. 2, pp. 752–756.
- [6] W. S. Kim, B. H. Cho, and K. C. Lee, "Design and analysis of high-voltage transformer for HID lamp igniter," in *Proc. IEEE APEC*, Mar. 2005, vol. 2, pp. 1043–1047.
- [7] J. H. Campbell, "Initial characteristics of high intensity discharge lamps on high frequency power," *Illum. Eng.*, vol. 64, no. 12, pp. 713–722, Dec. 1969.
- [8] C. F. Scholz, "Characteristics of acoustical resonance in discharge lamps," *Illum. Eng.*, vol. 65, no. 12, pp. 713–717, Dec. 1970.
- [9] H. L. Witting, "Acoustic resonances in cylindrical high-pressure arc discharges," *J. Appl. Phys.*, vol. 49, no. 5, pp. 2680–2683, May 1978.
- [10] W. Dennemen, "Acoustic resonances in high-frequency operated low wattage metal halide lamps," *Philips J. Res.*, vol. 38, no. 4/5, pp. 263–272, Apr./May 1983.
- [11] J. M. Davenport, "Direct current operation of low voltage metal halide lamps," *Illum. Eng.*, vol. 14, no. 1, p. 274, 1984.
- [12] H. Nishimura, H. Nagase, K. Uchihashi, T. Shiomi, and M. Fukura, "A new electronic ballast for HID lamps," *J. Illum. Eng. Soc.*, pp. 70–76, Summer 1988.
- [13] N. Fukimori, H. Nishimura, K. Uchihashi, and M. Fukura, "A study of HID lamp life when operated by electronic ballasts," *J. Illum. Eng. Soc.*, vol. 49, pp. 41–47, Winter 1995.
- [14] Y. Tsutomu, O. H. Masato, S. Toshihisa, K. Gunji, and K. Takeshi, "Characteristics of ballast for HID lamp with single-ended resonant-type inverter circuit using leakage inductance of transformer," in *Proc. IEEE Int. Conf. Power Electron. Drive Syst.*, Piscataway, NJ, Jun. 1995, pp. 246–250.
- [15] J. M. Alonso, C. Blanco, E. Lopez, A. J. Calleja, and M. Rico, "Analysis, design and optimization of the LCC resonant inverter as a high-intensity discharge lamp ballast," *IEEE Trans. Power Electron.*, vol. 13, no. 3, pp. 573–585, May 1998.
- [16] M. Gulko, S. Ben-Yaakov, and A. Giter, "Current-sourcing push-pull parallel-resonance inverter (CS-PR): Theory and applications as a discharge lamp driver," *IEEE Trans. Power Electron.*, vol. 41, no. 3, pp. 285–291, Jun. 1994.
- [17] S. Ben-Yaakov, M. Gulkho, and A. Giter, "The simplest electronic ballast for HID lamps," *IEEE Trans. Ind. Electron.*, vol. 41, no. 4, pp. 634–640, Sep. 1996.
- [18] S. Y. R. Hui, H. Chung, L. M. Lee, and Y. Ho, "An electronic ballast with wide dimming range, low EMI and high power factor," *IEEE Trans. Power Electron.*, vol. 16, no. 4, pp. 465–472, Jul. 2001.
- [19] S. Y. R. Hui and H. Chung, "Dimming control of electronic ballasts," U.S. Patent 6 486 651, Nov. 26, 2002.
- [20] Y. K. Ho, H. Chung, S. Lee, and S. Y. R. Hui, "A comparative study on dimming control methods for electronic ballasts," *IEEE Trans. Power Electron.*, vol. 16, no. 6, pp. 828–836, Nov. 2001.
- [21] M. Rico-Secades, L. Corominas, J. M. Alonso, J. Ribas, J. Cardesin, A. J. Calleja, and J. Garcia, "Complete low-cost two-stage electronic ballast for 70-W high pressure sodium vapor lamp based on current-mode-controlled buck-boost inverter," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 728–734, May/June 2005.
- [22] J. M. Alonso, A. J. Calleja, and J. Ribbas, "Evaluation of a novel single-stage high-power-factor electronic ballast based on integrated buck half-bridge resonant inverter," in *Proc. IEEE APEC*, Feb. 2000, vol. 1, pp. 610–616.
- [23] H.-J. Chiu, T.-H. Song, S.-J. Cheng, C.-H. Li, and Y.-K. Lo, "Design and implementation of a single-stage high-frequency HID lamp electronic ballast," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 674–683, Feb. 2008.
- [24] B. P. Divakar and K. W. E. Cheng, "Study of dimming control methods for HID automotive lamps," in *Proc. Int. Conf. Power Electron. Syst. Appl.*, 2006, pp. 277–282.
- [25] B. P. Divakar, K. W. E. Cheng, D. H. Wang, and P. Dong, "Examination of the power conditioning driving circuit for automotive HID lamp," in *Proc. APSCOM*, 2006, CD ROM.
- [26] H. Liu, Y. Wang, X. Zhang, D. Xu, and L. Guo, "Dimmable electronic ballast for 250 W HPS lamp in street lighting with analog dimming interface circuit," in *Proc. IEEE APEC*, Feb. 2007, pp. 259–262.
- [27] B. Roberts and T. Aboumrard, "Automotive high intensity discharge ballast," U.S. Patent 0 157 694, Jul. 3, 2008.
- [28] T. J. Ribarich and P. Green, "Automotive high intensity discharge lamp ballast circuit," U.S. Patent 7 288 898, Oct. 30, 2007.



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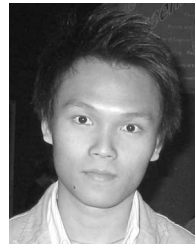
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