High-Intensity-Discharge Lamp Ballast With Igniter Driven by Dual-Frequency Inverter

Yuequan Hu and Milan M. Jovanović
Delta Power Electronics Laboratory
Delta Products Corporation
P.O. Box 12173, 5101 Davis Drive
Research Triangle Park, NC 27709

***Abstract*-An automotive high-intensity-discharge (HID) lamp ballast with an igniter which has a voltage doubler driven by a dual-frequency inverter is proposed. As in a conventional ballast, the proposed implementation consists of a high frequency dc/dc converter and a low frequency dc/ac inverter. However, in this implementation, the inverter is driven at a much higher frequency during the ignition stage, making it possible to use only one large capacitor to store the energy for ignition compared to two large capacitors required in the conventional implementation, resulting in a higher density igniter. Furthermore, to simplify the hardware, a low-cost micro-controller is employed to implement a software-based detection of lamp ignition, lamp status, and to regulate the lamp power. The performance of the proposed igniter, ignition and power controller were evaluated on a 35-W HID lamp ballast.**

I. INTRODUCTION

High-intensity-discharge (HID) lamps include the group of electrical lights commonly known as mercury vapor, metal halide, high-pressure sodium, and xenon short-arc lamps. Compared to conventional halogen lamps, HID lamps produce higher lumens and have found application in the automotive headlight. A drawback of HID lamps is that they require a high ignition voltage (about 25kV) and more sophisticated control for reliable operation, which makes them much more expensive than conventional halogen counterparts. As a result, ballast manufacturers are focusing their R&D efforts on finding solutions to lowering the cost of the HID lamp ballast and increasing its customer acceptance.

A typical ballast circuit for igniting and powering a high-intensity-discharge (HID) lamp is shown in Fig. 1. The ballast comprises an input reversed polarity protection circuit, an EMI filter, a flyback dc/dc voltage booster, a dc/ac inverter, a controller, a driver circuit, and an igniter. The flyback converter converts the battery voltage (normally 9V-16V) to a voltage, V_B, which is typically 380V before ignition of the lamp, and in the 65V to 135V range during normal operation. The inverter powers the lamp with a fixed switching frequency that is limited to the range of 100Hz-500Hz to avoid acoustic resonance [1], [2]. The igniter with a voltage doubler generates a high voltage pulse to strike the lamp and initiate the arc.

A major drawback of the ballast in Fig. 1 is that the stored energy used for ignition of the lamp is determined by the series connection of capacitors C9 and C10, leading to an effective capacitance $C_{eff} = C9 \cdot C10/(C9+C10)$. Assuming C9 = C10, the utilization of the total energy storage capacity of C9 and C10 is only 50%, which has a detrimental effect on the volume of the igniter. Another disadvantage of the circuit in Fig. 1 is that the firing of the primary winding is not synchronized to the turn on

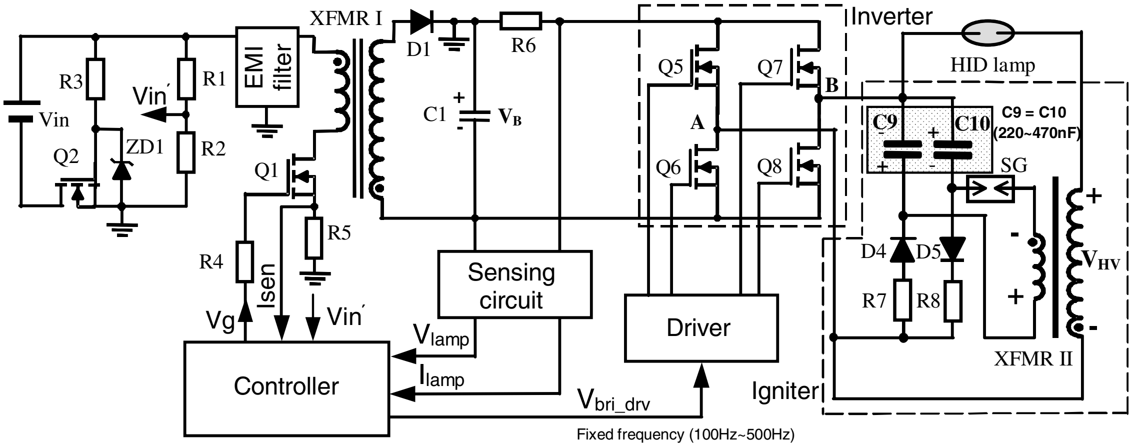

Figure 1. Typical HID lamp ballast circuit.

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instant of switch pairs Q5 and Q8, or Q6 and Q7. As a result, the peak ignition voltage across the lamp, which is the sum of voltages V_{BA} and V_{HV} across the secondary winding of XFMR II after spark gap SG is fired, may not be maximized because the inverter output voltage V_{BA} may be in opposition with voltage V_{HV}, preventing optimization of the HID lamp ignition.

A number of igniter implementations have been proposed in [3]-[5]. For example, the implementation in [3] uses the secondary winding of the flyback transformer to generate the required turn-on voltage for the spark gap, whereas the igniter implementation in [4] employs a voltage doubler driven by an inverter. One major drawback of the igniter implementation in [4] is that it needs four wires to connect to the power circuit, which complicates the ballast packaging. Another major drawback is that it requires a large capacitance for temporary energy storage due to the low switching frequency of the inverter. In the implementation described in [5], a flyback converter with stacked windings is used to obtain a boosted voltage as the igniter input. The stacked winding arrangement not only makes the flyback transformer design more complex, but also requires a four-wire connection between the power board module and the igniter module. Because the stacked winding operates with a high voltage (typically ≥ 800V), the transformer design, PCB layout, and the insulation of the wire connections between the igniter and power circuit require special care, leading to an increased cost.

Another important design aspect for successful turn-on of the HID lamp is a prompt detection of lamp ignition. Typically, lamp ignition is detected by circuits that consist of a sensing resistor, op-amps, and comparators, as described in [6], [7]. A discrete lamp-off timer is also included in [7] to measure the elapsed time between the last turn-off and restart, which is used to control the required power during restart. Generally, this additional circuitry adds to the design complexity, and very often, exhibits a lack of flexibility. Therefore, there exists a need for a ballast that is more compact, cheaper, and overcomes the drawbacks of the previous approaches.

This paper proposes a micro-controller based HID lamp ballast with programmable control and an igniter driven by a dual-frequency inverter with minimum external circuitry. Based on the sampled output voltage and current, the micro-controller is used for lamp power or current control in different stages, lamp ignition and status detection, generation of optimal inverter drive signals, and protection under abnormal conditions. The proposed igniter employs a voltage doubler (or multiplier) which uses a small capacitor(s) for temporary energy storage and only one relatively large capacitor for providing enough energy to generate a high voltage pulse to strike the HID lamp. Before lamp ignition, the voltage doubler or multiplier is driven by the inverter at a much higher switching frequency than the normal operating frequency.

II. PROPOSED BALLAST WITH AN IGNITER DRIVEN BY A DUAL-FREQUENCY INVERTER

Figure 2 shows the proposed automotive HID lamp ballast with an igniter driven by a dual-frequency inverter. It differs from the circuit shown in Fig. 1 in that it employs an igniter with a voltage doubler in a different configuration than that in Fig. 1, a combination of a micro-controller and a PWM controller for the ballast power regulation, and an arc sustaining circuit consisting of R8, R9, diode D2 and energy storage capacitor C2.

According to sensed lamp voltage V_{lamp} and current I_{lamp}, the micro-controller generates appropriate control signal V_{pwr_ctl} to ensure a reliable ignition, warm-up, and constant power operation of the lamp during steady state, avoiding over-power or under-power of the lamp. A unique advantage of using a micro-controller is the flexibility to control the ignition, regulate the lamp current and power, as well as a significantly lower component count, space, and cost compared to analog solutions.

The voltage doubler, consisting of capacitors C9 and C10, diodes D4 and D5, as shown in Fig. 2, provides an ignition trigger voltage by charging capacitor C9 during a charge time interval, T_{charge}, and discharging it into capacitor C10 during a

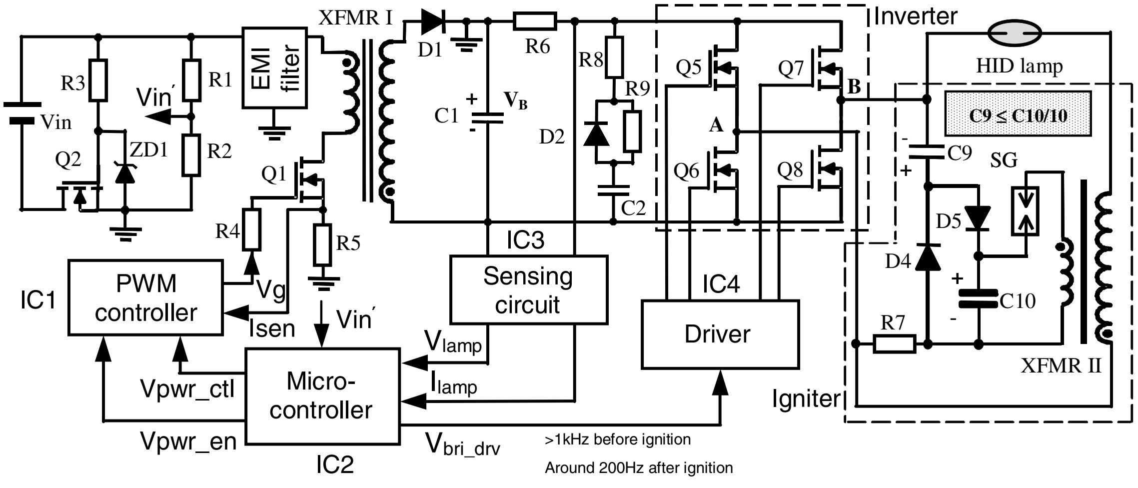


Figure 2. Simplified power and control circuit diagram of proposed HID lamp ballast.

discharge interval, $T_{discharge}$. Capacitor C9 functions as a charge-pump capacitor and capacitor C10 functions as an energy storage capacitor. The sum of charge and discharge time intervals T_{charge} and $T_{discharge}$ corresponds to the switching period during ignition, which is higher than that during normal operation. When switches Q5 and Q8 are turned on during charge time interval T_{charge}, diode D4 is forward biased and capacitor C9 is charged by the current flowing through resistor R7 and diode D4. Charge time interval T_{charge} is determined by resistor R7 and capacitor C9, i.e., $T_{charge} \approx 5 \cdot R7 \cdot C9$. The charge interval ends when capacitor C9 is charged up to 99% of V_B. Since discharge time interval $T_{discharge}$ of capacitor C9 is also mainly determined by the values of R7 and C9, switching period T_s of the power inverter is $T_s = 2 \cdot T_{charge} = 2 \cdot T_{discharge}$. For example, for C9 = 10nF and R7 = 2.2kΩ, switching period T_s = 220us.

The voltage across capacitor C10 is equal to the sum of the voltage across capacitor C9 and the output voltage V_B, since capacitor C9 is charged to output voltage V_B, capacitor C10 is charged to $2V_B$. Spark gap SG is turned on when the voltage across capacitor C10 reaches SG breakdown voltage, for example, 600V. At that time a voltage pulse is applied to the primary winding of the transformer XFMR II, and because of the high ratio of secondary to primary turns, a high voltage pulse is generated at the secondary winding of XFMR II which ignites the HID lamp.

Once the HID lamp is ignited, the lamp has a low impedance, and the voltage across capacitor C1 drops to approximately 20V for a cold lamp and approximately 65V for a hot lamp. In order to prevent the lamp from extinguishing, the arc sustaining circuit provides immediate current by discharging C2 via diode D2 and resistor R8, where resistor R8 is typically 100Ω. The micro-controller detects the ignition moment and generates the required full-bridge drive signal, V_{bri_drv}, and power control signal, V_{pwr_ctl}, to warm up the lamp and regulate the lamp power during steady state operation. The ignition, DC warm-up, and power control of the HID lamp will be detailed in the next section.

The proposed scheme operates the power inverter at two frequencies. The switching frequency during ignition is in the 1-10kHz range, resulting in an appreciable size reduction of charge-pump capacitor C9 of the voltage doubler. For example, if the capacitance of capacitor C10 is in the range from 100nF to 470nF, the capacitance of capacitor C9 is in the range of 10nF to 47nF.

The micro-controller generates the control signal, V_{bri_drv}, which sets the appropriate switching frequency of the power inverter during each operating state. The proposed igniter scheme uses only one large storage capacitor and reduces the overall size of the igniter without lowering the voltage pulse amplitude as compared to previous approaches. Furthermore, the turn-on instant of Q6 and Q7 is synchronized with the firing instant of spark gap SG so that the maximum voltage, which is equal to the sum of inverter voltage V_{BA} and secondary winding voltage V_{HV} of transformer XFMR II, is always applied across the lamp. Finally, only two leads are necessary for connecting the inverter to the igniter, simplifying ballast packaging. It should be noted that the voltage multiplier, used to boost the output voltage of the flyback converter to generate a striking pulse, is not restricted to the voltage doubler shown here, but can be implemented with a voltage tripler, a voltage quadrupler, or any type of voltage multiplier.

III. LAMP IGNITION AND POWER CONTROL

Figure 3 shows a flow chart of the micro-controller-based control of the HID lamp ignition, warm-up, power regulation, fault detection and protection. In this control, the micro-controller starts to monitor scaled input voltage V_{in} via an internal analog-to-digital converter after Q2 is turned on. If the input voltage goes outside the normal operating range (9V - 16V), the micro-controller disables the PWM controller (UC3843) by setting V_{pwr_en} to HIGH so that MOSFET switch Q1 remains off and no power is delivered to the output. If the input voltage is within the normal operating range, the micro-controller enables the PWM controller by resetting V_{pwr_en} to LOW and the PWM controller outputs a gate drive signal to switch Q1 so that voltage V_B across capacitor C1 increases. During this phase, the inverter operates with a fixed frequency, e.g., 1kHz or higher, to charge capacitors C9 and C10. When the voltage across capacitor C10 reaches the break-over voltage of spark gap SG, a high voltage pulse is induced and applied across the lamp to initiate the discharge.

It is critical to instantaneously detect the moment of lamp ignition in order to provide a controlled warm-up period and prevent the lamp from extinguishing. The detection of lamp ignition is achieved by sampling scaled lamp voltage V_{lamp} at the output of op-amp IC3 and comparing it to preset thresholds V_{thr1} and V_{thr2}, where $V_{thr2} - 50 > V_{thr1}$. Note that thresholds V_{thr2} and V_{thr1} are separated by 50V in order to prevent false detection of ignition due to noise and sampling error. After power-on, the micro-controller waits until V_{lamp} has reached the preset threshold voltage V_{thr2} and then continues to sample V_{lamp}. If the sampled voltage is lower than the preset voltage V_{thr1}, an ignition is considered to have occurred. However, if the sampled output voltage never increases to V_{thr2}, or never drops to V_{thr1} from V_{thr2}, indicating that there may be a short circuit at the output or a damaged lamp, the micro-controller disables the PWM controller and the main switch Q1 is turned off to ensure safety of both the ballast and the vehicle when these abnormal conditions exist. Another means of detecting lamp ignition is based on the sampled current I_{lamp}, which is obtained by measuring the voltage across resistor R6. Before ignition, the HID lamp exhibits a high impedance and the current that flows through the lamp current-sensing resistor R6 is close to zero. By comparing sampled current I_{lamp} to a reference level (equivalent to 0.3A) ignition of the lamp can also be determined.

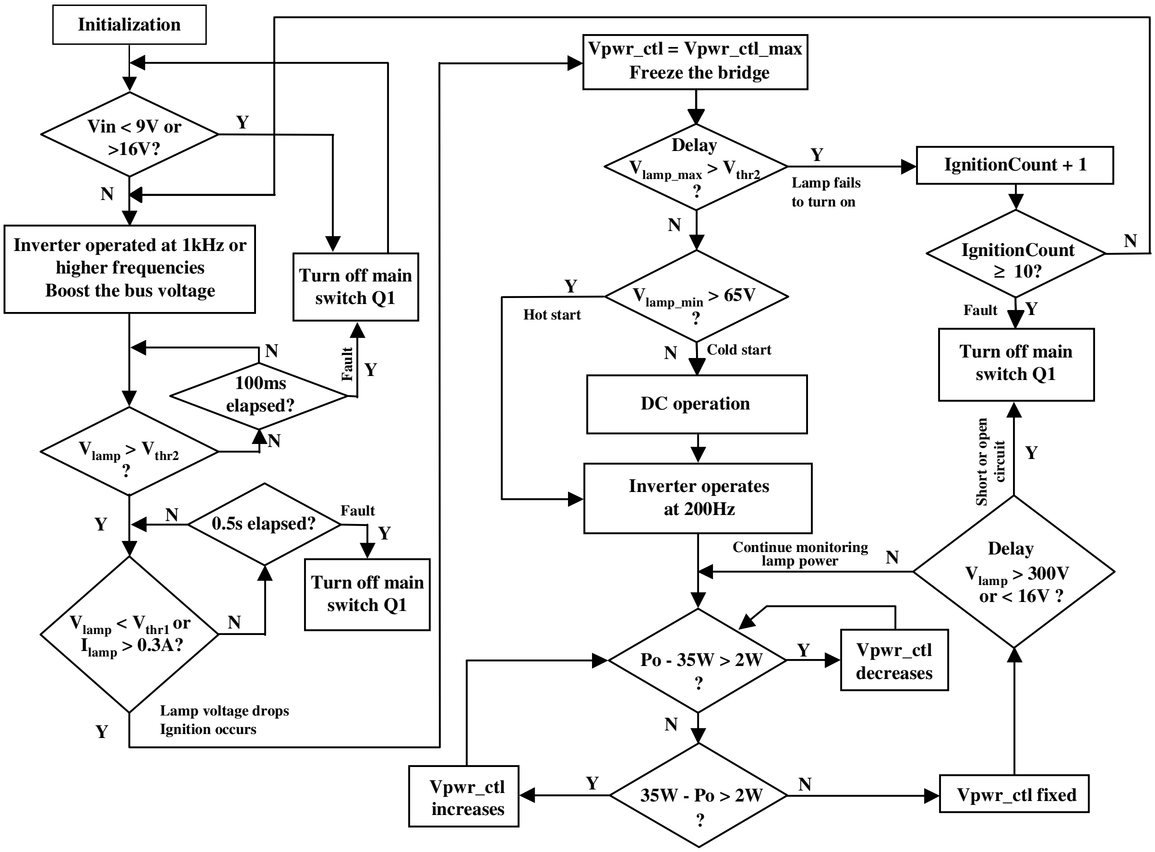


Figure 3. Flow chart of the micro-controller based control of HID lamp ignition sequences, power regulation, and fault detection and protection.

After the detection of lamp ignition, the micro-controller continues to sample the output voltage of the flyback converter. If the output voltage after the ignition rises again it means that the lamp has extinguished and another ignition attempt is needed, until the number of attempts reaches a preset number, e.g. 10, at which point the micro-controller interrupts power delivery to the output.

To sustain the arc after the ignition and complete the turn-on of the lamp, a high-current dc operation, i.e., a period when the state of bridge switches is held constant, is required, especially, for a cold lamp [8][9][10][11]. This dc operation period is typically in the range of 50ms to 200ms. Under dc operation, the electrodes can rapidly reach thermal emission temperature of electrons. If the arc is disturbed by an immediate ac operation following ignition, the ionization of the gas cannot be maintained since the electrodes, especially the one acting as anode at ignition, are not sufficiently warm to emit electrons, and the lamp tends to extinguish.

After successful ignition of the lamp, the micro-controller determines whether the lamp is hot or cold. If the lamp is hot, a long dc operation should be avoided to reduce the chances of excessive power operation of the lamp, which leads to a shortened lamp life. However, if the lamp is not hot enough, a longer dc operation period is required to successfully turn on the lamp and shorten the time to full rated light output. In order to avoid an unnecessarily long dc operation period and high warm-up power, an adaptive control of the dc operation time and warm-up power of the HID lamp is implemented in the control program based on the actual lamp voltage at a predetermined time right after ignition. A colder lamp with lower voltage after ignition requires a longer dc operation time and higher warm-up power. After dc operation, the micro-controller allows the lamp to enter ac operation, and adjusts the power control signal until the lamp power reaches the nominal power, e.g., 35W.

Since during normal operation of the HID lamp the battery voltage and the lamp impedance may vary, the power control signal needs to ensure that the lamp operates with constant power, and therefore, constant lumens. As a result, the micro-controller continuously samples the lamp current and lamp voltage and calculates the actual power of the lamp. If the difference between the actual lamp power and the nominal lamp power is more than a preset value, e.g., 2W, the power control signal is changed to bring the lamp power into its required range. However if the absolute value of the difference between the actual lamp power and the nominal power is less than the preset value, the power control signal stays unchanged.

The proposed control scheme also includes protection against an output short-circuit and open-lamp conditions during both start-up and normal operation based on the continuous monitoring of the lamp voltage after turn-on. If the detected lamp voltage is out of the normal operating voltage range, e.g., > 300V for open-lamp or < 16V for output short-circuit, the micro-controller disables the gate drive of Q1 and pulls the power control signal to zero. As a result, no current flows at the input side and no power is delivered to the output to avoid a catastrophic failure.

IV. EXPERIMENTAL RESULTS

An HID lamp ballast prototype with an igniter employing a voltage doubler driven by a dual-frequency inverter was built to verify the proposed control scheme. Figure 4 shows the photograph of the ballast for a D2S HID lamp. The input voltage of the ballast is 9V-16V, and the lamp nominal power is 35W. The parameters for major components are listed in Table I.

Table I
LIST OF MAIN COMPONENTS

XFMR I	Flyback transformer PQ20/20, Np : Ns = 6 : 36, Lp = 5uH
Q1	2× STP40NF10, 100V, 50A
Q2	FDP038AN06A0, 60V, 80A
D1	MUR860, 600V, 8A
C1	5× 0.1μF, 630V
C2	4.7μF, 400V
Q5-Q8	STP10NK60Z, 600V, 10A
XFMR II	High voltage transformer Np : Ns = 3 : 200
C9	22nF, 630V
C10	330nF, 630V

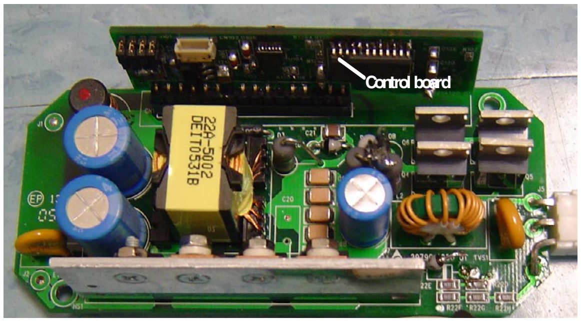
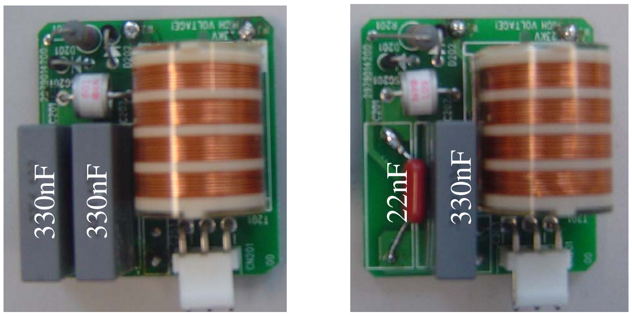


Figure 4. Photograph of the proposed HID lamp ballast.

Igniter high-voltage transformer XFMR II utilizes a rod core (R6.0mm×20mm). Its primary winding was made using copper foil to improve the coupling between the primary and secondary windings [12] whereas a 4-slot bobbin was used to minimize the winding capacitance.

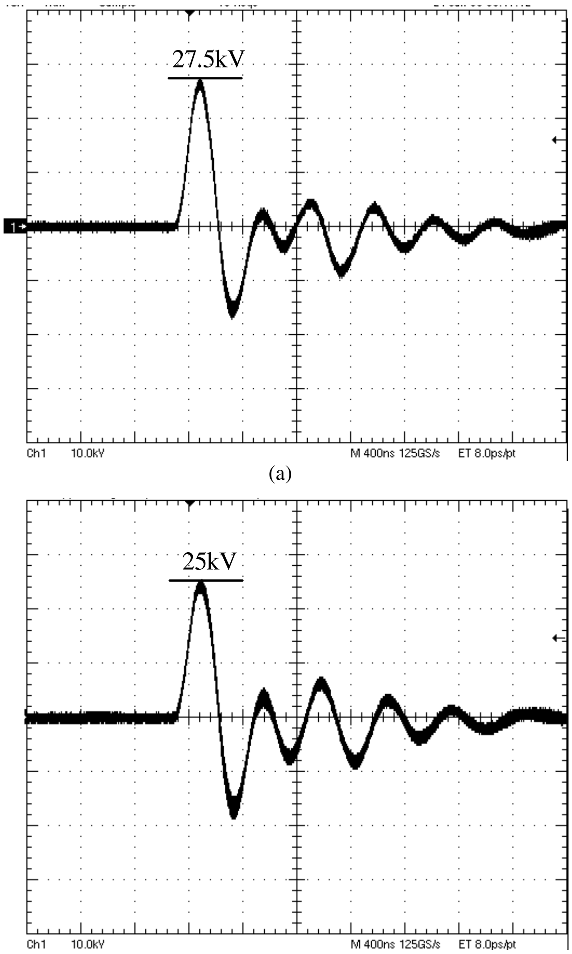
Figure 5 shows a comparison of fixed-frequency and dual-frequency igniters. One 330nF capacitor in the fixed-frequency voltage doubler shown in Fig. 5 (a) is replaced by a 22nF capacitor in the dual-frequency doubler shown in Fig. 5 (b). As a result, the dual-frequency driving scheme for the igniter results in both space saving and cost reduction. The waveform of the open-circuit voltage pulse of the proposed igniter implemented with 22nF for C9 and 330nF for C10 and with a 600V spark gap under open circuit test is shown in Fig. 6 (a). It exhibits a peak voltage of 27.5kV with a width of about 320ns whereas the conventional fixed-frequency igniter using two 330nF capacitors has a peak voltage of 25kV as shown in Fig. 6 (b).

Figure 7 shows the measured waveforms of the lamp current and lamp voltage at start-up and steady state operation. It can be seen that the inverter operates at much higher frequency before the ignition of the lamp than 200Hz during steady state operation.



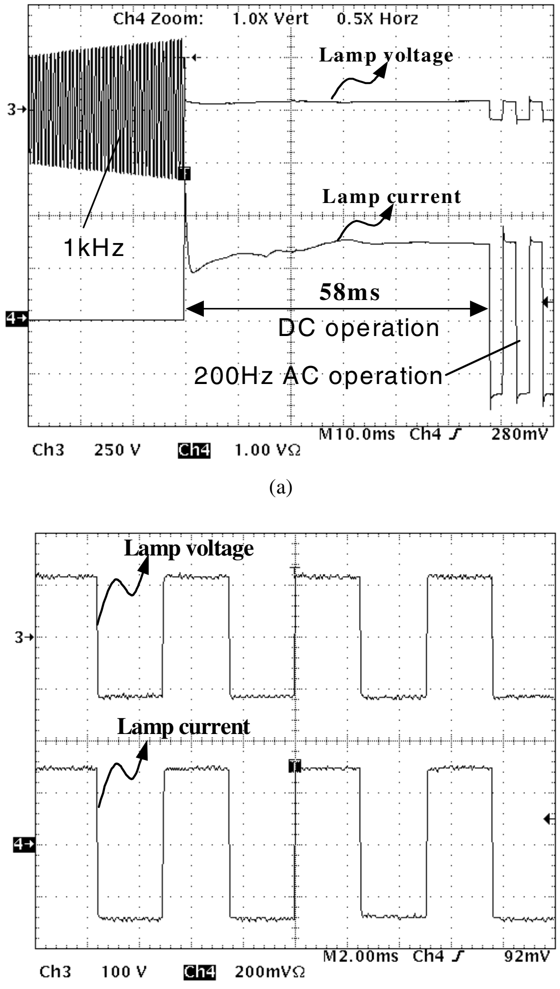
(a) (b)

Figure 5. Photos of igniters: (a) conventional fixed-frequency igniter, and (b) proposed dual-frequency igniter.



(b)

Figure 6. Induced open-circuit test voltage pulses: (a) the proposed igniter, and (b) conventional igniter. Voltage scale: 10kV/div, time scale: 400ns/div.



(a)

(b)

Figure 7 Measured lamp current and voltage waveforms: (a) at start-up (time scale: 10ms/div), and (b) at steady state operation (time scale: 2ms/div).

V. CONCLUSION

A new control scheme for the automotive high-intensity-discharge (HID) lamp ballast with an igniter driven by a dual-frequency inverter is proposed. The igniter is implemented with a voltage doubler driven by an inverter whose frequency before lamp ignition is in the range of 1-10kHz, resulting in a much more compact igniter and higher voltage pulse amplitude compared with its conventional counterpart. A micro-controller-based system features software-based detection of lamp ignition, lamp status, an adaptive dc operation time, warm-up power control, fault detection, and protection. The performance of the proposed control scheme has been verified on a 35-W experimental HID lamp ballast.

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