Paper

Novel Electronic Ballast for Automotive HID Lamps

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ABSTRACT

Simplifying the composition of the automotive HID lamp electronic ballast has been considered. This paper describes the novel electronic ballast that is composed of a DC/DC converter, a capacitor connected to a lamp in series, a switch (S_3) connected to the capacitor in parallel, a switch (S_2) placed between the output terminals of the DC/DC converter and also connected in parallel to the lamp and the capacitor in series, and an igniter. All MOSFETs (S_1 in the DC/DC converter, S_2 and S_3) in the ballast are operated on the common voltage position (GND) of the circuit. The DC/DC converter is operated intermittently and the operation of S_2 synchronizes with the operation of it to supply the lamp with an alternate square wave voltage. Operating an automotive HID lamp succeeded using the novel ballast and by settling some issues below.

1) The occurrence of the power loss when S_2 is turned on.
2) The occurrence of extinction of gas discharge.

This paper describes how the loss can be decreased if a part of the energy stored in the output capacitor of the DC/DC converter is used to operate the lamp before S_2 is turned on. It also describes how an inductor and a capacitor were added to the proposed electronic ballast to raise the lamp voltage in order to prevent the current from disappearing.

KEYWORDS: HID lamp, electronic ballast, automobile, circuit, low cost, downsizing

1. Introduction

High Intensity Discharge (HID) lamps have the excellent advantages of high brightness and low consumption of electricity. Recently, HID-type headlights have spread rapidly. Consumers have been attracted by HID-type headlights, which are superior to conventional halogen ones[1]. Unfortunately, the HID headlight system has the disadvantage of requiring electronic ballast. Space is also required for the electronic ballast, and the cost is higher than that of halogen lights. We have studied downsizing and decreasing the cost of electronic ballast for automotive HID lamps.

The conventional automotive HID lamp ballast comprises three parts[2]: a DC/DC converter to boost the battery voltage up to the value required by the lamp, a DC/AC full bridge inverter that converts the DC voltage to a square wave and an igniter that generates a high voltage pulse (in the range of 15k-25kV) to ignite the lamp. The process of lighting a HID lamp consists of three phases which are ignition, a DC phase and an AC phase. In the DC phase the electronic ballast supplies the lamp with the same polarity current for 20-40 milli-seconds to stabilize the gas discharge voltage. In the AC phase the electronic ballast supplies the lamp with a 250–650Hz alternating square wave current. In the early AC phase the electronic ballast supplies the lamp with about 70W, which is twice as much as normal, to ensure a quick rise to normal light intensity. Finally, the electronic ballast supplies the lamp with the normal power of 35W. The lamp voltage is about 85V and the lamp current is about 0.41A when the lamp is operated with the normal power.

To remedy the disadvantages, space and cost, of electronic ballast for automotive HID lamps, a MHz electronic ballast that does not need a DC/DC converter[3], and an electronic ballast composed of a resonant DC/DC converter and a square-wave half bridge inverter[4] have been presented. We here suggest a novel HID headlamp ballast simplified by using a different method from these to settle these problems. The novel electronic ballast comprises a DC/DC converter, a capacitor connected to a lamp in series, a switch connected to the capacitor in parallel, a switch placed between the output terminals of the DC/DC converter and also connected in parallel to the lamp and the capacitor in series, and an igniter. It supplies the lamp with alternating square wave current by controlling the DC/DC converter and the switch placed between the output terminals of the DC/DC converter. All MOSFETs in it are operated on the common voltage position (GND) of the circuit. We succeeded in operating an automotive HID lamp using the novel electronic ballast.

First, this paper describes the composition and operation of the novel electronic ballast. Secondly, it describes (a) the occurrence of power loss because of simplifying the electronic ballast, (b) the occurrence of extinction of gas discharge and a consideration of them. Finally, it shows the experimental waveforms of an automotive HID lamp driven by the novel electronic ballast.

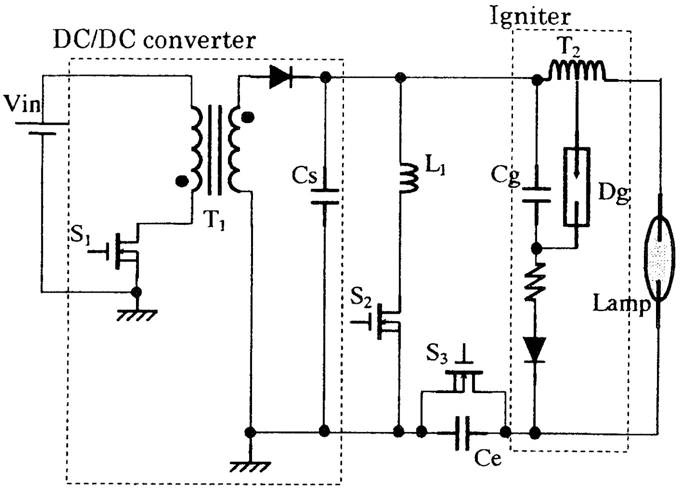

Fig. 1. Schematic circuit of the proposed electronic ballast for automotive HID lamps.

2. Consideration of the Novel Electronic Ballast

2.1 The Novel Method for Operating a HID Lamp

In the novel electronic ballast the number of components is decreased and it can operate an automotive HID lamp using the same current waveform as the conventional one. We decided to decrease the number of MOSFETs in the inverter circuit and to drive all of them on the common voltage position (GND) in the circuit to reduce the cost of the electronic ballast and to simplify its structure. Conventional electronic ballast requires insulated driving devices (transformers or HVICs) to drive MOSFETs on the floating position from GND.

A schematic circuit of the proposed electronic ballast is shown in Figure 1. The number of MOSFETs in the conventional electronic ballast with a full bridge inverter is five. The number of ones in the proposed electronic ballast is three (S_1, S_2, S_3). The DC/DC converter is composed of the MOSFET S_1, the transformer T_1, the diode and the capacitor Cs. The igniter is composed of the transformer T_2, the capacitor Cg, the gap-switch Dg, the resistor and the diode. The MOSFET S_2 works to change the polarity of the voltage supplied to the lamp. The lamp is operated with an alternate square wave voltage because the DC/DC converter works intermittently and the operation of S_2 synchronizes with the operation of it. The electrolytic capacitor Ce supplies stored energy to the lamp. The MOSFET S_3 works to reset the charge stored in Ce and to control the energy supplied to the lamp during the DC phase. The energy depends on the period for which it turns on.

The operation of the proposed electronic ballast is now described. Figure 2 shows the current waveform flowing through the lamp, the voltage waveform supplied to the lamp, the voltage waveform across Ce and the gate signals of S_1, S_2 and S_3. In the standby period, S_2 is turned off, S_3 is turned on and the gate signal of S_1 is the continuous pulses of a frequency of 100kHz. The voltage across capacitors Cs and Cg rises steadily up to approximately

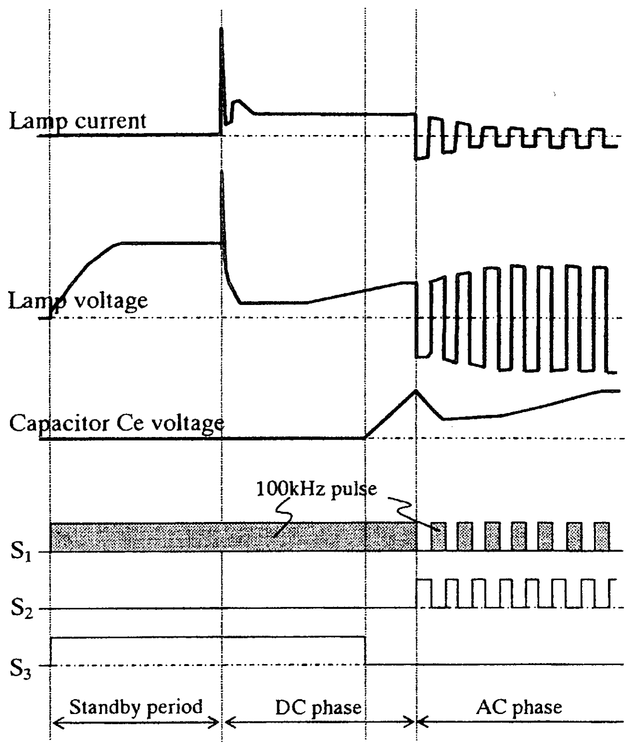

Fig. 2. Timing chart showing the waveforms of the signals of the MOSFETs S_1, S_2 and S_3, the lamp current, the lamp voltage and the capacitor Ce voltage.

450V. When the voltage across capacitor Cg reaches 450V, the gap switch Dg is brought into conduction, a large current flows through the primary winding of the transformer T_2 and a high voltage of about 20kV appears at the secondary winding of T_2. Consequently, the lamp starts to discharge.

In the early DC phase, the states of the switches are the same as those in the standby period (S_1 works, S_2 turns off and S_3 turns on) and the energy is fed to the lamp for 20-40 milli-seconds. After the ballast supplies a predetermined amount of energy to the lamp, S_3 is turned off. Then capacitor Ce is charged up in order to supply a negative current in the AC phase while the lamp is fed energy.

After the voltage of capacitor Ce reaches a predetermined value, the DC phase comes to an end and the AC phase starts. In the AC phase, when the ballast supplies negative current to the lamp, S_3 and S_1 are turned off (the DC/DC converter stops) and S_2 is turned on. The current flows from the charged capacitor Ce to the lamp. When the ballast supplies positive current to the lamp, S_2 and S_3 are turned off and the DC/DC converter feeds current to the lamp (A series of pulses is supplied to the gate of S_1). The ballast controls the electric power supplied the lamp and keeps it at 35W by regulating the on-duty of the continuous pulses supplied to the gate of S_1.

2.2 Consideration of the Power Losses When the State of the Inverter Switch Changes from Off to On

The energy stored in capacitor Cs is consumed at MOSFET S_2 every time the circuit is turned on because the proposed electronic ballast does not have any switches between S_2 and Cs, and the resonant frequency of L_1 and Cs is enough high compared to the frequency of operating S_2. The energy loss can be decreased if the capacitance of capacitor Cs is lowered, but the voltage and current ripples caused by the operation of the DC/DC converter are increased. The loss can also be reduced if a part of the energy stored in Cs is used to light the lamp before S_2 is turned on. The relationship between the switching loss and the capacitance of capacitor Cs when using a part of the energy to light the lamp is now described.

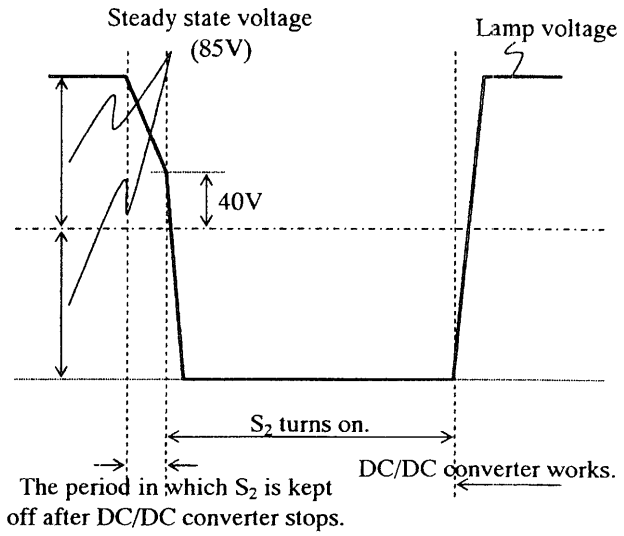

Fig. 3. Waveform of the lamp voltage when a part of the energy stored in Cs is used to light a lamp.

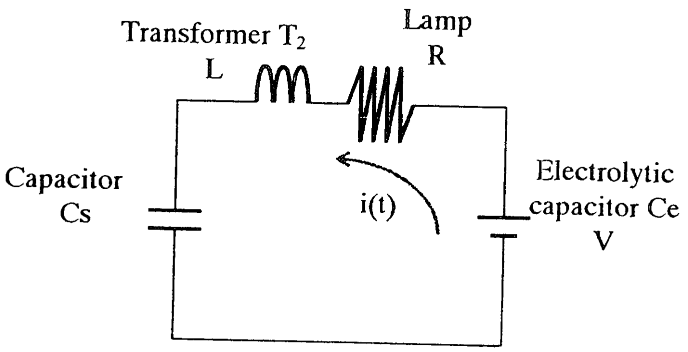

Fig. 4. Simplified equivalent circuit of the proposed electronic ballast in the period in which the MOSFET S_2 is kept off after the DC/DC converter stops in the AC phase.

Consider the calculation of the loss. The loss occurs when the MOSFET S_2 is turned on, after the voltage of the lamp goes down from a steady state voltage (85V) to 40V during the period in which S_2 is kept off after the DC/DC converter stops (Figure 3). The lamp current reaches to about half of a steady state current when the lamp voltage is 40V. We determined that the point at which S_2 turns on is enough high for the lamp current to keep flowing. Figure 4 shows a simplified equivalent circuit of the proposed ballast in this period. The electrolytic capacitor Ce is the same as the DC voltage source V because the capacitance of Ce is significantly larger than that of Cs. The inductor L is the secondary winding of the transformer T_2 and the resistance is the impedance of the lamp.

The waveforms of voltage and current are damped oscillation when the capacitance of capacitor Cs is small and they are over damping when the capacitance of Cs is large. The voltage $V_c(t)$ of Cs and the voltage $V_r(t)$ of R (lamp) can be found by the equations shown below. These equations were easily reached by calculating the differential equations of the circuit shown in Figure 4.

Condition of damped oscillation:

$$V_c(t) = \frac{1}{C} e^{\alpha t}(A\cos\beta t + B\sin\beta t) + V \quad \cdots (1)$$

$$V_r(t) = R e^{\alpha t}\{(\alpha A + \beta B)\cos\beta t + (\alpha B - \beta A)\sin\beta \quad \cdots (2)$$

$$\alpha = -\frac{R}{2L} \quad \beta = \frac{\sqrt{\frac{4L}{C} - R^2}}{2L} \quad A = C(V_0 - V) \quad B = \frac{I_0 - \alpha A}{\beta}$$

V_0: Initial voltage of Cs I_0: Initial current in the circuit

Condition of over damping:

$$V_c(t) = \frac{1}{C}(K_1 e^{\alpha_1 t} + K_2 e^{\alpha_2 t}) + V \quad \cdots (3)$$

$$V_r(t) = R(K_1\alpha_1 e^{\alpha_1 t} + K_2\alpha_2 e^{\alpha_2 t}) \quad \cdots (4)$$

$$\alpha_1 = \frac{-R + \sqrt{R^2 - \frac{4L}{C}}}{2L} \quad \alpha_2 = \frac{-R - \sqrt{R^2 - \frac{4L}{C}}}{2L}$$

$$K_1 = C(V_0 - V) - K_2 \quad K_2 = \frac{I_0 - \alpha_1 C(V_0 - V)}{\alpha_2 - \alpha_1}$$

Figure 5 shows $V_c(t)$ and $V_r(t)$ calculated using the equations shown above. The inductance of L was 2.5 mH and the resistance of R was 210 Ω which resulted in an 85V lamp voltage and a 0.41A current in steady state operation. The initial voltage of Cs was 170 V, the voltage of capacitor Ce was 85 V, and the initial current was 0.41A. The values of the capacitance of Cs were 0.1 μF, 0.2 μF, 0.4 μF and 0.68 μF. Figure 5 makes us find the voltage (V_c*) of Cs at the time when the voltage of the lamp dropped from the steady state voltage (85V) to 40V. The loss (P_{loss}) was calculated using Equation (5).

$$P_{loss} = \frac{1}{2} C V_c^2 f \qquad (5)$$

f: Frequency

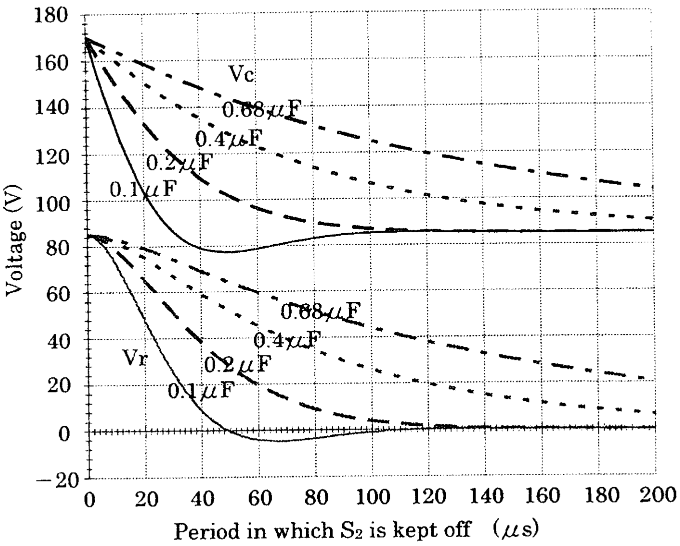

Fig. 5. V_c across Cs and V_r across R (lamp) as a function of the period in which S_2 is kept off for different values of the capacitance of Cs. The calculated results of V_c and V_r are shown in this figure. The switch S_2 and the capacitor Cs are placed between the output terminals of the DC/DC converter.

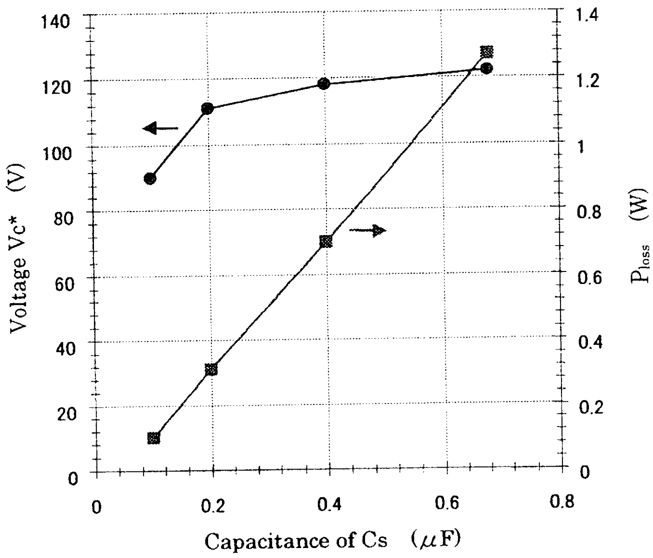

Fig. 6. V_c* and P_{loss} as a function of the capacitance of Cs. The capacitor Cs is placed between the output terminals of the DC/DC converter. V_c * is the voltage of Cs when the voltage of the lamp drops from the steady state voltage (85V) to 40V. P_{loss} is the loss occurring at the MOSFET S_2 when it is turned on.

In Figure 6, V_c and P_{loss} are shown as a function of the capacitance of Cs. The frequency (f) was 250Hz. The figure indicates that a capacitor of 0.4 μF can be chosen if a loss which is 2% of the lamp consumption power is permitted in this electronic ballast. The lamp current ripple, which is caused by operation of the DC/DC converter, becomes larger as the capacitance of Cs becomes smaller. The current ripple could cause the problem of acoustic resonance[5] if it was large. However, this problem can be disregarded because the inductance of the transformer T_2 is large enough to diminish the current ripple of the lamp. As the result of our experiment, in the steady state operation the current ripple was 16mAp-p when the capacitance of Cs was 0.1 μF and it was 8mAp-p when the capacitance was 0.2 μF (T_2=2.5 mH).

2.3 Consideration of Extinction of Gas Discharge Immediately after DC Phase

When an automotive HID lamp that had not been lit for several minutes was operated (cold start) by the proposed electronic ballast, a lack of current (the partial extinction of gas discharge) was frequently observed in the early AC phase. It is feared that this lack of current causes the lighting failure. It occurs when the energy is supplied from the electrolytic capacitor Ce to the lamp. The conventional electronic ballast, which includes a full bridge inverter, is able to raise enough voltage to supply the lamp to prevent the current from disappearing because the DC/DC converter increases the voltage until the current has grown sufficiently.

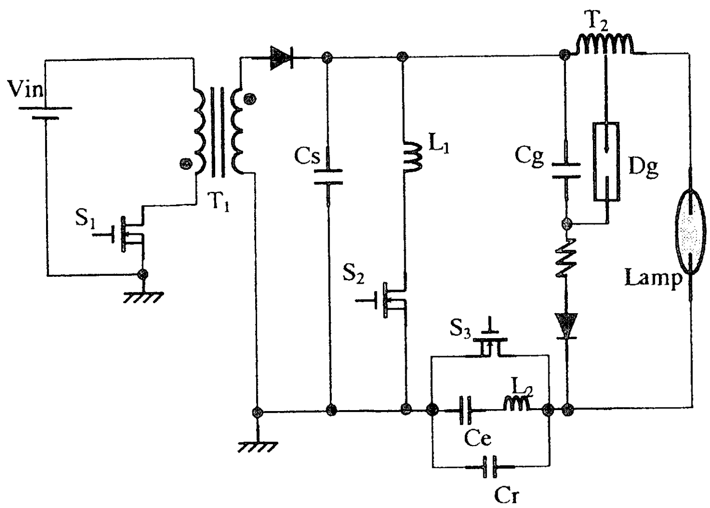

Fig. 7. Proposed electronic ballast to which the components (Cr and L_2) are added to raise the voltage. The inductor L_2 is connected with the capacitor Ce in series. The capacitor Cr is connected with the MOSFET S_3 in parallel.

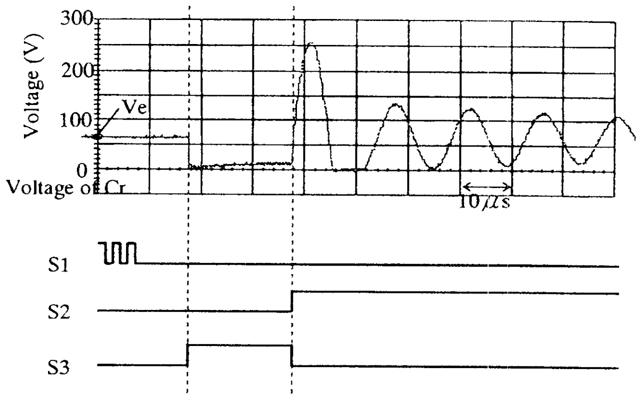

Fig. 8. Waveforms of the voltage of the capacitor Cr and the gate signals of the MOSFETs S_1, S_2 and S_3, when the polarity of the current is changed (from the positive to the negative), in the proposed electronic ballast to which the raising voltage function is added.

The inductor L_2 and the film capacitor Cr were added to the proposed electronic ballast in order to resolve this lack of the current. Figure 7 shows the proposed electronic ballast to which these components are added. Here, Cr is connected with MOSFET S_3 in parallel and L_2 is connected to electrolytic capacitor Ce in series. Together they work to raise the lamp voltage when MOSFET S_2 is turned on. The waveforms of the voltage (measured value) of capacitor Cr and the gate signals of MOSFETs S_1, S_2 and S_3 are shown in Figure 8 when the polarity of the current is changed from the positive to the negative (when the energy source is changed from the DC/DC converter to Ce).The operation of raising the voltage is now described below. First, S_1 is turned off and the DC/DC converter stops. Secondly, S_3 is turned on, the charge stored in Cr is discharged and the portion of the energy stored in Ce transfers to L_2. Thirdly, S_3 is turned off and S_2 is turned on. The Cr is charged by the stored energy of Ce and L_2 and the voltage of Cr (between the electrodes of the lamp) rises above the voltage of Ce. The amplitude of the voltage depends on the period in which S_3 turns on. S_3 turns off when the current through L_2 reaches to 5A. The time is about 10 μs. Figure 8 shows that the voltage of Cr rises from 65V to 250V by operating the added components. This operation is effective to make the current keep flowing and is need in the early AC phase.

We investigated the necessary voltage (V_e) of Ce and the amount of charge (Q_{dc}) supplied to the lamp in the DC phase using the proposed electronic ballast equipped with the function of raising the lamp voltage as described above. Q_{dc} and the lighting failure are correlated. The more an electronic ballast supplies Q_{dc} to a lamp, the less the number of the lighting failure in the total number of trial times is. However, a HID lamp manufacturer does not recommend too much Q_{dc} to be fed to a lamp because the lifetime of the lamp gets shorter. We observed the lamp current when the stage changed from the DC phase to the AC phase each trial time, and counted the number of times a failure of the lamp current occurred. The

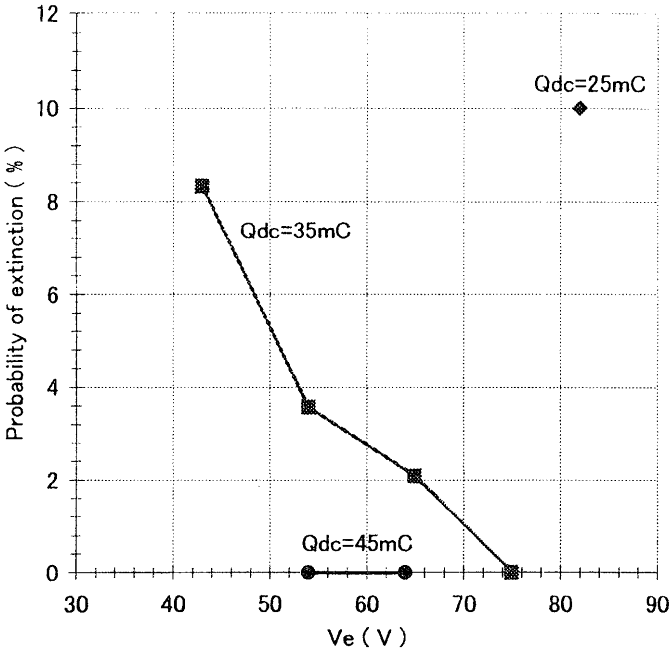

Fig. 9. Relationship between the probability of the occurrence of a lack of lamp current and V_e for different values of Q_{dc}. V_e is the voltage of the electrolytic capacitor Ce at the end of the DC phase. Q_{dc}. is the amount of electric charge supplied to the lamp during the DC phase.

relationship between the probability of the occurrence of a lack of lamp current and V_e for different values of Q_{dc} is shown in Figure 9. The number of times a lack of the lamp current occurred divided by the number of the tests gave the probability for each condition. We used an automotive HID lamp whose operating time had exceeded its designed lifetime. The figure indicates that Ve should be above 75 V when Q_{dc} is 35mC and above 54V when Q_{dc} is 45mC in order to prevent the lamp current from disappearing. We knew that we could choose a lower V_e if we chose a larger Q_{dc}.

3. Lighting an Automotive HID Lamp by the proposed Electronic Ballast

We operated an automotive HID lamp by controlling input power using the proposed electronic ballast with the function of raising the voltage. We used the system for lighting the HID lamp shown in Figure 10. The electronic ballast was controlled by a personal computer (PC) through the control circuit. The amount of charge supplied to the lamp during the DC phase was 35mC. The frequency at which a lamp was operated was approximately 500Hz. The capacitance of the capacitor Cs was 0.1 μF, the inductance of the secondary winding of the transformer T_2 was about 2.5mH and the capacitance of the electrolytic capacitor Ce was 100 μF. The operation of raising the voltage when the polarity of the current changed from positive to negative was made from the primary pulse to 16th pulse (for about 32 ms) in the AC phase. With the PC observing the lamp voltage, the input power was decreased gradually from 70W to 35W by

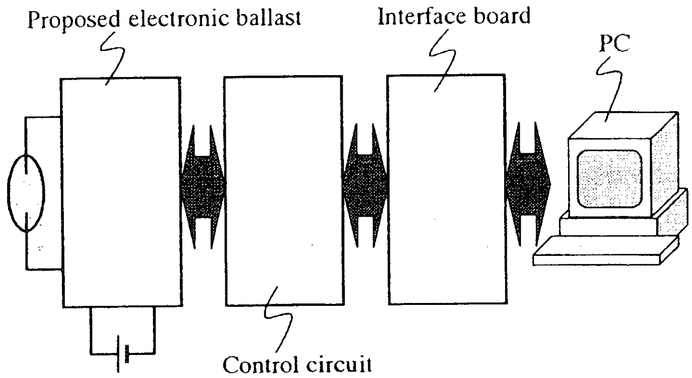

Fig. 10. Schematic of the system for operating an automotive HID lamp. The electronic ballast was controlled by a personal computer (PC) through the control circuit. The proposed electronic ballast includes a circuit for raising the lamp voltage.

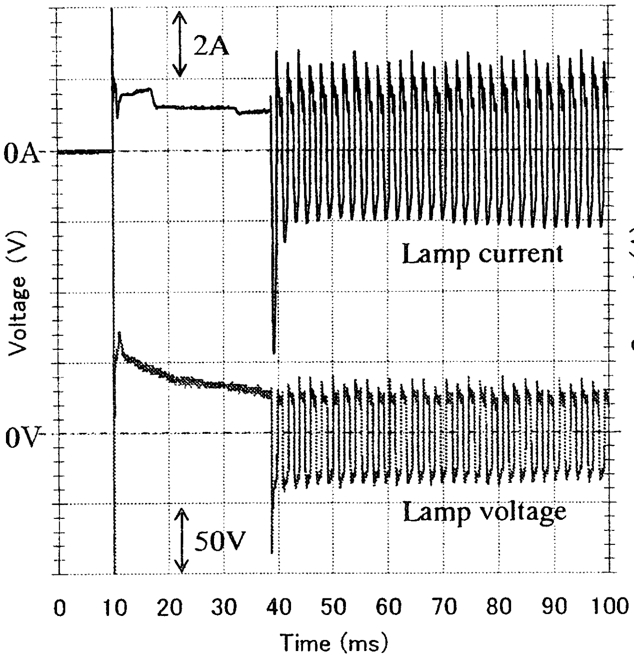

Fig. 11. Waveforms of the lamp current and voltage while the state of the lamp changes from breakdown to the AC phase.

regulating the on-duty of the continuous pulses supplied to the gate of the MOSFET S_1. It took about 30s to reach the steady state (35W).

Figure 11 shows the waveforms of the lamp current and voltage while the state of the lamp changes from breakdown to the AC phase. Figure 12 shows the waveforms of the lamp current and voltage in the steady state operation. We were sure that the proposed electronic ballast was able to operate an automotive HID lamp.

4. Conclusions

We have presented a novel electronic ballast for automotive HID lamps to reduce the cost of the system closer to that of the conventional halogen type headlight

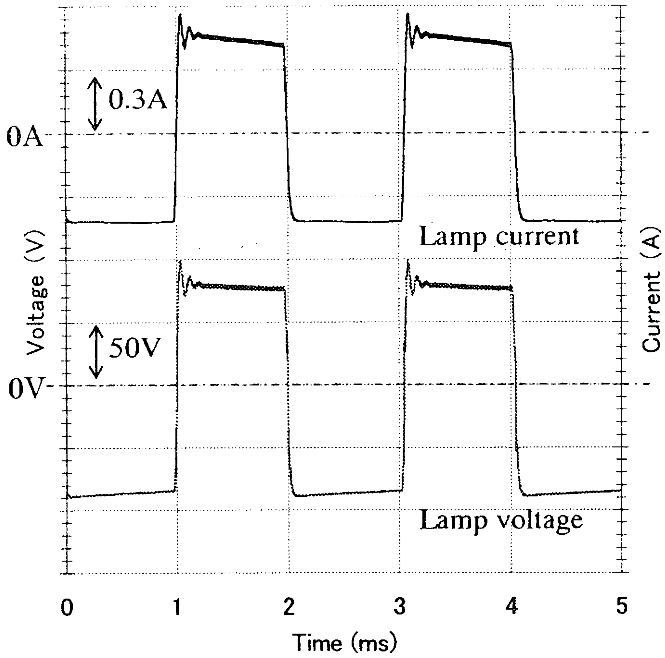

Fig. 12. Waveforms of the lamp current and voltage in the steady state operation (35 W operation).

system. The proposed electronic ballast has the following features.

1) The circuit comprising a DC/DC converter, a single switch and a capacitor supplies the lamp with alternate square wave current.
2) All MOSFETs in the electronic ballast are operated on the common voltage position (GND) of the circuit.

The proposed electronic ballast had the issues shown below.

1) The occurrence of the power loss when the switch (S_2) placed between the output terminals of the DC/DC converter is turned on.
2) The occurrence of a lack of the lamp current in the early AC phase.

We described how the loss can be decreased if a part of the energy stored in the capacitor is used to light the lamp before S_2 is turned on. Moreover, we also described how a capacitor of 0.4 μF can be chosen if loss which is 2% of the lamp consumption power is permitted in this electronic ballast. To this end an inductor and a capacitor were added to the proposed electronic ballast to raise the lamp voltage in the early AC phase in order to prevent the current from disappearing.

Moreover, we succeeded in lighting an automotive HID lamp using the proposed electronic ballast which included the added components for raising the lamp voltage. There are three MOSFETs compared with five in a conventional electronic ballast. The proposed electronic ballast does not need insulated driving devices (transformers or HVICs) because all of the MOSFETs can be operated on the common voltage position (GND) of the circuit. This novel electronic ballast will be less expensive than a conventional one.

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