High-Efficiency Ballast for HID Lamp using Soft-Switching Multi-Level Inverter

Baek-Haeng Lee* and Hee-Jun Kim†

Abstract – Soft switching was applied to the multi-level inverter to enhance the performance of the high-intensity discharge (HID) ballast used in vehicle headlights. The electrical properties were investigated and the available modeling of ballast in steady state was calculated using mathematical methods. The result was used in analyzing the power characteristics. The modeling was confirmed by the experiment.

Keywords: HID Lamp, Electronic Ballast, Soft-Switching, Multi-Level Inverter

1. Introduction

The Xenon high-intensity discharge (HID) lamp has more than twice the brightness of other lamps and is an innovation in terms of safety, convenience and approval. Also, as HID products are eco-friendly owing to their long lifespan and high efficiency, they offer the user reduced energy consumption.

But as HID products must meet strict technical requirements regarding their entry into the automobile industry, the development of light bulb technique using gas discharge was required, which led to the development of the very miniaturized gas discharge technology with merely a 4.2-mm interval between electrical poles. This new technique is defined as micro-power xenon lighting. [1-3]

Although the lamp does not make use of a filament, unlike the case of the halogen lamp, it is required to be able to sustain quick start and re-start and to have a stable output under normal condition, which makes the design of the electronic ballast important to control these characteristics.

The HID market is currently expanding, pushing active research on the HID system. However, as the structure and control of ballast is complex, the number of elements in the ballast is increasing, thereby pushing the price of end products higher than ever. The creation and development of highly efficient ballast through proper algorithm and proper circuit technique are therefore urgently needed. [3-4]

This paper tries to interpret the turn-on characteristics of the lamp and the normal condition that satisfies all kinds of performances in lamp lifespan and motor headlamp and, by using a multi-level inverter, to achieve improvements in efficiency and harmonic frequency.

† Corresponding Author: Division of Electrical Engineering and Computer Science, Hanyang University, Korea (hjkim@hanyang.ac.kr)
* Dept. of Electronic, Electrical, Control, and Instrumentation Engineering, Hanyang University, Korea (leebh@katech.re.kr)
Received 10 January, 2007 ; Accepted 27 March, 2007

Table 1. Comparison of characteristics between halogen and HID lamps

	Halogen Lamp	HID Lamp
Light Source	Filament	Arc Discharge
Color Temperature	~ 3,000°K	~ 12,000°K
Lumens/Light Output	700–800 [lm]	3,200–4,000 [lm]
Light Source Watts	55 [W]	35 [W]
Life	300–600 hours	Up to 3,000 hours

2. V-I Turn-on characteristics of HID Ballast

The general operations of the Xenon HID system can be classified as shown in Fig. 1, broken down in proper sections namely during the beginning of discharge, glow discharge through collision, and arc discharge through electron release.

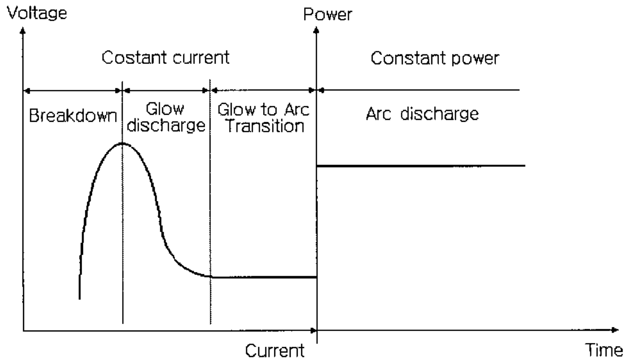


Fig. 1. The power characteristic analysis in all operations of the HID lamp

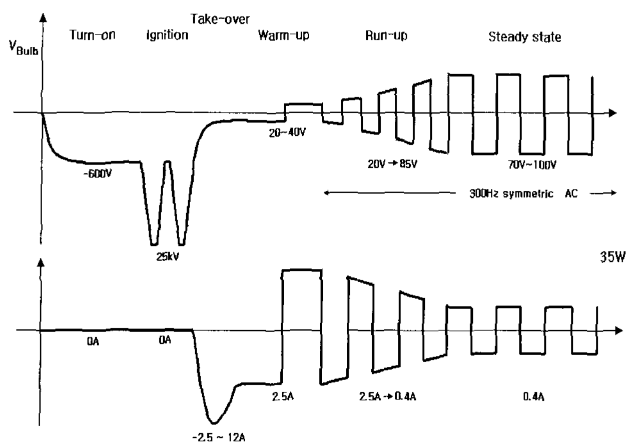


Fig. 2. Lamp V-I profile in all operations

Therefore, the ballast for HID should be composed of the optimum system considering the lighting characteristics of the lamp and the normal condition that satisfies all kinds of performances in terms of lamp lifespan and the requirements of the lamp's function as a motor headlight. Fig. 1 indicates the circuitry requirements by lamp operation mode. [3-4]

Stage 1: Turn-on Stage

During this stage, glow discharge condition is maintained after lamp ignition, in which hundreds of volts should course through the lamp before ignition and if they are not provided sufficiently the lamp turns off upon failure to maintain the glow discharge condition.

Stage 2: Ignition Stage

It breaks the internal isolation condition by being applied to the electrode of the lamp. It requires 20 kV in cold start, 25 kV in hot start. During re-ignition, it is possible to cool down the lamp using natural means to avoid high ignition voltage. It takes more than 10 minutes to cool down the lamp, so it is not appropriate for motor headlights. Therefore, an igniter that can generate more than 25 kV should be applied.

Stage 3: Take-over Stage

It is the current required in the shift from glow discharge condition to arc discharge condition of the lamp after ignition. Without a sufficient current supply, the ignition will fail. Right after arc discharge transformation, the voltage of the lamp is lowered and the lamp sustains arc discharge with the current supplied by the ballast. Until the ballast supplies sufficient current, consistent current from the take-over current circuit should flow to the lamp.

Stage 4: Warm-up Stage

After shifting from glow discharge condition to arc discharge condition, the internal temperature and pressure of the lamp gets higher by the power provided by the ballast. At this point, the lamp voltage and light output increase and reach the normal stage.

The current supplied during this operation section not only decides the warm-up time of the lamp but also the response characteristic of light output.

In the HID ballast, this characteristic serves a very important role and it is necessary to control the lamp power for the specific purpose.

Stage 5: Run-up and Steady-state Stage

Inefficient control lowers the lifespan of the lamp, so under normal conditions, to ensure consistent output, the voltage supplied by the lamp should be controlled by a consistent rating. [1, 5]

3. Multi-level Inverter using the Soft-Switching Method

Mode 1 (T0-T1)

During this mode, switching devices S_1 and S_2 turn on and the output current of the inverter circulates through C_{in1}, L_1, L_2 and L. In the beginning of this mode, more than half of the input voltage is impressed to the inverter output. In this case, the output voltage can be calculated as follows. At the beginning of this mode, the inverter starts switching from zero voltage through zero-voltage switching.

$$I_1(t) = V_{Cin} \times t = \frac{V_{in}}{2} \times t \quad (1)$$

Mode 2 (T1-T2)

During this mode, the only switching device S_2 is turned on and the current circulates from D_{c1} to S_2, L_1, L and L_2. At the beginning of this mode, when switching device S_1 turns off, each of the parasitic capacitances of switching devices S_1 and S_4 located outside the inverter turns on and discharges. Parasitic capacitance C_p is charged by $V_{in}/2$, parasitic capacitance C_p of S_4 is charged by 0, and switching device S_1 is charged through S_2, L_1, L and L_2, C_{in1}.

In this mode, if after the reverse parallel diode S_2 is turned on with the switching device S_2 turned on, the switching device S_4 is turned on, and the three-level DC/DC inverter is turned on during zero-voltage switching.

Mode 3 (T_2-T_3)

In this mode, switching devices S_3 and S_4 turn on and the output current of the inverter circulates through L_1, L_2, and L. At the beginning of this mode, half of the output voltage is impressed to the output of the inverter. The output current of the inverter can be determined through this formula. The current direction in this mode is the opposite

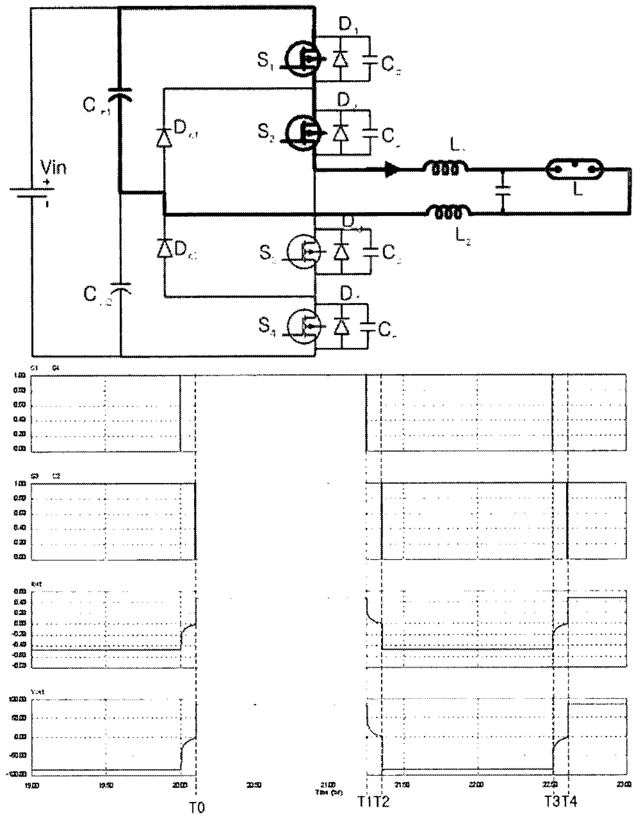


Fig. 3. Operation mode 1 of zero-voltage switching three-level inverter

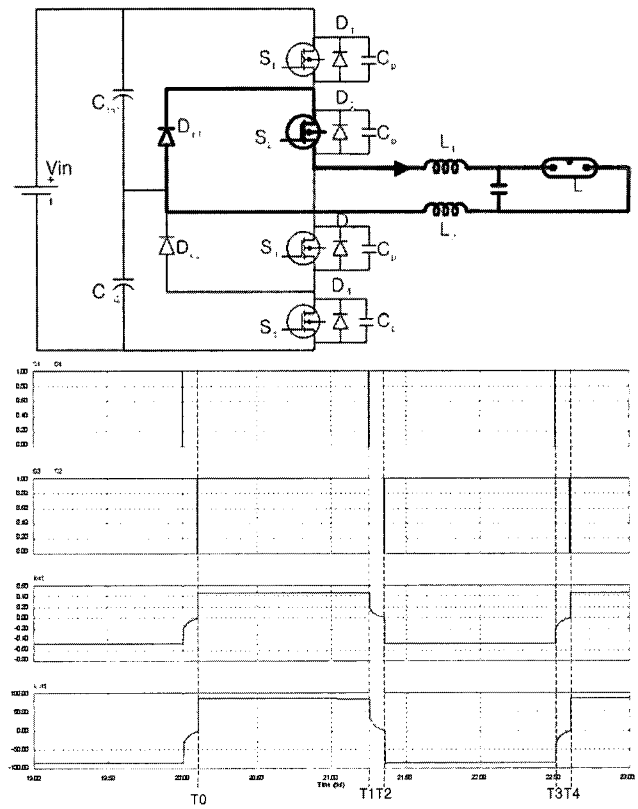


Fig. 4. Operation mode 2 of zero-voltage switching three-level inverter

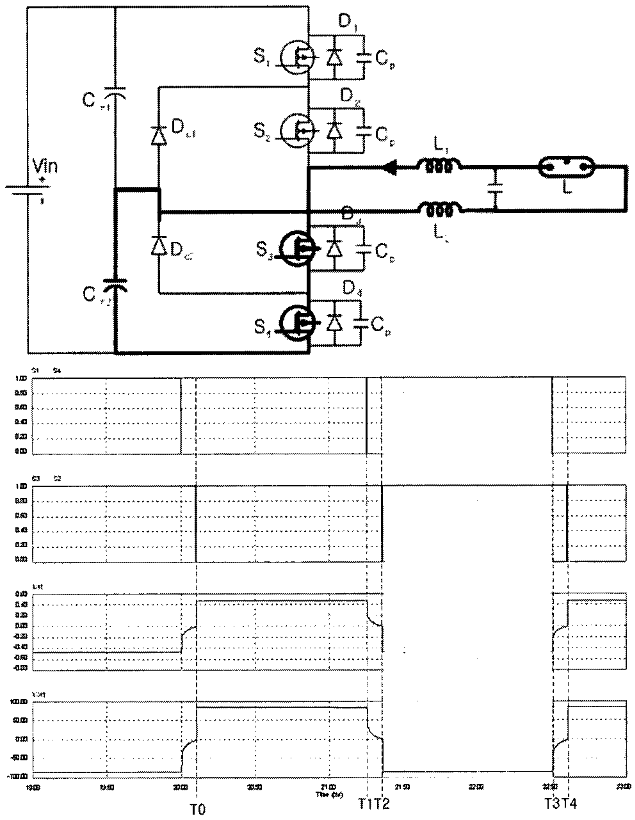


Fig. 5. pation mode 3 of zero-voltage switching three-level inverter

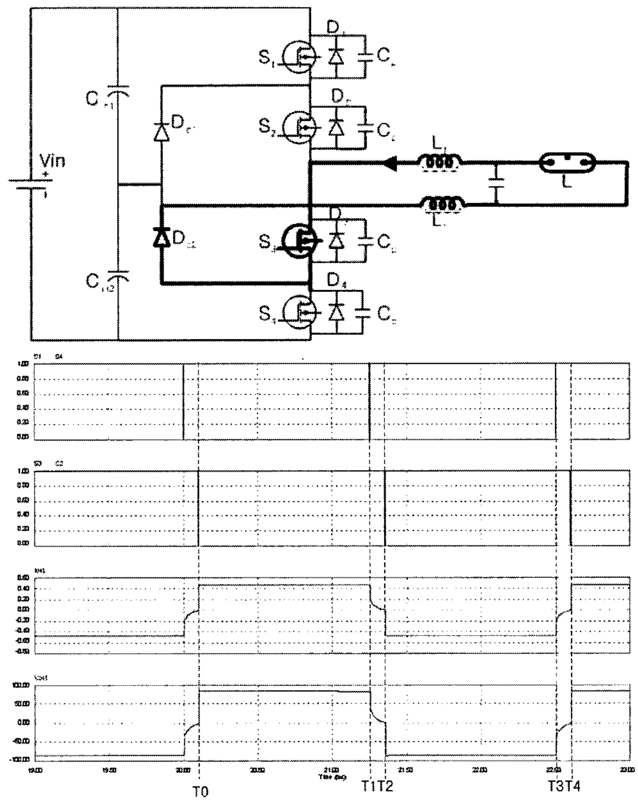


Fig. 6. Operation mode 4 of zero-voltage switching three-level inverter

of the current direction of that of mode 1 and the values are the same.

$$I_1(t) = -V_{Cin} \times t = -\frac{V_{in}}{2} \times t \tag{2}$$

Mode 4 (T_3-T_4)

At the beginning of this mode, only the S_3 switching device is turned on and the current circulates from D_{c2} to S_3, L_1, L, and L_2. When the switching device S_4 is turned off, parasitic capacitances of devices S_1 and S_4 located outside the inverter charge and discharge in this circulation mode, parasitic capacitance C_p is discharged to 0, and switching device S_4 is charged through S_3, L_1, L, L_2, and C_{in1}.

In this mode, if after reverse parallel diode D_1 of the switching device S_1 is turned on with the switching device S_3 turned on, the switching device S_1 is turned on and the three-level DC/DC inverter is turned on during zero-voltage switching.

4. Experimental Results

The HID system for motors using the 35[W] xenon lamp was made and subjected to experimentation. Table 1 shows the built system and Table 2 shows the experiment's parameters.

Table 2. Experimental parameters

Phase	Parameter	Value
Turn on	Open-circuit voltage	360 V (min.)
	Turn-on time	About 30 ms
Ignition	Circuit composition	1st: Flyback type(600V, 1:7 trans.) 2nd: High Volt. trans.(1:43 trans)
	Ignition voltage	25 kV min. (for hot lamp)
	Pulse duration	1 s max
	Repetition rate	20 Hz min
Take over	Take-over current	2.5A (min.) to 12 A
	Take-over time	300 us max.
Warm up	Warm-up current integral	12 (min) ~ 30 (max.) mAs
	Current	2.6 A max.
	Warm-up time	about 10 ms each half wave
Run up	Run-up current	2.6 A max.
	Run-up power	75 W max. until lamp reaches 50 V
	Run-up time	6 ~ 12 s
Steady state	Power	35 W
	Voltage	68 ~ 102 V
	Frequency	250 ~ 10 kHz
	Square wave asymmetry	< 1%
	Lamp current slope	100 mA/us min.

Fig. 7 indicates the wave forms of input and output voltage of the ballast supplied by the power supply. Fig. 8 shows the output wave form of the ballast and Fig. 9 reveals the soft-switching wave form of the three-level inverter.

Fig. 10 indicates the early output current wave form of ballast and Fig. 11 shows the output current wave form of the ballast reaching a stable condition, illustrating the comparative characteristics of the soft-switching three-level inverter method and the full-bridge inverter method.

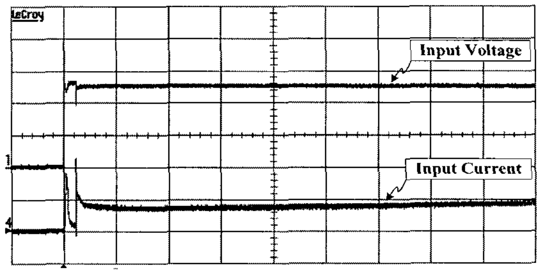


Fig. 7. Input voltage and current waveforms of HID ballast (5V/Div, 10A/Div, 100ms/Div)

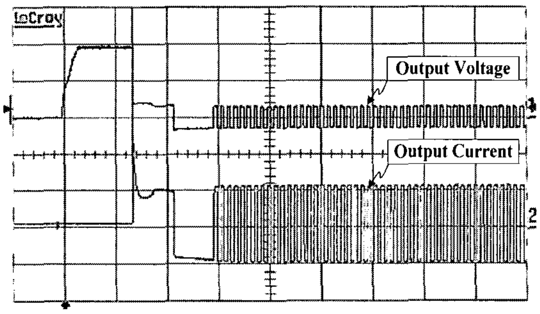


Fig. 8. Output voltage and current waveforms of HID ballast : Run-up (200V/Div, 1A/Div, 20ms/Div)

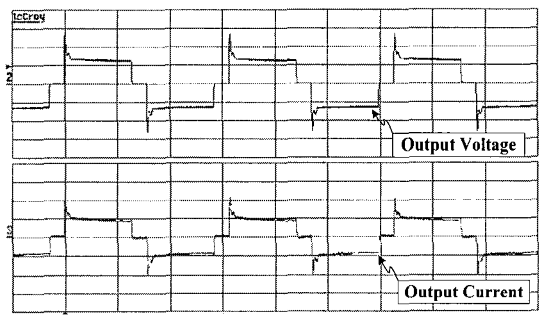
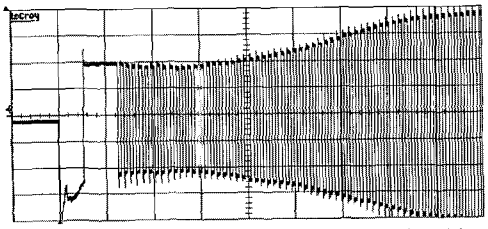


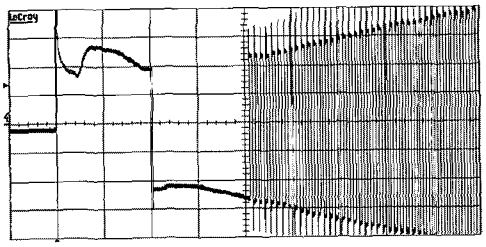
Fig. 9. Soft-switching waveforms of the three-level inverter : Steady state (50V/Div, 0.5A/Div, 1ms/Div)

As you can see in Fig. 11, noise in the output current wave form is reduced distinctively with the soft-switching three-level inverter method. As shown in Table 3, this kind of efficiency improvement is normal.

Fig. 12 shows the HID ballast using the experiment. Fig. 13 reveals the result tested 'TDK EMC Lab' to confirm the noise reduction and the advantage with the three-level inverter method. The limit line is represented by the CE Mark for automobiles prescribed by CE.



(a) Output current of the soft-switching three-level inverter

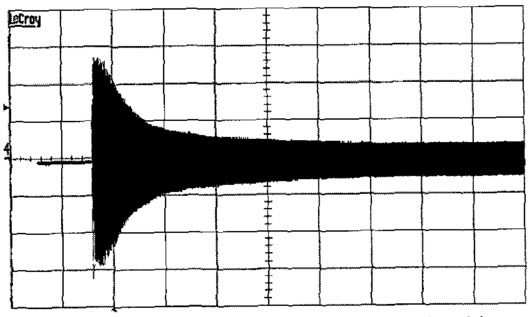


(b) Output current by the full-bridge inverter

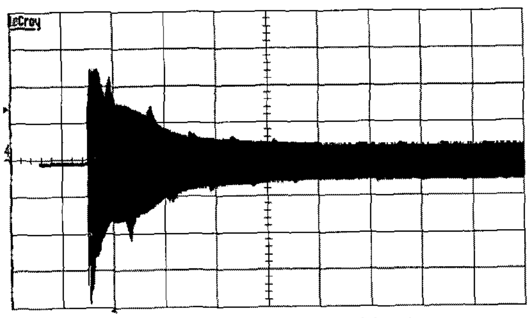
Fig. 10. Output current waveform comparison by inverter type (0.5A/Div, 20ms/Div)

Table 3. Efficiency comparison of inverter-type ballast

	Input voltage	Input current	Input power	Output voltage	Output current	Output power	Efficiency
Three-level Inverter	13.5 [V]	3.11 [A]	42 [W]	80 [V]	0.46 [A]	37 [W]	88 [%]
Full bridge	13.5 [V]	3.52 [A]	47.5 [W]	85 [V]	0.45 [A]	38 [W]	80 [%]



(a) Output current of the soft-switching three-level inverter



(b) Output current of the full-bridge inverter

Fig. 11. Output current waveform comparison by inverter type until reaching a stable state (1A/Div, 5s/Div)

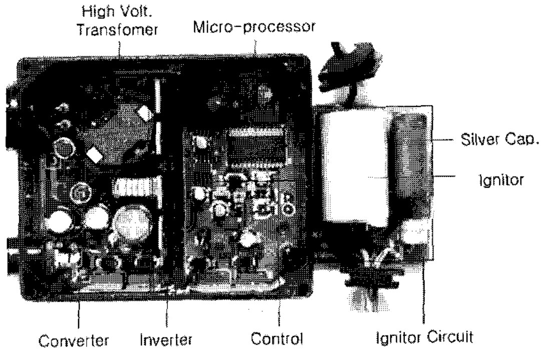
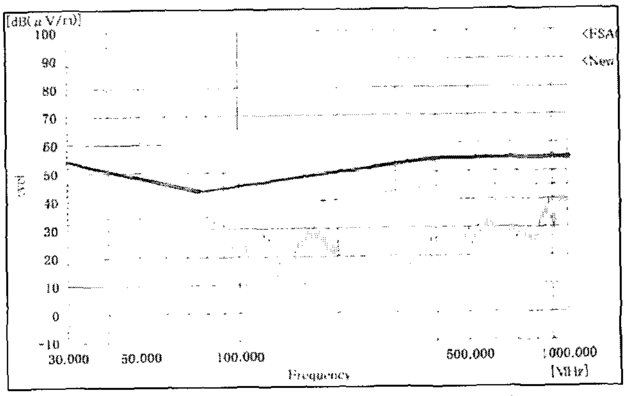
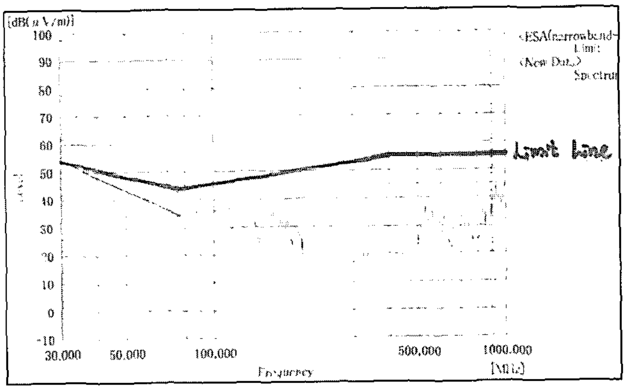


Fig. 12. The prototype HID ballast for experimental setup.



(a) EMC test of the soft-switching three-level inverter



(b) EMC test of the full-bridge inverter

Fig. 13. EMC test waveform comparison by inverter type

5. Conclusion

In this paper, we investigated the characteristics of the multi-level inverter using the soft-switching method to improve the performance of the ballast used in motor headlights.

For this purpose, and based on the results, we interpreted the modeling used in ballast design and voltage characteristics under normal conditions.

The experiment's results demonstrate the improvement on efficiency and the EMI characteristic of the multi-level inverter using the soft-switching method through the EMI testing performed by CISPR 25 size.

References

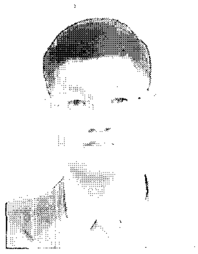
[1] H. J. Faehnrich and E. Rasch, "Electronics ballasts for metal halide lamps", journal of the Illuminating Engineering Society, pp. 131-140, 1998.

[2] E. Deng, S. Cuk, "Negative incremental impedance and stability of fluorescent lamps", Applied Power Electronics Conference and Exposition, Vol. 2, pp. 1050-1056, 1997.

[3] U. Mader, P. Horn, "A dynamic model for the electrical characteristics of fluorescent lamps", Industry Applications Society Annual Meeting, Vol. 2, pp. 1923-1934, 1992.

[4] G. Zissis, K. Charrada, "Two-temperatures modeling of the high pressure Hg discharge lamp: application to determination of the thermodynamic equilibrium state of the plasma", Plasma Science, IEEE Conference Record., IEEE International Conference, pp. 134, 1996.

[5] Y. Yang, Z. Qian, X. Wu, "A novel single-stage low-frequency square-wave electronic ballast for low-wattage HID lamps", Applied Power Electronics Conference and Exposition, Vol. 2, pp. 1048 – 1052, 2005.



Baek-Haeng Lee
He received B.S and M.S. degree in electrical engineering from Chung-Ang University, Seoul, Korea, in 1992 and 1994, respectively. He is presently a Ph. D. candidate in the Department of Electronic, Electrical, Control and Instrumentation Engineering in Hanyang University, Korea. His research interests are power converter, energy storage device and electronic ballast. He is currently the head of electronics R&D center in Korea Automotive Technology Institute.

Hee-Jun Kim
He received the B.S and M.S. degree in electronics engineering from Hanyang University, Seoul, Korea, in 1976 and 1978, respectively, and the Ph. D. degree in electronics engineering from Kyushu University, Kyushu, Japan, in 1986. Since 1987, he has been with the School of Electrical Engineering and Computer Science, Hanyang University, Ansan, Korea, where he is currently a professor. From 1991 to 1992, he had been with the Virginia Polytechnic Institute and State University, Blacksburg, as a Visiting Scholar. From 1988 to 2005, he had been a technical advisor with the Dong-Ah Elecomm Company, Korea. His fields of interest include switching power converters, electronic ballast, soft switching techniques, and analog signal processing. Dr. Kim is Fellow of the Korean Institute of Electrical Engineers, the Institute of Electronics Engineer of Korea, and the Korean Institute of Power Electronics.