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Modeling and Control of Automotive HID Lamp Ballast

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Abstract – This paper presents design and analysis of an HID lamp ballast for a fast turn on characteristics and stable operation. It produces a high open circuit voltage for the ignition and it is controlled to supply effectively the power required to shorten the warm-up period after the breakdown. The lamp modeling by empirical data is presented. It is very effective in the designing of the control loop in the steady-state operating region. A stable operation of the lamp power regulation in the steady state is achieved, which is crucial for the long life time and constant light output. Stability analysis of the system is performed and the results are verified through various simulation results and the hardware experiments.

I. INTRODUCTION

Metal Halide Discharge (MHD) lamp is a High Intensity Discharge (HID) lamp which is expected to receive much spotlight as a multi-purpose light source, due to its high efficiency, long lasting life span, and its natural colors. It is expected to have much value as an automotive light source due to its superb color rendering and fixed directional beam. However unlike halogen lamps, MHD lamps have a very complex transient characteristics to reach its steady state after the breakdown. Like many other discharge lamps, MHD lamps initially need a high voltage pulse for ignition (In the case of Philips D2S-35W lamp, 2kV for cold start, 25kV for hot start). And then an appropriate open circuit voltage and a take over current should be supplied to the lamp in order to transit the glow to the arc state.

In the steady state, the voltage of the MHD lamp is different for each lamp (the rated voltage is 85±17V) and varies with the operating time. For the long lifetime and constant light output, the power to the lamp should be controlled as the rated value in spite of the lamp voltage variation.

In this paper, in order to develop an optimal ballast with a fast turn on characteristics and stable operation, the following subjects were focused.

1. Production of high open circuit voltage before ignition and development of a method to control the converter to supply the power required effectively to shorten the transient period after breakdown.
2. Modeling of a MHD lamp and ballast in the steady state.
3. Control design and stability analysis of the ballast including the lamp dynamics.

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II. SYSTEM DESCRIPTION

For the automotive headlight application with a HID lamp, it is critical to shorten the turn on time, i.e., less than 4 second to reach 80% of the rated light output with a cold bulb (ECE REG. No.99). This can be achieved by supplying an appropriate power (several times of nominal power) to the lamp when it starts up. Also, it is important to maintain a constant power operation in the steady state.

Fig. 1 shows the automotive ballast system for MHD lamp. The vehicle's battery source (12Vdc) should be boosted to supply the lamp voltage (about 85V in the steady state) and high input voltage to the igniter. The flyback converter is suitable for these purposes and makes it easy to generate the multiple output. In Fig. 1, Rdis, Ct and Rch are devices of the take over current circuit. The capacitor, Ct, charges current through the charging resistor, Rch, before ignition and discharges the current through the discharging resistor, Rdis, to the lamp to transit the glow to the arc state immediately after the ignition.

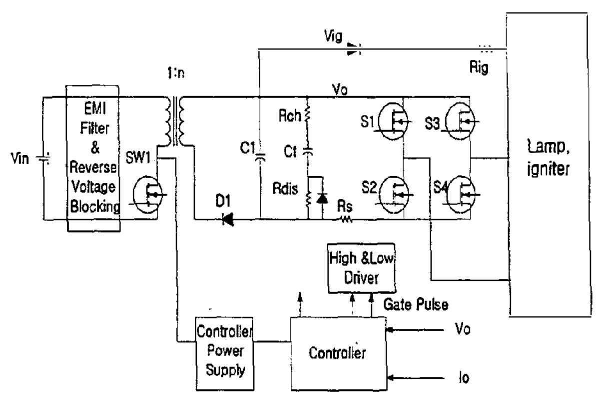


Fig. 1. Automotive MHD lamp ballast system

Also MHD lamps need to be operated in an alternating current in order to prevent the lamp from becoming blackened. A rectangular alternating current circuit (with 400Hz switching frequency full bridge inverter) is used to avoid acoustic resonance phenomenon as well[1].

The lighting characteristics of MHD lamps are largely affected by the temperature and the pressure of the tube. As shown in Fig.2, a duty ratio control scheme with a variable current reference according to the lamp voltage is applied to the ballast to supply the sufficient power to the lamp in the warm-up period and regulate the constant power in the steady state.

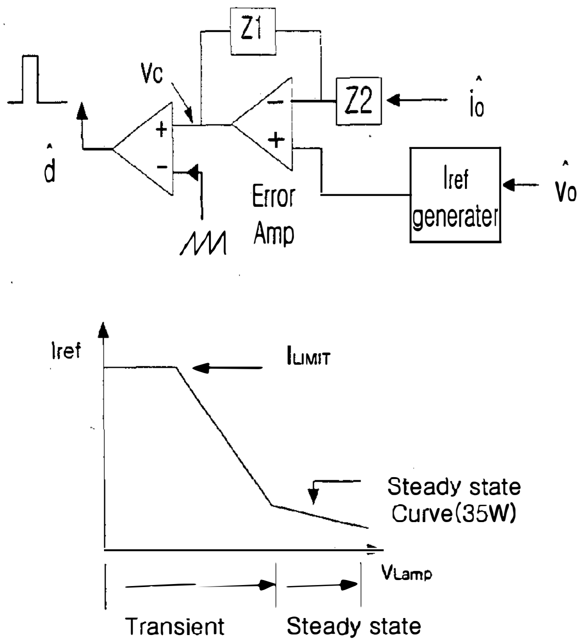


Fig. 2 Ballast control block and lamp current reference characteristics

III. OPERATING CHARACTERISTICS AND CONTROL MECHANISM

A lamp that is supplied with the sufficient current from the take over current circuit to transit the glow to the arc state immediately after ignition goes through the warm-up period of operation. In this mode, the lamp voltage depends on its bulb temperature and pressure that are decided by the supplied energy to the lamp. The lamp voltage slowly increases with time when sufficient energy is delivered to the lamp and then reaches the steady state operation voltage. The rate of increase of the lamp voltage is proportional to the supplying power to the lamp during the transient[7]. Thus it is necessary for the ballast to supply the maximum current in order to shorten the lamp turn-on time.

In Fig.1, there are two control loops consisting of the voltage loop through the current reference generator and the current loop. To shorten the lamp turn-on time, the current reference

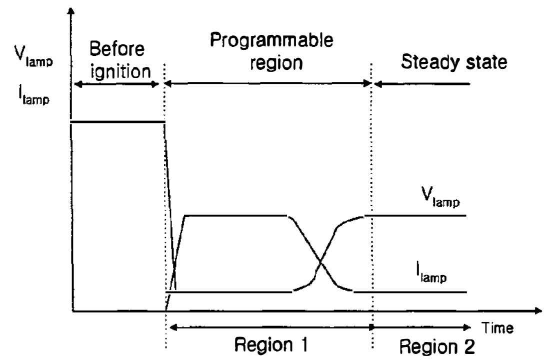


Fig. 3. The characteristics of MHD lamp

profile with respect to the lamp voltage shown in Fig.2 is used to generate the maximum current during the transient and the constant power in the steady state. During the warm-up period, the lamp voltage becomes low and thus the current reference level is set to high as illustrated in Fig.2. The sensed output current is compensated by the error amplifier with respect to the current reference. As the lamp voltage rises, the reference current is lowered to maintain the rate of increase of the lamp voltage almost constant, which prevents an overshoot in the light output (lm/W) waveform from occurring.

In the steady state, the lamp power should be controlled to be constant. When the lamp voltage rises, the reference current level is lowered to regulate the lamp power and vice versa.

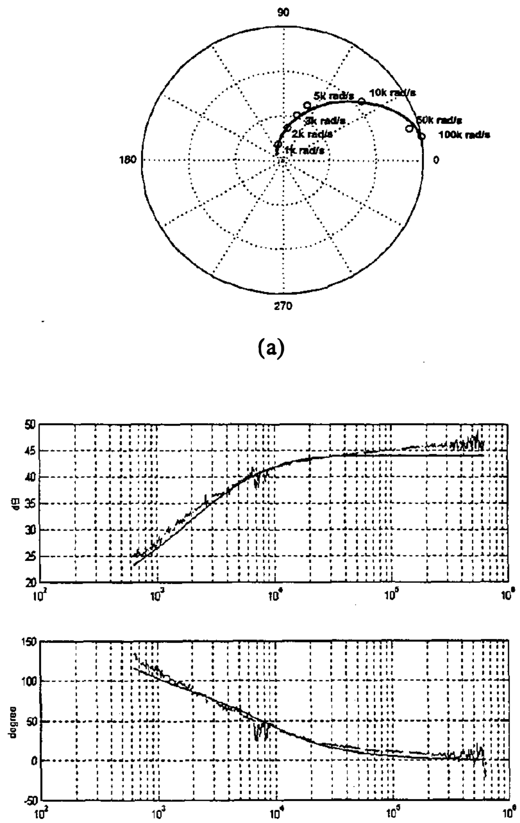
IV. STEADY STATE SMALL SIGNAL ANALYSIS

As shown in Fig.2, the change in the current reference with respect to the lamp voltage becomes small in the steady state. Thus, for the small-signal analysis and the control loop design the current loop dominates and the voltage loop can be ignored

A. Empirical data modeling of HID lamps

Either a physics-oriented modeling technique or an approach based on the time domain lamp behavior is too complicated to get a design insight of the overall ballast system. In the steady state operating region, it is appropriate to describe the small signal characteristics as an incremental impedance with a complex quantity. Measured impedance data are plotted in Fig. 3(a), as a locus of the impedance points on the R versus jX plane in the operating frequency range of interest. In the figure, the small signal impedance shows negative value in the low frequency region(below 1krad/s) and positive resistive value if the frequency is high enough(above 50k rad/s). The phase shift between the current and voltage in mid frequency range arises from the nonlinear variation of resistance with time and current, and the "negative" incremental resistance is simply a result of the fact that the large signal lamp conductance is a nonlinear function of the current [3].

Based on this information, an equivalent lamp impedance model is set as in Eq.(1)[4]. The control loop design and the stability analysis of the ballast can be done using this model.



(a)

(b)

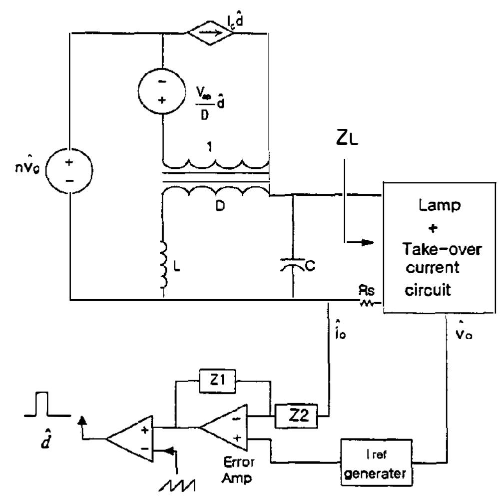
Fig. 3 small-signal empirical data modeling of HID lamp
(a) small signal impedance on the (R+jX) plane
(b) complex curve fitting of the HID lamp
(dot : measured , solid : fitted)

Using the MHD lamp (Philips D2S-35W), the small-signal impedance $Z_{LAMP}(s)$ is measured and the parameter values in the model in Eq.(1) can be identified using the complex curve fitting algorithm[5]. The fitted parameter values are K= -7.39, z=-372 rad/s, p=8.08 krad/s. The measured data and impedance curve from the fitted function are compared in Fig. 3(b).

$$Z_{LAMP}(s) = K\frac{1+s/z}{1+s/p} \quad (1)$$

B. Small signal modeling of the ballast

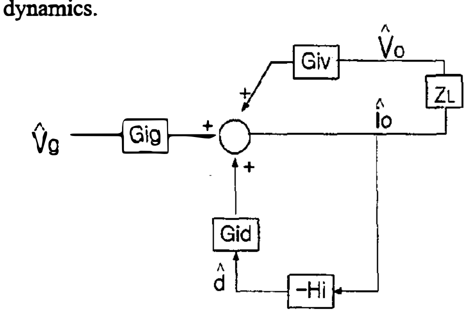
Fig. 4 shows the small signal equivalent circuit using the PWM switch model[2]. The primary circuit is reflected to the secondary part in the model. Rs is a sensing element of the output current. The output terminal of the ballast is connected to the lamp and the take-over current circuit is treated as part of the load of the ballast. The output current is sensed by Rs and fed into the error amplifier, and the output voltage is divided and fed into the current reference generator. The current loop behaves as the major loop because the voltage loop gain is very small in the steady state.



D: duty ratio
$\hat{d}$: duty perturbation
$\hat{v}_g$: input voltage perturbation
V_{ap}, I_c : DC operating point
Z_L : parallel combination of
the take over current circuit and the lamp load

Fig.4 small signal equivalent circuit of ballast

The block diagram of the circuit is shown in Fig.5. The ballast controls and supplies the output current to the lamp and receives voltage from the lamp. Therefore the input variables of the ballast are the input voltage and the load voltage, and the output variable is the output current for the small signal dynamics.



Giv: output voltage to output current gain
Gid: duty to output current transfer function
Hi: output current to duty transfer function
Z_L: load impedance

Fig. 5 Block diagram of small signal equivalent circuit

C. Control loop design

Since the effective load seen by the ballast includes the take over current circuit and the lamp impedance, From the inherent characteristics of flyback converter, there is a right half plane zero in the control to output transfer function, which limits the control bandwidth. Two pole one zero compensator shown in Fig.6 is used to compensate the loop gain below the resonance frequency and right half plane zero frequency. In the warm up period, the voltage loop is designed at the worst operating condition (Vin=8V, P_{LAMP}=105W, V_{LAMP}= 60V) to shorten the lamp turn-on time. In the steady state operation (Vin=12V, P_{LAMP}=35W, V_{LAMP}= 85A), the right half plane zero and the system resonance frequency are located at 183krad/sec and 34.4krad/sec respectively. The control loop gain of the ballast at a given steady state operating condition is,

$$T = Gid \cdot Hi$$

$$G_{id} = \left.\frac{\hat{i}_o}{\hat{d}}\right|_{\hat{v}_g=0} = \frac{nV_g}{R_s D'^2}\left(\frac{1}{1+Y_o Z_L}\right)\left(\frac{1-\frac{LI_o}{D'nV_g}s}{1+\frac{L}{R_s D'^2}s+\frac{LC}{D'^2}s^2}\right) \qquad (2)$$

$$\text{where,}\quad Y_o = \frac{1}{R_s}\,\frac{1+\frac{LC}{D'^2}s^2}{1+\frac{L}{R_s D'^2}s+\frac{LC}{D'^2}s^2}$$

where Gid is the control-to-output current transfer function and Hi is the loop compensation gain.

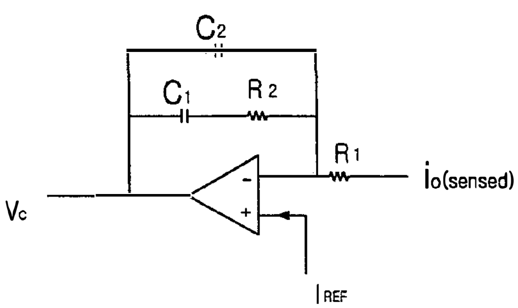


Fig 6. Two pole one zero compenator

The designed parameter values of Hi are R1=330kΩ, R2=510kΩ, C1=0.68nF and C2=0.68nF. The simulation curve of the loop gain T, in Fig.8 shows the designed ballast system is stable with the phase margin of about 40 degree.

V. EXPERIMENTAL RESULT

A prototype of the automotive ballast is built for the 35W MHD lamp (D2S-35W Philips). The design parameters of the power stage in Fig. 1 are as follows

S_1=IRF540x2; $L_{secondary}$=640μH; C1=0.33μF; f_{SW}=180kHz; Duty=0.5

Fig. 7 plots the measured duty ratio to output current transfer function (Gid). Fig. 8 plots the measured loop gain of the overall system, which matches well with the simulation results. Fig. 9 shows the turn-on characteristics of the lamp voltage, lamp current, and light output response with a cold lamp. It shows the warm-up time to reach 80% lighting output level of nominal value is less than 4 seconds using the proposed power control.

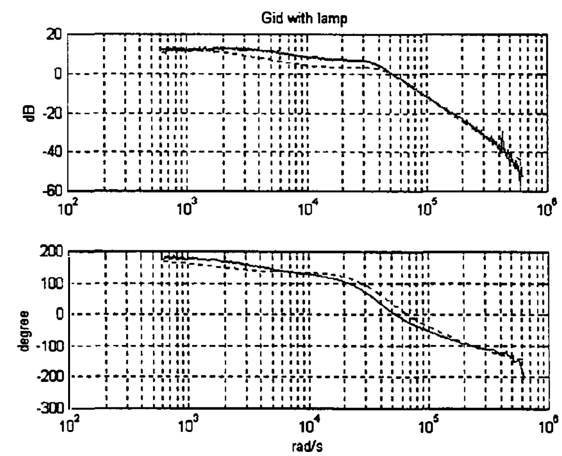


Fig. 7 duty ratio to output current transfer function (Gid)
(dot : simulated , solid : measured)

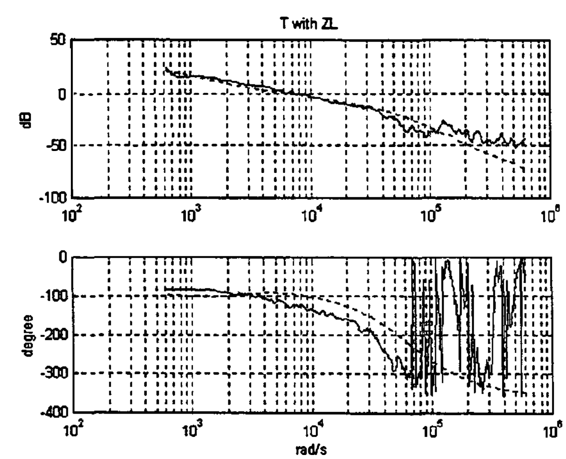


Fig. 8 closed loop gain
(dot : simulated , solid : measured)

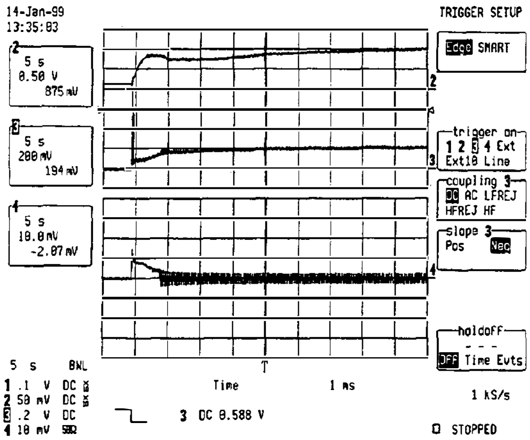


Fig. 9 Turn-on characteristics

VI. CONCLUSION

In this paper, design and analysis of an HID lamp ballast for a fast turn on characteristics and stable operation, is presented. It produces a high open circuit voltage for the ignition and it is controlled to supply effectively the power required to shorten the warm-up period after the breakdown.

The lamp modeling by empirical data is presented. It is very effective in the designing of the control loop in the steady-state operating region. A stable operation of the lamp power regulation in the steady state is achieved, which is crucial for the long life time and constant light output. Stability analysis of the system is performed and the results are verified through various simulation results and the hardware experiments.

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