Electronic Ballast for 400W Metal Halide Lamp

Ph.D. Chi-Hwan Lee

KOREA
www.digitalballast.com & http://www.pwm.pe.kr/ email: chlee@uiduk.ac.kr

Ⅰ. Introduction

Increased efficacy, longer lifetime, control over lamp power, and smaller and lighter ballast are some of the advantages for driving MHD lamps from a high frequency source. Nevertheless, due to occurrence of acoustic resonance, high frequency ballasting of HID lamp has been a major challenge. Designers of electronic ballast have been interested in determining the frequencies of de-stabilizing resonance to avoid in the lamp, or conversely, the allowed frequency bands and threshold levels for modulation components in the lamp power. The acoustic resonance causes various problems such as arc instability, light output fluctuation, color temperature variation, and may crack arc bulbs in the worst case. On the other hand, high voltage stress may be caused due to the arc extinguishing, which is very dangerous to the ballast.

Spectrum spreading of lamp power is one way to prevent acoustic resonance since generation of acoustic waves occurs only if the sound wave source is sufficiently high in the sensitive frequency region. Varying switching pattern by frequency modulation or angle modulation give a distributed power spectrum. Operating the lamp with a low-frequency square wave is a different way to avoid the acoustic resonance. The low-frequency square-wave driving generates a dc power wave for the lamp, so no excitation is present and the arc remains stable. In another ballast design, the lamp is operated with narrow frequency band or with very high frequency where there is no acoustic resonance. It is difficult to control the lamp power in varying switching pattern, an operation with narrow frequency band can not be adapted to all MHD lamps. An operation above 100kHz causes high EMI level.

In the design of electronic ballast for MHD lamps, impedance characteristics of the lamp and resonant characteristics of circuit must be considered. In general, a series resonant inverter is a common configuration and the lamp power is controlled by frequency. The electrical characteristic of MHD lamp plays an important role in the resonant circuit and the state of lamp is changed dramatically from warm-up to the fully warmed state. It is not easy to get a transfer function of the ballast since the resonant inverter has nonlinear characteristics.

In this paper, the control loop including the resonant inverter is analyzed and the current controller is designed. A new method is adapted to avoid acoustic resonance related instability in MHD lamp and a prototype electronic ballast is designed and implemented. The lamp current is controlled with taking into account the voltage of lamp to make a rated power. To make the spread spectrum effect for removing acoustic resonance, the disturbance as a modulating signal is injected in current control loop. The experimental results show the validity of the proposed ballast and the good performance as PF 0.93, ballast loss 22W at output 400W and the conducted EMI level meets the FCC class A requirements.

Ⅱ. Current Controller

Typical topology of electronic ballast with half-bridge resonant inverter is shown Fig. 1.

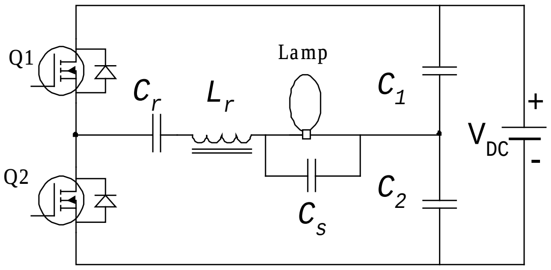


Fig. 1. Configuration of electronic ballast for MHD lamps.

The value of *Cs* is small enough than *Cr* and it is chosen for generating igniting voltage at a frequency $1/(2\pi\sqrt{L_r C_s})$. *Cr* and *Lr* determine the fundamental resonant frequency. Since high frequency driven MHD lamp acts like a pure resistor, the voltage and current of the lamp are in phase. Therefore, variation of lamp characteristics can be dealt with as load changing. The lamp has the smallest resistance R_{min} at the starting and the largest resistance R_{max} at the steady state.

$$R = [R_{\min} \quad R_{\max}] \qquad (1)$$

Fig .2 shows the starting characteristics of general MHD lamps. The starting voltage is very low and the starting current is 120% of rated for less warm-up time. The characteristic curves of the ballast are shown in Fig. 3. The forced voltage on resonant circuit is calculated by Fourier series analysis of rectangular voltage waveform with amplitude V_{DC}.

$$v_f = \frac{4V_{DC}}{\pi}\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \cdots\right) \qquad (2)$$

The lamp current can be presented as equation (3) taking account into the fundamental voltage of equation (2)

$$I_r = \frac{\sqrt{2}V_{DC}}{\pi Z_0\sqrt{(R/Z_0)^2 + (\omega/\omega_0 - \omega_0/\omega)^2}} \qquad (3)$$

where $Z_0 = \sqrt{L_r/C_r}$, $\omega_0 = \sqrt{L_r C_r}$.

With starting condition of the lamp, the lamp current I_2 is calculated as equation (4) at initial driving frequency ω_2

$$I_2 = 1.2\, I_n$$

$$= \frac{\sqrt{2}V_{DC}}{pZ_0\sqrt{\left(R_{\min}/Z_0\right)^2 + \left(w_2/w_0 - w_0/w_2\right)^2}} \qquad (4)$$

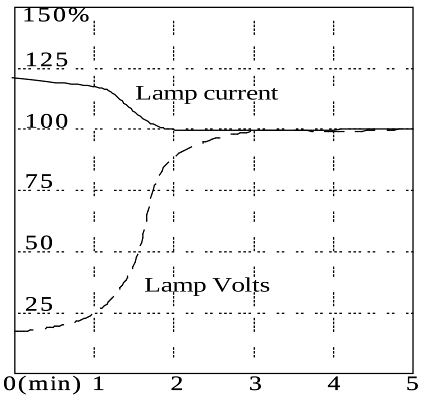


Fig. 2. Typical starting characteristics of MHD lamps.

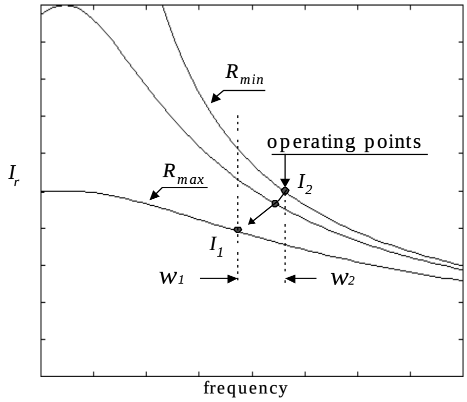


Fig. 3. Characteristic curves of a series resonant inverter.

At the steady state, the driving frequency w_1, the lamp current I_1 is as following:

$$I_1 = I_n$$

$$= \frac{\sqrt{2}V_{DC}}{pZ_0\sqrt{\left(R_{\max}/Z_0\right)^2 + \left(w_1/w_0 - w_0/w1\right)^2}} \qquad (5)$$

The rate w_1/w_0 is calculated as equation (6) from given $V_{DC}, Z_0, R_{MAX}, I_n$ and equation (5). The driving frequency w_1 at the steady state is also calculated.

$$\frac{w_1}{w_0} = \frac{Q_1 + \sqrt{Q_1^{\,2} + 4}}{2} \qquad (6)$$

$$Q_1 = \sqrt{\left(\frac{\sqrt{2}V_{DC}}{pZ_0 I_n}\right)^2 - \left(\frac{R_{\max}}{Z_0}\right)^2} \qquad (7)$$

The driving frequency w_2 at the starting can also be solved using the equations (8,9,10).

$$1.2\, I_n = \frac{\sqrt{2}V_{DC}}{pZ_0\sqrt{\left(R_{\min}/Z_0\right)^2 + \left(w_2/w_0 - w_0/w_2\right)^2}}$$

$$\approx \frac{\sqrt{2}V_{DC}}{pZ_0\left(w_2/w_0 - w_0/w_2\right)}, \quad \mathrm{R}_{\min} << Z_0 \qquad (8)$$

$$Q_2 = \frac{\sqrt{2}V_{DC}\, w_0}{1.2pZ_0 I_n}, \quad w_2 >> w_1 \qquad (9)$$

$$w_2 = \frac{Q_2 + \sqrt{Q_2^{\,2} + 4w_0^{\,2}}}{2} \qquad (10)$$

The behavior of resonant inverter is nonlinear and complex. We can make a linear transfer function by using the local linearization technique. Electronic ballast for MHD lamp is operated in high frequency far from resonant frequency w_0, the behavior of the inverter can be modeled by constant, $-K_{inv}$ as:

$$\frac{\Delta I}{\Delta w} = \frac{I_{r(w_1)} - I_{r(w_2)}}{w_1 - w_2} = -K_{INV} \qquad (11)$$

Since the inverter is driven from voltage-controlled oscillator, the transfer function including VCO is presented as following:

$$I_r = (-K_{INV} \cdot K_v)v + I_0 = -K_r v + I_0 \qquad (12)$$

where I_o is offset. Generally, the measured current is fed back to controller through rectifier and LPF. Fig. 4 shows a block diagram of the ballast.

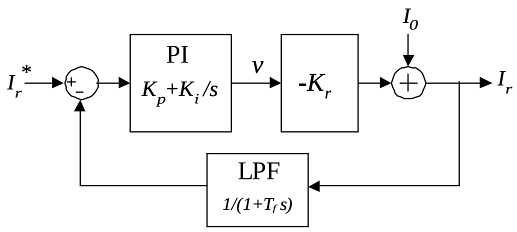


Fig. 4. The block diagram of electronic ballast.

From Fig. 4, the transfer function of control loop is presented as:

$$\frac{I_r}{I_r^*} = \frac{K_r(K_pT_fs^2(K_iK_f + K_p)s + K_i)}{T_fs^2 + (1+K_rK_p)s + K_rK_i} \qquad (13)$$

The poles of system are placed on:

$$P_1, P_2 = -\frac{K_rK_p + 1}{2T_f} \pm \sqrt{\left(\frac{K_rK_p + 1}{2T_f}\right)^2 - \frac{K_rK_i}{T_f}} \qquad (14)$$

To achieve stable operation, the system bandwidth f_{BW} must be selected as below the crossover frequency of LPF. Letting Kp=0 in equation (14), the real part of poles becomes half of LPF's bandwidth. Thus, the system yields the poles and zero as:

$$P_1, P_2 = -\frac{1}{2T_f} \pm \sqrt{\left(\frac{1}{2T_f}\right)^2 - \frac{K_rK_i}{T_f}} \qquad (15)$$

$$z = \frac{1}{T_f}$$

To make the system slightly under-damped, the following condition is required.

$$k_i > \frac{1}{4T_f K_r}, \quad K_p = 0 \qquad (16)$$

This means that the current controller of the ballast is an integrator(I-control).

Ⅲ. Elimination of Acoustic Resonance

The acoustic resonance appears when discharge occurs in bulb of the lamp. MHD lamps exhibit arc instability when operated at a high frequency. The source of this instability is the excitation of acoustic pressure waves in the arc gas by variations in the power input. These pressure waves cause the arc to vibrate and change shape erratically. This is undesirable because the light moves and flickers. Sometimes the arc may touch the wall of the discharge bulb, extinguishing the arc or shattering the bulb. The bulb of a high pressure sodium lamp has a thin and long shape like a post, has only one fundamental frequency of acoustic resonance. Unstable frequency regions exist regularly and have narrow bands as shown in Fig. 5. A MHD lamp has a thick and ellipse shape. The frequencies of acoustic resonance in MHD lamp depend on the bulb shape. The unstable frequency regions are spread widely as shown in Fig. 6.

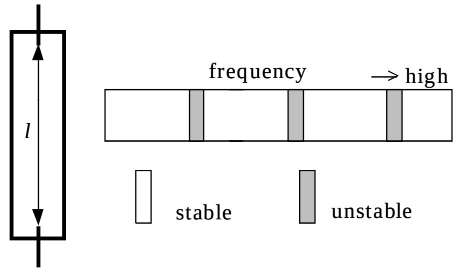


Fig. 5. Shape of HPS lamp and bands of acoustic resonance.

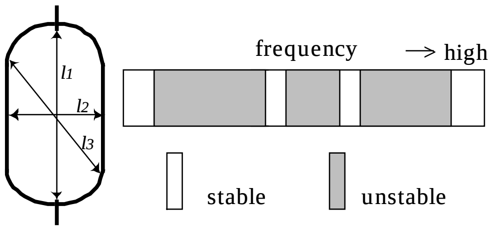


Fig. 6. Shape of MHD lamp and bands of acoustic resonance.

The main frequencies of acoustic resonance are given by

$$f_1 = \frac{C}{2L_r}, \quad f_1 = \frac{3.83C}{2pR_r}, \quad f_1 = \frac{1.84C}{2pR_r} \qquad (17)$$

where C is acoustic velocity in bulb, 560 [m/sec], L is the length of arc and R is the cylindrical bulb height.

Normally, a resonant-type electronic ballast is operated at a higher frequency than its resonant frequency and the current waveform is not sinusoidal but triangular that has multiple harmonics. In this case, audible acoustic resonance does not occur but unstable arc is observed.

To eliminate unstable arc, a sinusoidal waveform is injected on current command in controller shown in Fig. 7. Rectangular or triangular waveform is also usable for modulating signal, but these waveforms are apt to produce audible acoustic noise. The modulating frequency f_{MOD} is selected as $f_{MOD} << f_{BW}$ so that the lamp current looks like amplitude modulated. The modulating index m is given by

$$\mathbf{m} = \frac{\mathbf{A} - \mathbf{B}}{\mathbf{A} + \mathbf{B}} \times 100\% \qquad (18)$$

The bandwidth of spread spectrum effect is calculated from equation (3) with modulation index m as follows:

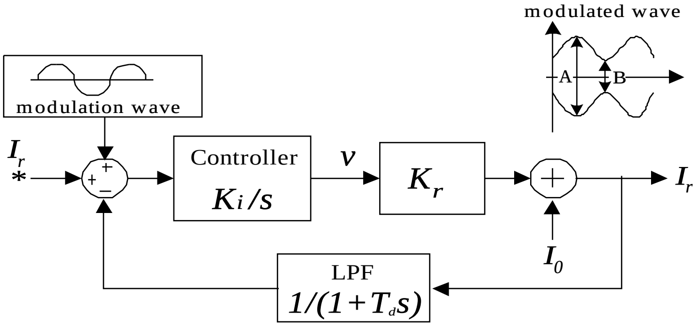


Fig. 7. Ballast with the amplitude modulation.

Modulated current causes power variation that has the same period of the modulating signal. Also, the switching frequency is changed simultaneously. It means the spread spectrum effect. Spread spectrum with angle modulation and low-frequency driving techniques require extra controllers. But modulating of amplitude on the current controller does not need an extra hardware and it is easy to find the condition of free acoustic resonance by experiment.

Ⅳ. Experimental Results

Electronic ballast for 400W MHD lamp is designed and implemented as shown in Fig. 9. The PFC controller offers 400V on DC bus, and igniting voltage is generated from capacitor C_s in parallel with lamp. Switching band is selected around 35kHz. The current controller consists of OP-amps, VCO and gate drives. The modulating signal is extracted from 120Hz ripple wave on DC side. The modulation index is determined by observing the arc instability of the lamp. Fig. 10 shows waveforms of AC line and output. The AC voltage and current are in phase due to by power factor correction. The changing of output amplitude and frequency can be seen in Fig. 10 b).

The electrical characteristics of the prototype ballast are shown in table. 1. The electronic ballast consumes 22W only while the conventional ballast consumes 50W at 400W output. Fig. 11 shows the spectrums of the lamp current with and without the amplitude modulation. At modulation index m=20%, the spreading band is about 5kHz and there is no acoustic resonance. Fig. 12 shows the conducted EMI level measured with LISN and it meets FCC class A requirements.

Table 1. Electrical characteristics of the prototype ballast.

	Electronic ballast	Conventional ballast
Input power	422 W	450 W
Output	400 W	400 W
Power factor	0.93	0.86
Modulation index	20 %	0 %

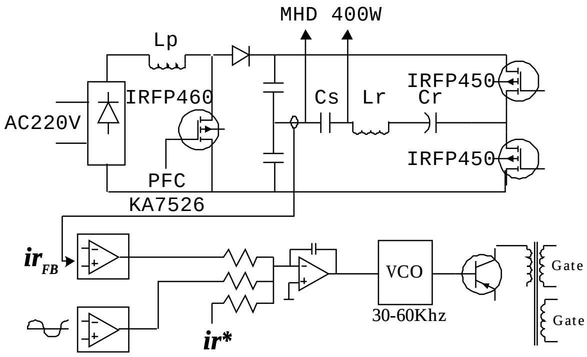


Fig. 8. Configuration of ballast for MHD lamp.

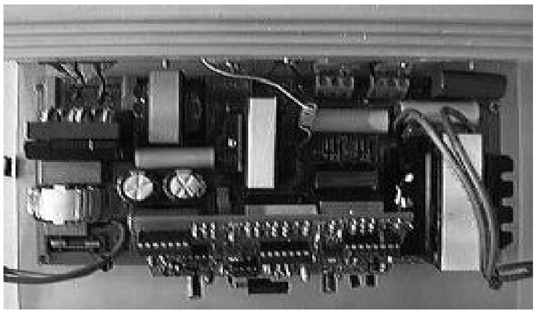
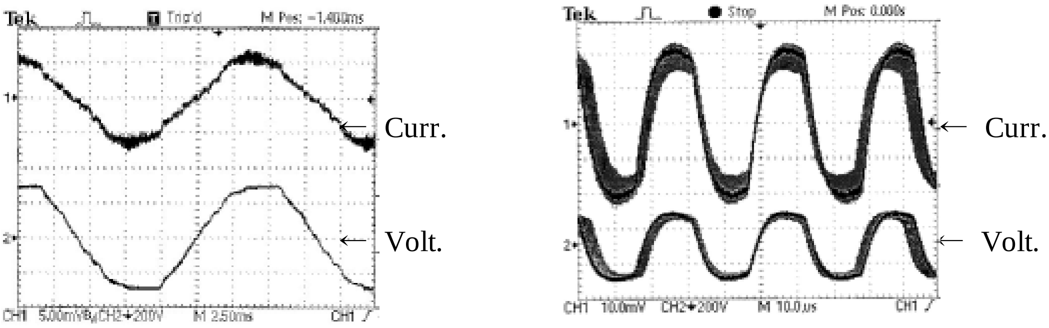


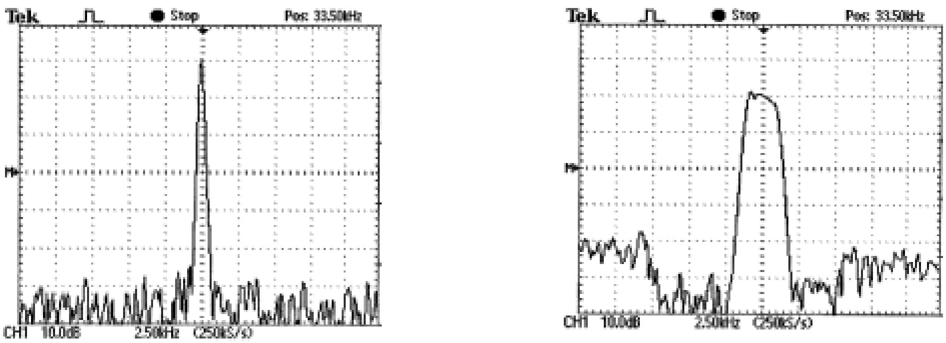
Fig. 9. Picture of the ballast for MHD lamp.



a) AC line voltage and current

b) the lamp voltage and current

Fig. 10. Current and voltage waveforms of AC line and lamp.



a) without amplitude modulation

b) with amplitude modulation

Fig. 11. Spectrums of the lamp current.

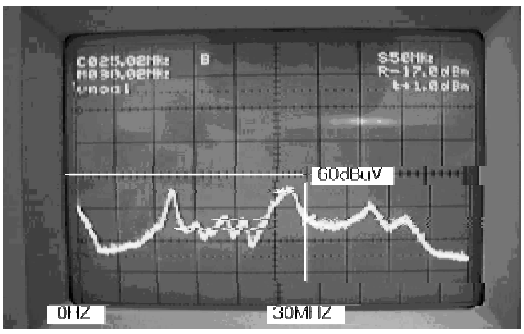


Fig. 12. Conducted EMI level.

Ⅴ. Conclusion

A new electronic ballast for free acoustic resonance is proposed and implemented. The resonant inverter based ballast is analyzed and the transfer function is obtained. To eliminate acoustic resonance on MHD lamp, the amplitude modulation is employed and it is easily realized without an extra controller. The prototype ballast was implemented for 400W MHD lamp. At 35kHz switching band and 20% modulation, no acoustic resonance occurs. The efficiency 95% is achieved, input power 422W for 400W output. The conducted EMI level is below 60dB*u*V.