A High-Power-Factor Electronic Ballast for Metal Halide Lamps with Hot Restarting

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Abstract

An electronic ballast with a high-power-factor dc-linked resonant inverter is proposed for driving metal halide lamps with hot restart capability. An ignitor is included to generate a relatively high ignition voltage for hot restarting. The dc-link voltage of the electronic ballast is designed to meet the requirements of ignition voltage for cold starting, open-circuit-voltage for hot restarting, and steady-state operation. Satisfied results are obtained from experimental tests on a prototype circuit for an MHQ 70-W metal halide lamp.

1 Introduction

The metal halide lamp has become an attractive light source for its compactness, good color rendering, and high efficacy [1]. As a member of gas discharge lamps, it is well known that the lighting performance can be further improved when driven by a high-frequency electronic ballast. Even though the advantages of using an electronic ballast for the metal halide lamp is the same as those for fluorescent lamps, up to now, however, the electronic gear for metal halide lamps are not so popular because it needs more complicated ballasting circuitry. A much higher voltage is necessary for igniting the metal halide lamp during starting period [2-5]. Moreover, the lamp driven by a high-frequency electronic ballast may suffer from acoustic resonance [6,7].

For a cold lamp, an ignition voltage up to several kV is required for breaking down the electrodes during starting period. The ignition voltage for cold starting can be generated either by an additional ignition circuit or directly from the ballast circuit. A cost-effective approach is to generate an open-circuit-voltage on the lamp by deliberately operating the inverter at a frequency very close to the resonant frequency of the load circuit during the starting period [8]. Such a design resorts to the pre-knowledge about the starting characteristics of the lamp. Unfortunately, the breakdown voltage of metal halide lamps may vary from time to time and lamp to lamp, and is sensitive to operating temperature and lamp life.

On the other hand, the ignition voltage for restarting a hot lamp can be ten times that for a cold lamp. To generate such a high ignition voltage directly from the ballast circuit becomes impracticable. In this case, an ignition circuit has to be included. In addition to the high ignition voltage, a sufficiently high open-circuit-voltage on the lamp is necessary for restarting. All these make it difficult in the design of an electronic ballast for applications with hot restarting [9].

In this paper, an electronic ballast with an ignitor for hot restart is proposed for ballasting metal halide lamps. The electronic ballast can generate a high ignition voltage upon the lamp electrodes for starting a cold lamp. For hot restarting, a sufficiently high open-circuit-voltage is applied upon the lamp and then an extremely high voltage is generated by the ignitor to start the lamp. Throughout the entire operation, the electronic ballast is precisely operated at the specific frequency at which acoustic resonance will not occur [10]. In addition to these features, a high-power-factor can be achieved by supplying current directly to the load resonant circuit in every high-frequency switching cycle of the inverter [11,12]. The proposed electronic ballast is designed for driving an MHQ 70-W metal halide lamp as an illustrative example.

2 Circuit Configuration

Fig. 1 shows the proposed circuit configuration of the electronic ballast with an ignitor for hot restarting. The ballast circuit consists of a diode bridge rectifier followed by a half-bridge series-resonant inverter with parallel-load. Q_1 and Q_2 are the two active power switches of the inverter, which are alternately switched on and off at the desired high frequency. The anti-paralleled diodes, D_1 and D_2, carry the negative freewheeling currents of the active switches. The load resonant circuit comprises the metal halide lamp and the resonant energy tank, L_S and C_S. The capacitor, C_b, is connected in

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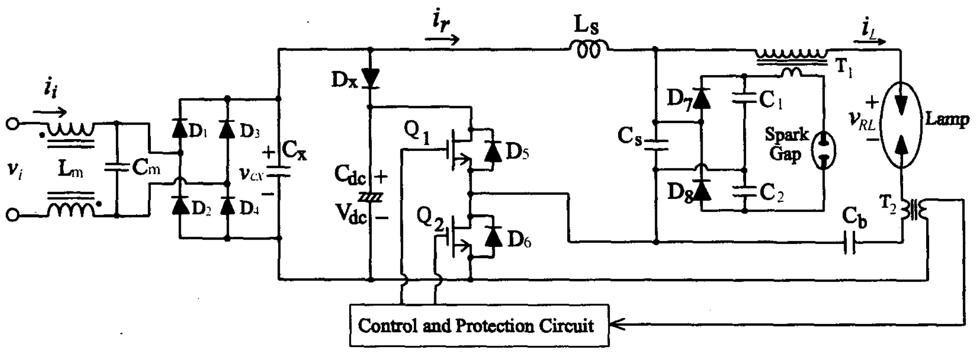


Fig. 1 High power factor electronic ballast with ignitor for hot restarting

series with the load resonant circuit for blocking the dc voltage, and C_{dc} is used as the energy reservoir which is large enough for providing a smooth dc-link voltage for the inverter.

The load resonant circuit is connected between the output terminal of the rectifier and the midpoint of the inverter switches. A diode, D_x, and a small capacitor, C_x, is used as an energy transfer switch for determining the conducting time of the rectifier in every switching cycle. The high-frequency contents of the input current are removed by a small passive filter circuit, L_m and C_m, in front of the rectifier.

The ignitor is composed of a voltage doubling rectifier, a spark gap, and a step-up transformer, T_1. The secondary of the transformer is connected in series with the metal halide lamp. The ignitor is actuated when the sum of series voltages on C_1 and C_2 reaches the specified level to breakdown the spark gap. This voltages is then applied on the primary of the transformer inducing a very high pulse superimposed on the inverter output for hot re-ignition.

In this circuit topology, the dc-link capacitor is not supplied directly from the ac line source. Instead, it is charged from the resonant energy tank of the load circuit. Therefore, the averaged dc-link voltage is not a constant determined by the ac line source, but is a variable affected by the amount of the energy transferred to and from the load circuit. As a result, the dc-link voltage varies in accordance with the load condition as well as the switching period of the energy transfer switch. An appropriate feature can be deliberately designed to obtain an ignition voltage for cold starting and an open-circuit-voltage sufficiently high for hot restarting. In addition, fast transition through glow-to-arc stage can be achieved. Nevertheless, the dc-link voltage may be very high to destroy the circuit components under abnormal load conditions . For this reason, a small current transformer, T_2, is used to detect the lamp current for protection when the lamp is removed or fails to start up.

3 Circuit Operation

The electronic ballast is supplied from the ac line voltage source.

$$v_i(t)=\sqrt{2}V_i\sin 2\pi f_i t \qquad (1)$$

where V_i is the r.m.s. value and f_i is the line frequency of the ac source. For proper circuit operation, V_{dc} must not be lower than the peak of the ac line voltage. In addition, the inverter switching frequency, f_s, should be relatively high in comparison with the ac line frequency so that the variation at the input line voltage can be treated as a constant within one high-frequency switching cycle.

The conducting interval of the diode is determined by the voltage on C_x. This capacitor is charged and discharged by the load resonant current which can be assumed as a sinusoidal current [8].

$$i_r(t)=\sqrt{2}I_r\sin 2\pi f_s t \qquad (2)$$

where I_r is the r.m.s. value.

According to the charge and discharge of C_x, the circuit operation can be divided into four modes. The operation of the electronic ballast circuit can be explained with the help of theoretical waveforms in Fig. 2. The equivalent circuits with the conducting switches for the operating modes are shown in Fig. 3, the rectifier is replaced by a diode, D_r, and the load resonant circuit is represented by the resonant current, i_r.

Mode I:

Mode I starts at the instant i_r becomes positive. During this mode, both D_r and D_x are reverse-biased. C_x is discharged by the positive i_r and the voltage across it is decreasing.

$$v_{cx}(t)=V_{dc}-\frac{1}{C_x}\int_0^t i_r(t)dt$$

$$=V_{dc}-\frac{I_r}{\sqrt{2}\pi f_s C_x}(1-\cos 2\pi f_s t) \qquad (3)$$

Mode II:

As soon as v_{cx} has declined below the rectified ac voltage, D_r becomes forward-biased, and Mode II is entered. This instant is denoted as the cut-in angle of D_r, α. At this point, the rectified ac voltage is

$$|V_i|=V_{dc}-\frac{I_r}{\sqrt{2}\pi f_s C_x}(1-\alpha) \qquad (4)$$

Then, α can be solved as:

$$\alpha=\cos^{-1}\left[1-\frac{\sqrt{2}\pi f_s C_x}{I_r}\left(V_{dc}-|v_i|\right)\right] \qquad (5)$$

During this mode, the load resonant circuit draws a current

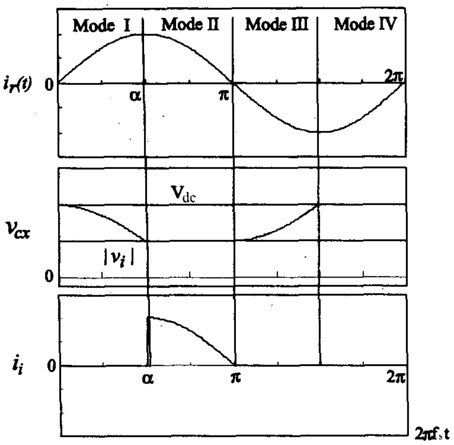


Fig.2 Theoretical waveforms for the operating modes

through Dr from the ac line source. Meanwhile, V_{cx} is held at the same level as the rectified ac voltage. Mode II ends at the instant when i_r goes to zero.

Mode III:

At $2\pi f_s t = \pi$, the load current resonates to zero, and then goes to negative. C_x is charged up again, and V_{cx} can be expressed as

$$v_{cx}(t) = |v_i| - \frac{1}{C_x}\int_{T_s/2}^{t} i_r(t)dt$$

$$= |v_i| + \frac{I_r}{\sqrt{2}\pi f_s C_x}(1+\cos 2\pi f_s t) \tag{6}$$

where T_S is the inverter switching period

$$T_s = \frac{1}{f_s} \tag{7}$$

At $2\pi f_s t = \alpha + \pi$, v_{cx} reaches the dc-link voltage. D_X turns on and Mode IV is entered.

Mode IV:

In Mode IV, v_{cx} is clamped at V_{dc}, and the energy stored in the resonant energy tank is transferred to the dc-link capacitor.

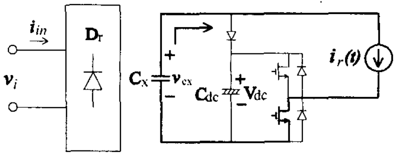
4 Circuit Analysis

4.1 Equivalent Circuit

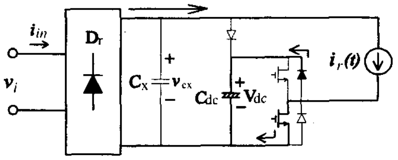
Since the current in the load resonant circuit is assumed to be sinusoidal, the analysis can be performed by fundamental approximation. With such an approximation, the voltage applied to the load resonant circuit can be simplified to its fundamental component.

$$V_1 = \frac{\sqrt{2}}{\pi}V_{dc} \tag{8}$$

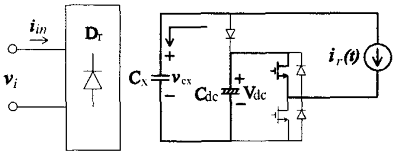
where V_1 is the r.m.s. value of the fundamental voltage of the inverter output, and the fundamental frequency is identical to the inverter switching frequency.



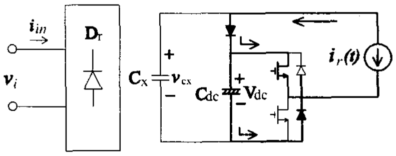
(a) Mode I



(b) Mode II



(c) Mode III



(d) Mode IV

Fig. 3 Equivalent circuits for operating modes

Fig. 4 is the equivalent circuit for the load resonant inverter circuit. The metal halide lamp, when operated at a high frequency, can be treated as an equivalent resistance, R_L [7]. A resistance, R_S, is placed in series with L_S to account for the intrinsic losses of the circuit components, which is particularly attributed to the winding and core losses of the inductor, and the conducting and switching losses of the power switches. Then, the load circuit can be represented by a resistance, R_e, in series with a reactance, X_e. The equivalent series resistance and reactance are:

$$R_e = R_s + \frac{R_L X_{cs}^2}{R_L^2 + (X_{cs} + X_{cb})^2} \tag{9}$$

$$X_e = X_{LS} - \frac{X_{cs}[R_L^2 + X_{cb}(X_{cs} + X_{cb})]}{R_L^2 + (X_{cs} + X_{cb})^2} \tag{10}$$

where X_{LS}, X_{CS}, and X_{Cb} are the reactances of L_S, C_S, and C_b, respectively.

Then, the resonant current can be obtained as:

$$I_r = \frac{V_1}{Z_T} \tag{11}$$

where Z_T is the total impedance of the load circuit.

$$Z_T = \sqrt{R_T^2 + X_e^2} \tag{12}$$

4.2 High-Power-Factor Operation

Since the load resonant circuit draws the current from the ac source in every high-frequency cycle, the input line current

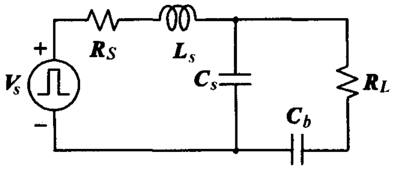


Fig. 4 Equivalent circuit for the load resonant inverter

becomes a pulsating waveform. The pulsed current starts to flow at the conducting angle α and ends at π. In other words, the pulsed current lasts for a period from α to π. Then, the average power in one high-frequency cycle can be calculated.

$$p_i(t)=\frac{1}{T_s}\int_o^{T_s} v_i(t)\cdot i_{in}(t)dt$$

$$=\frac{1}{2\pi}\int_\alpha^\pi |v_i|\cdot i_r(t)d(2\pi f_s t)$$

$$=\left(\frac{\sqrt{2}I_r}{\pi}-f_s C_x V_{dc}\right)|v_i|+f_s C_x v_i^2 \tag{13}$$

For a line frequency cycle of the ac source, the average input power can be obtained as:

$$P_{in}=\frac{1}{2\pi}\int_0^{2\pi} p_i(t)d(2\pi f_i t)$$

$$=\frac{2\sqrt{2}}{\pi}\left(\frac{\sqrt{2}I_r}{\pi}-f_s C_x V_{dc}\right)V_i+f_s C_x V_i^2 \tag{14}$$

In order to achieve a high power factor at the input line, the resonant current, I_r, can be set to a value so that the first term in Eq. (13) is zero.

$$I_r=\frac{1}{\sqrt{2}}\pi f_s C_x V_{dc} \tag{15}$$

This can be done by choosing the component values of the load resonant circuit. With such a design, the average input power for one high-frequency cycle in Eq. (13) can be expressed as:

$$p_i(t)=f_s C_x v_i^2 \tag{16}$$

The average input power in Eq. (14) becomes

$$P_{in}=f_s C_x V_i^2 \tag{17}$$

Eq. (16) also indicates the instantaneous input power of the ballast circuit. If the inverter is operated at a constant frequency, this equation implies that the ac source is virtually loaded by a resistive circuit with the equivalent resistance.

$$R_{eq}=\frac{1}{f_s C_x} \tag{18}$$

4.3 Variation of Dc-link Voltage

Eq. (14) indicates the average input power varies with I_r, V_{dc}, and V_i. This implies that the dc-link voltage depends on the load power consumption. When the power consumption of the lamp-ballast circuit is less than the input power, the residue will be deliver to the dc-link capacitor. As a result, the voltage of the capacitor increases. On the contrary, the dc-link capacitor supplies power to the load and decreases in voltage when the power consumption is greater than the input power.

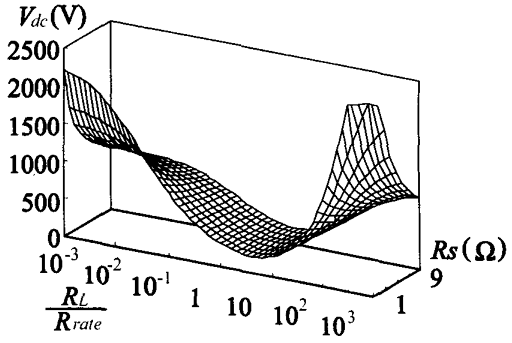


Fig. 5 Variation of V_{dc}

From the viewpoint of power balance, the average input power must be equal to the total power consumption in the ballast-lamp circuit at steady-state. The power consumption includes the circuit losses and the lamp power.

$$P_{in}=P_{tr}=I_r^2 R_T=I_L^2 R_L+I_r^2 R_s \tag{19}$$

where I_L is the r.m.s. value of the lamp current.

Then, by equating P_{tr} in Eq. (19) with P_{in} in Eq. (14), the average dc-link voltage can be solved as:

$$V_{dc}=\frac{\pi Z_T V_i}{\sqrt{2}R_T}\left[\frac{2}{\pi^2}-Z_T f_s C_x+\sqrt{\left(Z_T f_s C_x-\frac{2}{\pi^2}\right)^2+R_e f_s C_x}\right] \tag{20}$$

This equation indicates that the average dc-link voltage is a function of the impedance of the load resonant circuit. The load resonant circuit comprises the resonant energy tank, the equivalent lamp resistance, R_L, and the equivalent resistance of the circuit losses, R_S. As described above, R_S and R_L are the two power consumption elements that mainly affect the dc-link voltage. The resonant energy tank can be expressed as a voltage transfer factor, M_v.

$$M_V=\left|\frac{X_{CS}}{X_{CS}-X_{LS}}\right| \tag{21}$$

The variation of the dc-link voltage with respect to the equivalent lamp resistance is illustrated by Fig. 5.

4.4 Open-Circuit-Voltage

When the lamp is in a state of open circuit, it should be mentioned that a half of the dc-link voltage will be superimposed to the generated voltage. As a result, the open-circuit-voltage on the lamp for a given dc-link voltage can be obtained as:

$$V_{oc}=\left(\frac{2M_v}{\pi}+\frac{1}{2}\right)V_{dc} \tag{22}$$

In this equation, R_S is neglected since it is very small as compared with the series inductance. Nevertheless, R_S contributes to the variation of the dc-link voltage. Therefore, the lamp open-circuit-voltage will be significantly reduced if the inverter circuit is subjected to more intrinsic losses as illustrated in Fig. 6. Fortunately, for a well designed circuit, the estimated equivalent resistance for intrinsic losses is never greater than one tenth of the lamp resistance at the rated power.

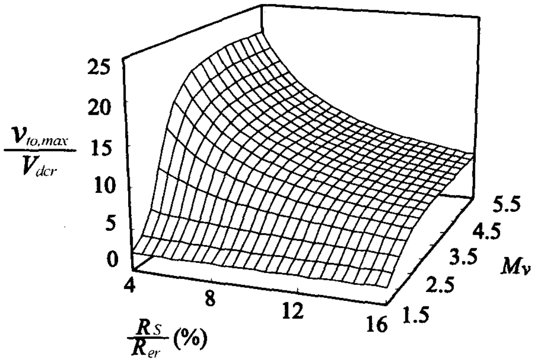


Fig. 6 Variation of open-circuit-voltage

Besides, an adequate M_V can be designed to obtain a sufficiently high voltage for the breakdown. This can ensure the successful ignition.

If an open-circuit-voltage of 1.2 kV is required for starting, R_S should be limited less than 9% of R_{er}, the equivalent series resistance at rated power. In practice, R_S lies in a range from 3% to 6%. In the design case of this paper, R_S is 5%, and M_V is 3.5, then the open-circuit voltage, v_{to}, can reach to 15 times the rated dc-link voltage, v_{dcr}.

5 Design Example

An electronic ballast with the proposed configuration is designed for a 70W metal halide lamp. The electronic ballast is supplied from an ac line source of 220-V, 60-Hz. The equivalent lamp resistance at the rated power, $R_{L(rated)}$, is 90Ω. The inverter is operated at a constant frequency of 22.5kHz, which is approximately at the center of the stable operating range in which acoustic resonance will not occur. At steady-state, the dc-link voltage is equal to the peak voltage of the ac source, 311V. The open-circuit-voltage is designed to have a peak of 2kV. This voltage is much higher than the ignition voltage for the cold lamp, which is approximately at 1.2kV, to ensure successful starting. The spark gap is adjusted to have a breakdown voltage of 3.5kV. Hence, the ignitor will not be actuated during cold starting. For hot restarting, the voltage doubling rectifier can breakdown the spark gap generating a striking pulse on the lamp.

Once the input power and the inverter frequency have been selected, the capacitance of the energy transfer switch can be determined by Eq. (17).

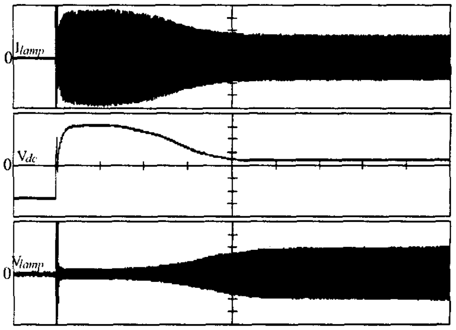
$$C_x = \frac{P_{in}}{f_s V_i^2} = 64.3nF$$

The amplitude of the load resonant current is then obtained from Eq. (15).

$$I_r = \frac{\pi f_s C_x V_{dc}}{\sqrt{2}} = 1.0A$$

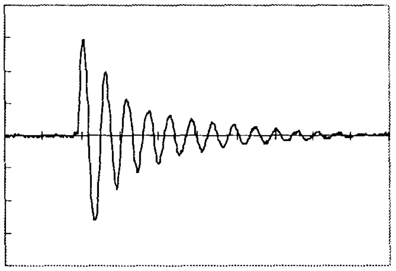
Then, the component values in the load resonant circuit can be obtained as:

$C_S = 50\ nF$, $C_b = 390\ nF$, and $L_S = 1.18\ mH$



Vlamp: 50V/div Vdc: 100V/div
Ilamp: 1A/div Time: 10s/div

Fig. 7 Waveforms for cold starting



Voltage: 10kV/div Time: 250ns/div

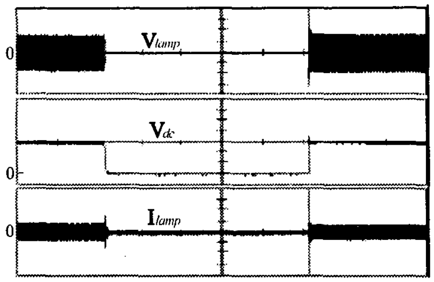
Fig. 8 Striking pulse for hot restarting

6 Experimental Results

A laboratory circuit of the electronic ballast is fabricated for experimental tests. Fig. 7 shows the waveforms of the lamp voltage and current for cold starting during an entire starting period. The dc-link voltage rises rapidly after switching on the ballast. As it reaches 500V, an open-circuit voltage of about 1.2kV is generated to ignite the lamp. After the breakdown, the drastic change of the glow discharging current results in an abrupt drop in the dc-link voltage. From glow discharge to thermionic arc, the effective lamp voltage is small and then gradually increased to its rated value. On the other hand, the dc-link voltage is first increased up to twice that at steady-state and then decreased. This transition stage lasts for about 40 seconds.

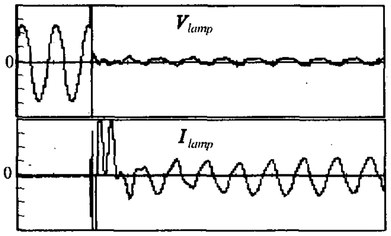
From experiments, it is found that the most difficult hot restart occurs in the period from 20 to 30 seconds after the lamp has been switched off. The minimal ignition voltage required for hot restarting is at about 28kV. Fig. 8 shows the striking pulse when the lamp is removed. The peak voltage of the striking pulse is as high as 30kV. Fig. 9 illustrates the switching transient for hot restarting after the lamp has been switched off for 25 seconds. Unlike the long transition time for cold starting, it can be found that the lamp reaches its thermal equilibrium immediately after re-ignition.

Fig. 10 shows the measured input voltage and current waveforms. The measured power factor is greater than 0.98 and the total harmonic distortion is less than 20%.



Vlamp: 200V/div Vdc: 100V/div Ilamp: 1A/div

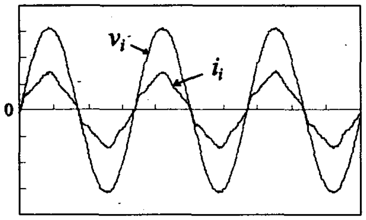
(a) Time: 5s/div



Vlamp: 500V/div Ilamp: 1A/div

(b) Time: 50us/div

Fig. 9 Switching transient for hot restarting



Voltage: 100V/div Current: 0.5A/div Time: 5ms/div

Fig. 10 Input voltage and current waveforms

7 Conclusions

In this paper, a compact, efficient and cost-effective electronic ballast with a simple ignition circuit for metal halide lamps is proposed. The electronic ballast is operated at a constant frequency, at which, the acoustic resonance problems can be avoided. A dc-link inverter with unified resonant energy tank is implemented to achieve a high-power-factor and to regulate the dc-link voltage. By properly designed circuit parameters, the dc-link voltage is able to generate a sufficiently high open-circuit-voltage for starting the cold lamp. When the lamp is under hot re-ignition, the open-circuit-voltage can be further increased up to actuate the ignition circuit.

A laboratory circuit is built for experimental tests. Experimental results show that the electronic ballast is with satisfied performance.

References

[1] M. Sugiura, "Review of Mental-Halide Discharge-Lamp Development 1980-1992," IEE Proceedings-A, Vol. 140, No. 6, Nov. 1993, pp. 443-449.

[2] E. Rasch and E. Statnic, "Behavior of Mental Halide Lamps with Conventional and Electronic Ballast," Journal of the Illuminating Engineering Society, Summer 1991, pp. 88-96.

[3] W. Pabst and D. Klien, "Igniting High-Pressure Lamps with Electronic Ballasts," Journal of the Illuminating Engineering Society, Summer 1992, pp. 14-20.

[4] W. W. Byszewski, A. B. Budinger and Y. M. Li, "HID Starting: Glow Discharge and Transition to the Thermionic Arc," Journal of the Illuminating Engineering Society, Summer 1991, pp. 3-9.

[5] G. Zaslavsky, S. Cohen and W. Keeffe, "Improved Starting of the 100-W Metal Halide Lamp," Journal of the Illuminating Engineering Society, Summer 1990, pp. 76-83.

[6] H. L. Witting, "Acoustic Resonances in Cylindrical High-Pressure Arc Discharges," 1978 Applied Physics, May 1978, pp. 2680-2683.

[7] H. Peng, S. Ratanapanachote, P. Enjeti, L. Laskai, I. Pitel, "Evaluation of Acoustic Resonance in Metal Halide (MH) Lamps And An Approach to Detect Its Occurrence, " IEEE Industrial Applications Society Annual Meeting, October, 1997, pp. 2276-2283.

[8] M. K. Kazimieroczuk, "Class D voltage-switching MOSFET power amplifier," IEE Proc. B, Electron. Power Appl., vol. 138, no. 6, Nov. 1991, pp. 285-296.

[9] H. Nishimura, H. Nagase, K. Uchihashi, T. Shiomi and M. Fukuhara, "A New Electronic Ballasts for HID Lamps," Journal of the Illuminating Engineering Society, Summer 1988, pp. 70-76.

[10] H. J. Faehnrich and E. Rasch, "Electronic Ballasts for Metal Halide Lamps," Journal of the Illuminating Engineering Society, Summer 1988, pp. 131-140.

[11] C. S. Moo, C. R. Lee, T. F. Lin, "A High-Power-Factor Dc-link Resonant Inverter, " IEEE Transactions on Industrial Electronics, vol. 46, no. 4, Aug. 1999, pp. 814-819.

[12] C. S. Moo, C. R. Lee, H. C. Yen, "A High-Power-Factor Constant-Frequency Electronic Ballast for Metal Halide Lamps, " IEEE Power Electronics Specialists Conference, May, 1998, pp. 1755-1760.