

# Control of Resonant Electronic Ballast for HPS Lamps

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**Abstract** - A novel design technique of an electronic ballast for HPS (high-pressure sodium) lamps is presented in this paper. A frequency-controlled resonant inverter for controlling power to HPS lamp and ZVS (zero-voltage-switching) technique with auxiliary inductor are employed. The auxiliary inductor guarantees ZVS action even at no-load state. A PI control scheme is selected for controlling the switching frequency and the PI gains are calculated by using the mathematical model of the electronic ballast with a low pass filter of current sensor. Experimental system is built for a commercial 250W HPS lamp and the results show a validity of the proposed technique and a good performance.

## I. Introduction

high pressure mercury lamps, metal halide lamps, HPS (high pressure sodium) lamps are widely recognized as the most efficient light source. They have been greatly developed and improved over last twenty years. Although they have high efficacy and long life-time, they need a ballast to counteract a negative resistance phenomenon, which means that lamp impedance decreases as lamp current increases. Besides the ballast should provide the high ignition voltage to start arc and regulated current to stabilize the arc. Especially HPS lamps require some kV ignition voltage to start. High frequency electronic ballast has many advantages compared with conventional electromagnetic ballast. The behavior of HID lamps driven at high frequency improves

luminary efficiency, decreases flicker and lessens weight and volume compared with that at line-frequency. Recent studies suggest the HID lamp should be represented by a resistive nature when driven at high frequency [1]. And acoustic resonance, which happens at specific frequencies [2], is also a problem.

In this paper, a novel electronic ballast for HPS lamps is designed and studied. A half bridge resonant inverter is employed and an auxiliary inductor is added to the resonant circuit to ensure operation of ZVS (zero-voltage switching) even at no-load condition. Ignitor for generating 3kV starting pulse is made of simple LC discharging circuit by using the secondary of the resonant inductor. The lamp current is controlled by V/F converter and PI feedback controller. The electronic ballast with the resonant inverter and HPS lamp are analyzed and modeled for determining the parameters of PI controller. And the experimental results with commercial 250W HPS lamp show stable operation with free acoustic resonance and the validity of the designed ballast.

## II. Electronic ballast

Typical topology of electronic ballast consists of a power factor controlled rectifier and a half bridge inverter. The proposed electronic ballast with series resonant inverter is shown Fig. 1. The rated voltages of commercial HPS lamps are around 100V, so a half bridge inverter can be chosen with DC bus 350V. The capacitor  $C_0$  is chosen for ZVS and the auxiliary

inductor  $L_{max}$  is needed to retain ZVS condition at no-load state (lamp is disconnected or happen to turn off). Two switching devices, Q1 and Q2, are controlled by V/F (voltage-to-frequency) pulse generator and always activated complementary with dead time  $T_d$ . Fig. 2. shows the switching waveforms of inverter.

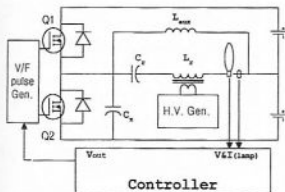


Fig. 1. Configuration of electronic ballast for HPS lamp

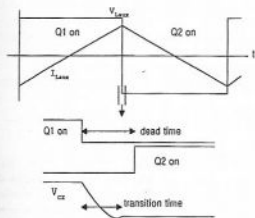


Fig. 2. Switching waveforms of inverter.

The current flowing through  $L_{max}$  should discharge  $C_x$  to be transferred during the dead time  $T_d$  of switching pulses and Q2. And when HPS lamp is not connected, the whole current on  $C_x$  flows through  $L_{max}$ . Since the peak current of  $L_{max}$  is determined by switching frequency  $f_s$ , the maximum value of  $L_{max}$  can be calculated in the half-bridge inverter

as

$$L_{max} = \frac{I_d - 2f_s I_d^2}{8f_s C_x} \quad (1)$$

The HPS lamp driven by high frequency ballast can be modeled to a pure resistance that is being changed from  $R_{min}$  (at starting) to  $R_{max}$  (at steady-state) [1]. Fig. 3. shows typical starting characteristics of general HPS lamps. The lamp voltage is very low and the starting current is 130% of rated current at starting.

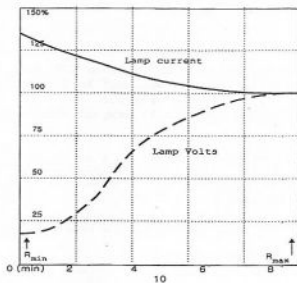


Fig. 3. Typical characteristics in starting

Because there are many bands causing the acoustic resonance when the lamp is operated at high frequency, we should operate the ballast in narrow frequency range. The frequency generating acoustic resonance is diverse as structures of lamps. Fortunately, HPS lamp has safe-frequency range from 25kHz to 35kHz and guarantees 6% higher luminous efficiency in frequency over 10kHz. And we should keep supplying 130% rated current on the lamp during the burning time. From these conditions, we can determine a range of switching frequencies from the characteristic curves of the high-Q resonant inverter as shown Fig. 4.

Since the operating band is apart from

the resonant frequency due to the lamp voltage is smaller than  $V_{dc}/2$ , the resonant circuit has big reactance and this makes the response of system fast (the system becomes zero order) [3].

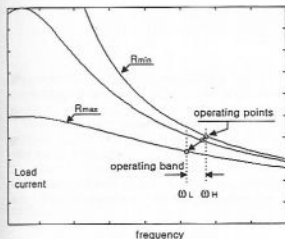


Fig. 4. Characteristics of a series resonant inverter

With the equivalent resistance [ $R_{min}$ ,  $R_{max}$ ] and the characteristic curves, we can determine the operating band [ $\omega_L$ ,  $\omega_H$ ]. By linearizing the characteristic curves around the operating points as shown Fig. 4, we can take a gain  $-K_r$  shown in Fig. 5(a) as a transfer function of the resonant inverter. The half bridge inverter is driven by output  $V$  of V/F converter and the transfer function from voltage to output current  $I_0$  of inverter is

$$i = -k_r V + I_0 \quad (2)$$

Fig. 5(b) shows the block diagram of frequency controlled series resonant inverter. Generally, output of detected current passes a low pass filter and the time constant of LPF is taken as 10 to 20 times of that of input. Hence, we must take into account LPF behavior.

A PI controller consists of a proportional and an integral parts; that is,

$$G_c(s) = k_p V + \frac{k_i}{s} \quad (3)$$

Fig. 5(b) depicts the system block diagram with LPF and by referring the lamp voltage, command  $I^*$  can be determined. The transfer function of the electronic ballast system is given by

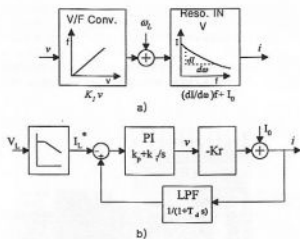


Fig. 5. The model of resonant ballast  
a) model of frequency-controlled inverter  
b) block diagram of the ballast

$$\frac{i}{I_0^*}(s) = \frac{K_r (K_p T_i s^2 + (K_i T_i + K_p) s + K_i)}{T_i s^2 + (1 + K_r K_p) s + K_r K_i} \quad (4)$$

and the poles of the system are

$$P_1, P_2 = -\frac{K_r K_p + 1}{2T_i} \pm \sqrt{\left(\frac{K_r K_p + 1}{2T_i}\right)^2 - \frac{K_r K_i}{T_i}} \quad (5)$$

Since the system band width must be smaller than that of LPF, the parameter  $k_p$  is set to zero. With  $k_p = 0$ , the poles become

$$P_1, P_2 = -\frac{1}{2T_i} \pm \sqrt{\left(\frac{1}{2T_i}\right)^2 - \frac{K_r K_i}{T_i}} \quad (6)$$

and zero of the system is

$$Z = -\frac{1}{T_i} \quad (7)$$

To make the system with slightly

under-damped response or to avoid over-damped response, following condition is required

$$K_i > \frac{1}{4T_i K_i} \quad (8)$$

Therefore, the controller of the inverter must have only integral action part.

The ignitor generating high voltage pulse consists of  $L_s$ - $C_s$  resonant circuit and one triac as shown in Fig. 6. the  $L_r$  is the main inductor of resonant circuit and  $L_s$  is secondary of it. The capacitor  $C_s$  is charged by  $V_{dc}$  through  $R_s$ .

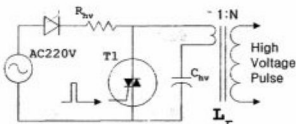


Fig. 6. H.V generator

The high voltage is generated when  $C_s$  is being discharged. The minimum condition is 1kV of 0.5usec for igniting of HPS lamps[4]. We need 3kV of 1usec pulse to ensure the ignition in worst case. Let  $V_{dc}$  be 300V, 10:1 turns ratio of  $L_s$  to  $L_r$  is required and the resonant circuit must meet the following condition

$$\pi \sqrt{L_s C_s} > 1 \times 10^{-5} \quad (9)$$

### III. Experiment and Result

The proposed resonant electronic ballast for experiment was implemented using MOSFET IRF450s and CMOS 4046 for a commercial 250W HPS lamp. The values of the circuit are  $L_r=400\mu H$ ,  $C_z=1.8\mu F$  and  $L_{aux}=2mH$ . Switching frequency band is between 25kHz and 27kHz. Fig. 7. shows implemented electronic ballast. Fig. 8. shows the transient time

response of lamp current and we can see some overshoot and oscillation. Fig.8. (a) shows the steady-state switching waveforms of lamp voltage and current and Fig. 8. (b) shows current-to-voltage X-Y waveform. These waveforms inform us that HPS lamp behavior with a high frequency ballast is similar to a pure resistor.

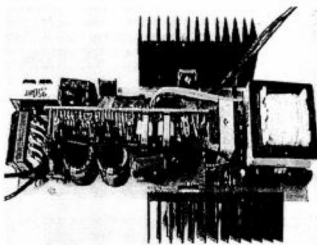


Fig. 7. The electronic ballast for experiment

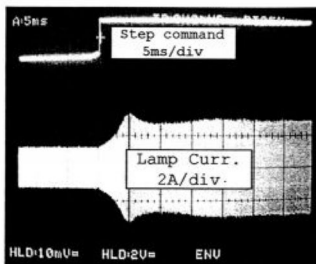
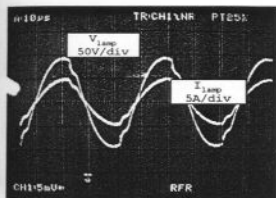


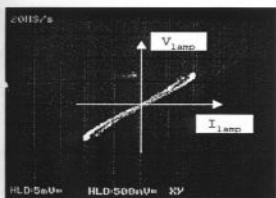
Fig. 8. Step response of HPS ballast

Fig. 10. shows output voltage waveform of high voltage pulse generator. The peak voltage is about 3kV. The HPS lamp is being ignited at 1kV and the duration

of the pulse is lusec. the frequency of high voltage pulse is about 250kHz.



a)



b)

Fig. 9. Voltage and current waveforms of HPS lamp

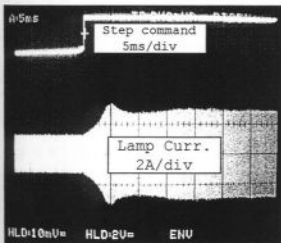


Fig. 10. Voltage waveform of H.V pulse generator

#### IV. Conclusion

The novel design of electronic ballast for HPS lamps have been proposed and the practical implementation have been presented in this paper.

Proposed electronic ballast consists of a half-bridge resonant inverter with 350 V<sub>DC</sub> bus, the auxiliary inductor for ZVS, PI controller for controlling current of HPS lamp and HV ignitor. The model for resonant inverter with LPF was established and by using the model, the values of control gain  $k_i$  and  $k_p$  were obtained for the proposed electronic ballast. As the result, it is found that the value of  $k_p$  must be zero and the value of  $k_i$  has to be a great.

By the experiments with 250W HPS lamp, it has been shown that the proposed electronic ballast for HPS lamp is working successfully.

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