Practical Design Considerations of LCC Resonant Inverter for Metal Halide Electronic Ballasts

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Abstract– **LCC resonant inverter is the main topology widely used in the electronic ballasts. The simplified methods of analysis and design are presented in this paper. These methods come from the practical requirements of metal halide electronic ballast. The analysis and design during ignition and steady state operating are included. A prototype of 250W metal halide electronic ballast verifies the methods.**

1 Introduction

Metal halide (MH) lamps are part of the lamp family known as HID lamps. Compare to other lighting sources, they have good luminous efficacies, excellent color rendering and long life. They are usually used for illuminating large areas, such as gymnasiums, warehouses and workshops, where color rendition is important.

Up to now, majority of MH lamps are supplied by traditional electromagnetic ballast. But the weights, volumes and power loss of electromagnetic ballasts are not assorted with metal halide lamps themselves. On the contrary, Electronic ballasts operating at high frequency are the good choice to drive metal halide lamps. They are small, light and high efficiency.

Many electronic ballast topologies and design methods have been proposed in the past. LCC resonant inverter is the popularly accepted topology because it has the simplest circuit components and can be suitable for both ignition and steady state operation compared to other topologies [1]. The former printed analyses are detailed but are too complex to design in practice, especially for MH lamp ballast [1,3~9].

This paper proposes a simplified design flow. In the first part, the practical requirements of MH lamp and relevant design considerations of electronic ballast are introduced. In the following, the analyses, simulations and detailed designs are given. Finally, The experimental results on the prototype 250W electronic ballast for MH lamp are presented and discussed.

2 Design Considerations

Design considerations of LCC resonant inverter must meet the requirements of both ignition and steady state operation of MH lamps.

Before ignition, the inverter should provide enough high voltage across the electrodes to initiate and maintain glow discharge. After ignition, the inverter should provide sufficient current at glow discharge voltage forcing the glow-to-arc transition. Hence, the ignition pulse needs not only high voltage but also enough pulse width. Such ignition conditions are much rigor than other HID lamp. For simpler design and lower cost, the ignition frequency and the operation frequency are designed to be same for metal halide lamp ballasts here.

Besides ignition, the resonant inverter needs to transport appropriate power to lamp, including rated lamp voltage and current. When the lamp works at high frequency, the lamp can be equivalent to a pure resistor. Moreover, the lamp resistor will be increased gradually during lifetime. Fortunately, this situation is not serious as in HPS lamp.

Since metal halide lamp ballasts operate with high frequency, acoustic resonance must be adverted by designer. The acoustic resonance is mainly related to operation frequency and the threshold energy at this operation frequency. Because LCC resonant inverter does not provide constant lamp power during one cycle, it can't avoid acoustic resonance automatically. Many methods are proposed to eliminate acoustic resonance. For example, we can select a fit operation frequency at which acoustic resonance is not observed. And that operation frequency of LCC resonant inverter would be beforehand decided based on avoiding acoustic resonance.

Power loss is another consideration of ballast design. Switching loss is the majority of power loss. Reduction of the switching loss can make whole ballast high efficiency and high reliability. Zero-voltage switch can be given by LCC resonant inverter as long as the angle of inductor current lags the input voltage [6,10].

3 Analysis and Design

LCC resonant inverter in electronic ballasts usually behaves as band-pass filter for the input voltage. Fig. 1 shows the simplified basic series-parallel LCC resonant inverter. Here the lamp is equivalent to a resistor.

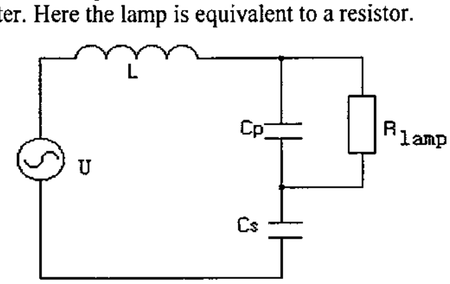

Fig. 1simplified LCC resonant inverter using fundamental approximation

The fundamental approximation is useful to analyze such kind of resonant inverter. In this way, only fundamental component is considered with sinusoidal excitation. So it is only valid in the frequency range within which the resonant tank acts as a good filter and the half bridge switches are driven symmetrically [3].

The following nomenclature is used for the following analyses of LCC resonant inverter.

Series-resonance parameters:

$$\omega_s = \frac{1}{\sqrt{LC_s}} \qquad Z_s = \sqrt{\frac{L}{C_s}}$$

$$Q_s = \frac{Z_s}{R} \qquad m = \frac{\omega}{\omega_s} \qquad (1)$$

Parallel-resonance parameters:

$$\omega_p = \frac{1}{\sqrt{LC_p}} \qquad Z_p = \sqrt{\frac{L}{C_p}}$$

$$Q_P = \frac{R}{Z_p} \qquad k = \frac{\omega}{\omega_p} \qquad (2)$$

Relationships between series-resonance and parallel-resonance:

$$\alpha = \frac{C_p}{C_s} \qquad Q_p Q_s = \sqrt{\alpha} \qquad (3)$$

where ω is the operation angle frequency which is decided by avoiding acoustic resonance.

3.1 Lamp Voltage gain

The LCC resonant tank voltage transfer function is given by equation (4).

$$H_V = \frac{U_{lamp}}{U} = \frac{1}{\sqrt{(1+\alpha-k^2)^2 + \frac{1}{Q_p^2}(k-\frac{\alpha}{k})^2}} \qquad (4)$$

This equation can be used to calculate the steady state lamp voltage roughly. It also can be used to estimate the lamp voltage when igniting.

Before igniting, the lamp loop is considered as open loop. So Q_p is infinity and equation (4) can be modified to equation (5).

$$\frac{U_{lamp}}{U} = \left|\frac{1}{1+\alpha-k^2}\right| \qquad (5)$$

From equation (5), the open loop voltage is related to two parameters, one is the circuit parameter α, the other is control parameter k. Smaller is the α or higher is the frequency ω, the voltage gain is higher. In practice, only LCC resonant inverter itself decides the open loop voltage gain, because the operation frequency is fixed in advance.

It is noticeable that the ignition frequency is selected to be same operation frequency as mentioned above. The steady state frequency is far from the parallel-resonant frequency of the inverter. The fundamental approximation brings big design error. The high harmonics of the input square wave voltage must be considered. Fig.2 gives the voltage gain of fundamental and 3rd harmonic assuming that α is one. It can be found that 3rd harmonic also has a rather high gain at lower frequency. The superposition voltage of fundamental and 3rd harmonic is enough to ignite metal halide lamp, especially for lamps with auxiliary electrode.

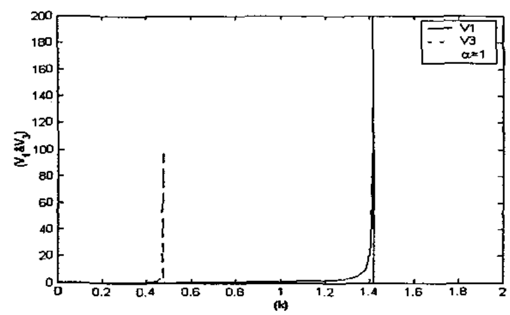

Fig. 2 Voltage gain of fundamental and 3rd harmonic(α =1)

According to HPS design experience [6], the switches of resonant inverter can not work at ZVS at such frequency during ignition. However, Due to a very low level switching frequency and short ignition period, the switching loss can be omitted.

3.2 Current in switches

The current in switches, equal to that in the inductor, is related to the circuit equivalent impedance saw from the source. During ignition period, the inverter is a pure LC resonant loop. The current in switches is larger than that in the steady state. So the current must be controlled under acceptable level. In steady state, if the series capacitor is small, the lamp impedance is rather lower than its paralleled capacitor. The inverter is an approximate LCR series loop. The current in switches is equal to the rated current of lamp. Because of the pure resistive of lamp with high frequency operating, the current in switches rests with lamp voltage.

For high ballast efficiency, the inverter should work in the zero voltage switching mode. The phase angle between inductor current and switch voltage is a key factor in ZVS. It is calculated by equation (6).

$$\theta = \tan^{-1}[kQ_p(1+\alpha-k^2) - \frac{(k-\alpha/k)}{Q_p}] \qquad (6)$$

For the purpose of ZVS in steady state, θ must be under zero. This angle is used to estimate the ZVS for its easy measurement on the oscillograph.

3.3 Lamp power

Usually, the nominal lamp equivalent resistor at 50/60 Hz is given in the specification. So the lamp power is easy estimated from equation (7).

$$P_{lamp} = \frac{|U_{lamp}|^2}{R_{lamp}} \qquad (7)$$

The lamp power is mainly restricted by the inductor and series capacitor in the approximate series-resonant inverter. This simplified analysis can make design easy because the lack of unimportant parameter.

The accurate power transfer function is

$$\frac{P_{lamp}}{P_0} = \frac{1}{\left[1 + Q_s^2\left(m - \frac{1}{m}\right)^2\right]} \qquad (8)$$

where P_0 is defined as equation (9)

$$P_0 = \frac{2U^2}{\pi^2 R} \tag{9}$$

From equation (8), the lamp power transfer function is below one. Many couples of L and Cs can satisfy lamp power equation. Usually, L is several hundred uH and Cs is several uF.

4 Simulation and Experimental results

A prototype of 250W electronic ballast is experimented to verify the rationality of the analysis and design. The parameter here used in ballast is L=220uH, Cs=2.2uF, Cp=3.3nF, f=50kHz. The lamp is HQI-E 250/N from OSRAM. The rated rms lamp voltage is 133V and rms lamp current is 2.10A. So the equivalent lamp resistor is 63.3 ohm.

At first, we see the lamp voltage in the ignition period. Both the Matlab simulation and the measured waveform contrast in Fig.3. It can be found the similarity between simulation results and the measurement ones. Due to the charge effect of Cs, the measured wave is not symmetrical.

Fig.4 is the simulation result of lamp power using equation (8). The lamp works at the cross point of two line and its calculated lamp power is about 240W. This result indicates the metal halide lamp will work on the verge of rated lamp power.

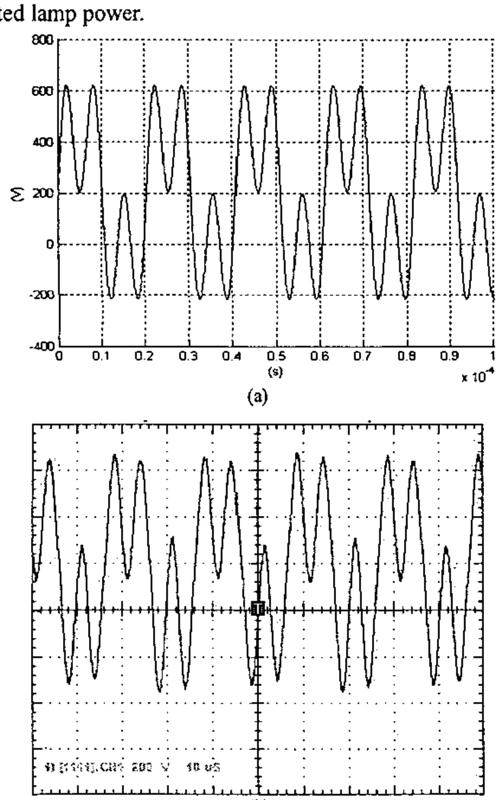

Fig. 3 (a)simulation results of ignition voltage

(b)measurement of ignition voltage

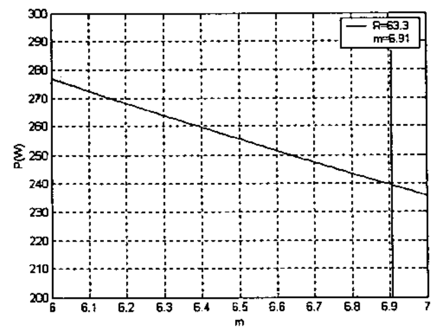

Fig.4 Lamp power as a function of m

Fig.5 shows the phase angle between inductor current and input source voltage. The value on the cross point is about -45°. This illuminates the inverter switches are operating at ZVS during steady lighting.

Fig.6 give the characteristic of lamp current and voltage. We can see that the metal halide lamp exhibit resistance impedance. The lamp current is obtainable by a sample resistor.

5 Conclusion and Discussion

This paper emphasizes the design requirements of metal halide lamp ballast. From this, the simplified analysis and design of LCC resonant inverter are given.

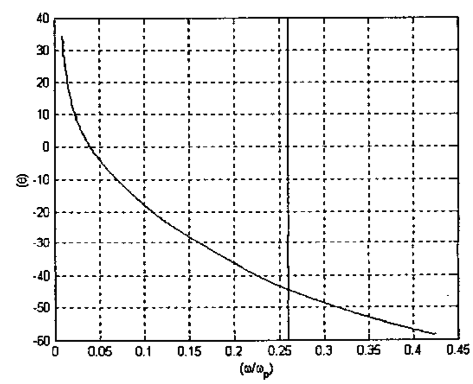

Fig.5 Phase angle between I_L and U versus k

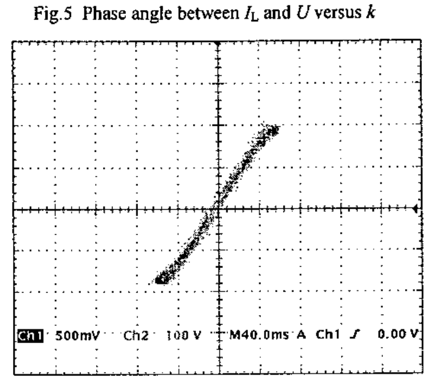

Fig.6 lamp voltage and current characteristic

The design of electronic ballast is implemented as following flow.

- Because the serious acoustic resonance occurs in metal halide lamp working at high frequency. Operation frequency is the preferential and key parameter to be decided.
- The ignition voltage must beyond the lamp arc breakdown voltage. So the ratio of *Cp* and *Cs* should be small to obtain higher open loop voltage during ignition. Here the 3rd harmonic of input voltage is considered in design procedure. The values of *Cp* and *Cs* can be selected.
- According to the lamp resistor indicated in the specification, the lamp voltage and power should be closed to rated values. After *L* is restricted, the parameters of resonant circuit are all determined here.
- Because many groups of parameters satisfy the former requirements, additional but important conditions are considered. The resonant current must be restricted and The phase angle should be under zero for reducing the switching loss.

It is noticeable that same single stable operation frequency may exist in one or several MH lamps. But for lots of lamps from different manufacturers, this frequency hardly can be found. Hence, the measures to avoid acoustic resonance should be researched in the future.

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