A UNITY POWER FACTOR HIGH FREQUENCY PARALLEL RESONANT ELECTRONIC BALLAST

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ABSTRACT

A simple electronic ballast circuit for Metal Halide Lamp is suggested. It operates at about 20 kHz resonant frequency with zero voltage switching scheme. It also adopts the self-oscillation control scheme for base drive with no additional driver and controller, so that the ballast becomes smaller and lighter. IT has little acoustic noise, low EMI, and reliable operation, as well. Furthermore, it operates with almost unity input power factor, without adding any additional power factor correction circuit. These features are verified through analysis, simulation and experiment.

I. INTRODUCTION

In rescent years, the electronic ballasting of lamps has been well established. For fluorescent lamps, a great many electronic ballasts have been already installed. But, even if the electronic ballasts for high intensity discharge lamp has been used widely due to their many advantages, it has not been much developed so far. This paper proposes a compact, unity power factor electronic ballast which generates no audible noise and has high light efficacy.

As conventional electric ballast is composed of choke coil or leakage transformer, the improvement of the features of the ballast is rather limited. Therefore, the electronic approach for ballast has been taken. Among the approaches, as a operation, PWM technique has been popularly employed. In spite of such merits as simplicity, easy control and low device stress, the technique has demerits such as difficulty in high frequency operation and low efficiency. In addition, it yields noises due to hard switching of employed elements. By the way, the resonant converters are known as their capability of high frequency operation and soft switching. Moreover, It is well known that some discharge lamps have better performance when operated at high frequency than at low frequency. Therefore, the resonant technique adopting high frequency operation and zero voltage switching gives advantages to the lamp as well as to the ballast itself. Zero voltage switching helps the circuit to have low switching loss, which makes the ballast more efficient. Moreover, it reduces EMI. This fact enables the ballast circuit to operate at high frequency. High frequency operation also helps to reduce the size of magnetic component and filter. In addition, the suggested ballast circuit

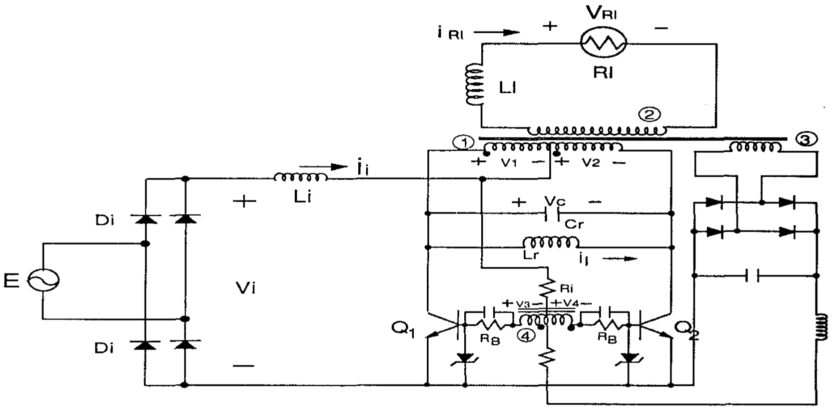


Fig.1 Schematic diagram of proposed ballast circuit

utilizes the self-oscillational base drive scheme so that the ballast needs no additional base driver or controller to make it compact and reliable.

Since the ballast for out-door lighting utilize the utility source as their input, it is mandatory for ballast to have a good input power factor. Some techniques have been developed to improve the input power factor. Most of them incorporate an additional circuit or complicated control algorithm in order to achieve good input power factor. But, this is not desirable because the ballast becomes complex, bulky and expensive. By the way, since resonant converter has been researched chiefly on DC to DC conversion, power factor has not been much considered. But, the suggested circuit obtains unity input power factor, conserving the merits of resonant operation and incorporating no additional circuit.

System characteristics are fully described by modeling of the circuit. Those facts are verified through analysis, simulation and experiment.

II. CIRCUIT DESCRIPTION AND OPERATION

Figure 1 shows the overall schematic diagram of the proposed ballast circuit which has self base driver and controller circuit. The circuit consists of full-wave rectifier and conventional push-pull inverter. with parallel resonance circuit. Resonance occurs mainly through C_r and L_r. Its operation is explained as follows.

In the steady state, the resonant voltage v_c becomes sinusoidal waveform. This voltage continues to turn the $Q_1(Q_2)$ on and simultaneously turn the $Q_2(Q_1)$ off in synchronization with the zero crossing points of the resonant voltage, and the zero voltage switching conditions of transistors are satisfied. In the driver circuit, diode bridge rectifier which is connected to the transformer leg 3 plays a role to supply the transistor base current steadily through proper filtering network. As a result, the square wave current flows into the bases of the transistors.

Typical waveforms of several points are illustrated in Fig. 2. The lamp voltage v_{Rl} looks distorted as in the figure because of the lamp characteristic.

III. ANALYSIS

From the operative behavior, the proposed circuit can be regarded as the subset of Quantum Parallel Resonant Converter (QPRC) [1]. The average value of the resonant capacitor voltage is to be obtained from the modeled circuit of QPRC. Since we know that the capacitor voltage undergoes a sinusoidal waveform, the resonant voltage can be easily given by analysis of the average value of the resonant capacitor voltage. Therefore, the overall operation can be described satisfactorily with the circuit shown in Fig. 3 which is the model of the proposed circuit because the parallel resonant circuit can be modeled as an equivalent capacitor. In this circuit, the voltage V_c is the average value of the resonant voltage v_c.

Following equation describes the dynamics of the circuit of Fig. 3:

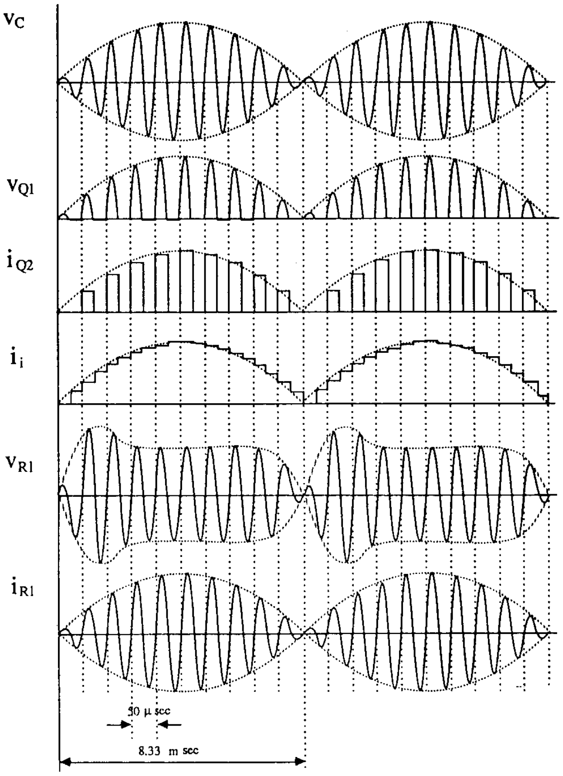


Fig.2 Typical waveforms of proposed ballast circuit: 20 KHz waveforms' periods are exaggerated for easy view

$$L \frac{d i_L}{d t} + V_c = V_i \tag{1}$$

$$C \frac{d V_c}{d t} + \frac{V_c}{R} = i_L . \tag{2}$$

Combining equations (1) and (2) yields

$$\frac{d^2 V_c}{d t^2} + \frac{1}{RC}\frac{d V_c}{d t} + \frac{1}{LC} V_c = V_i . \qquad (3)$$

We can also represent the equation (3) as

$$\frac{d^2 V_c}{d t^2} + 2h \frac{d V_c}{d t} + \omega_n^2 = V_i \qquad (4)$$

where

$$\omega_n = \frac{1}{(L_i C_{eq})^{1/2}} , \qquad h = \frac{1}{2RC} . \qquad (5)$$

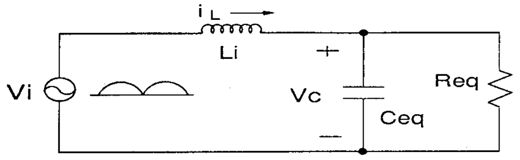
Substituting reasonable initial conditions $V_c(0)$, $i_L(0)$ in equation (4) and (5), they can be solved as

$$V_c = \left[1 - e^{-ht} \frac{\sin(\omega t + \theta)}{\sin\theta} \right] V_i \ , t \geq 0 \qquad (6)$$

where

$$\omega = (\omega_n^2 - h^2)^{1/2} , \qquad \theta = \tan^{-1}(\omega/h) . \qquad (7)$$

As time approaches infinity, V_c goes to V_i, that is, the voltage V_c of the model becomes equal to the full wave rectified average value of the resonant capacitor voltage v_c of original circuit transformed to the dc-link side.



$C_{eq} = \pi^2 C_r$

$R_{eq} = (1 + Q_l)^2 R_l$

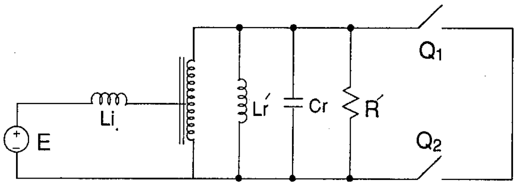
$Q_l = \omega_r L_l / R_l$

Fig.3 Model of suggested ballast

Thus, the knowledge of V_c of the model gives full description of v_c of the original circuit. The latter is the modulated sine wave which has resonance frequency with its average envelop just like the former.

Now, to analyze the system in detail, what we have to know is the resonant frequency which depends on C_r and equivalent parallel inductance L_r. The inductance L_r is obtained by considering the resonant inductor L_r, load inductor L_l and magnetizing inductance L_m of the transformer. Suggested circuit may be redrawn as shown in Fig. 4. If we consider the alternating switching operation, the circuit of Fig. 4 can be equivalently redrawn as shown in Fig. 5. From the Fig. 5, the resonant frequency ω_r can be given as

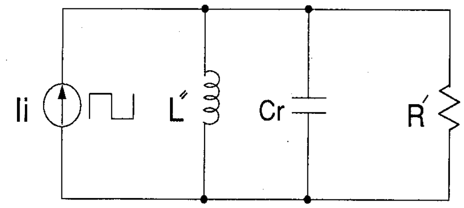
$$\omega_r = \frac{1}{2} \left\{ \frac{4}{L C_r} - \left[\frac{1}{R C_r} \right]^2 \right\}^{1/2} . \qquad (8)$$



$L_r' = L_r \,//\, \frac{Q_l^2}{(1+Q_l)^2} n^2 L_l \,//\, L_m$

$R' = (1+Q_l)^2 n^2 R_l \qquad (Q_l \gg 3)$

Fig.4 Equivalent circuit #1 of suggested circuit



$L'' = L' \,//\, 4L_i$

Fig.5 Equivalent circuit #2 of suggested circuit

IV. SIMULATION

We considered 60Hz−220V sinusoidal voltage as an input to drive 175 W Metal Halide Lamp. The waveform shown in Fig. 6 (b) is used as the dc−link voltage to improve the input power factor. Large ripple of the dc−link voltage gives some difficulties in designing the circuit. These difficulties are overcome by using the simplified model of the converter. The selected values of the components are as follows:

$L_i = 17\ mH$
$C_r = 0.62\ \mu F$
$L_r = 1.57\ mH$
$R_l = 82\ \Omega$
$L_l = 2.5\ mH$

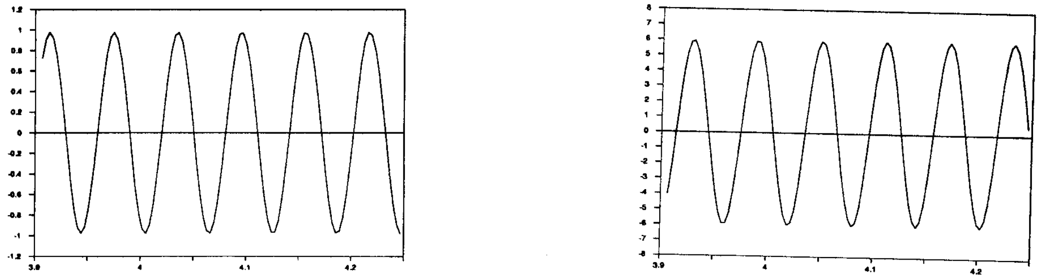
(a) Input voltage (b) Rectified input voltage

(c) Resonant voltage (×1000) (d) Resonant current

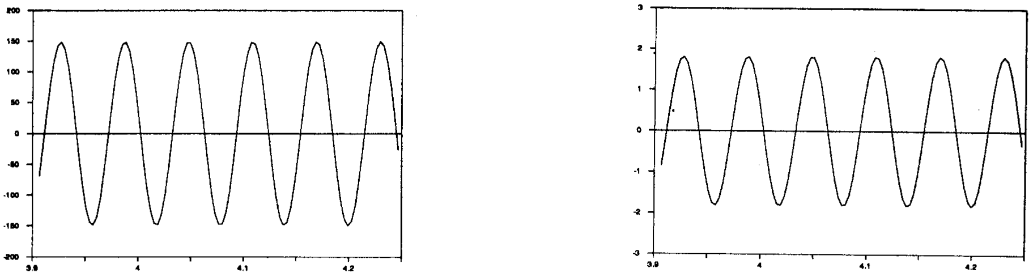
(e) Load voltage (f) Rectified current

(g) Transistor voltage (×1000) (h) Transistor current

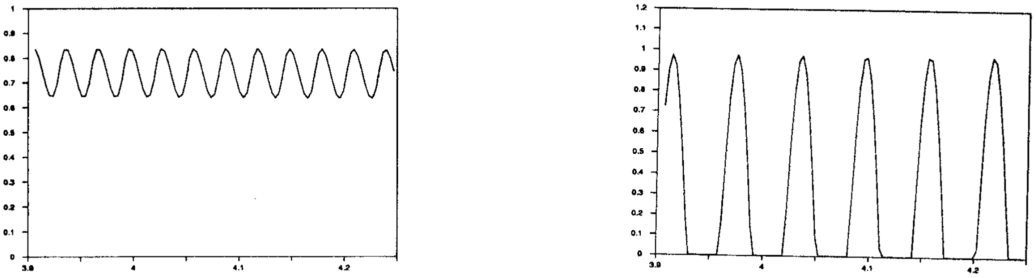
Fig.6 Waveform of each part at 60 Hz view



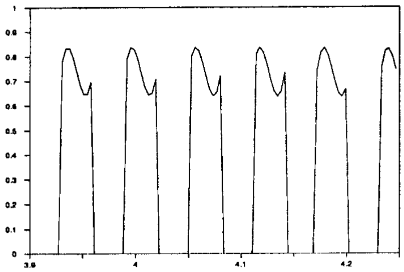
(a) Resonant voltage **(b) Resonant current**



(c) Load voltage **(d) Load current**



(e) Rectified input current **(f) Transistor voltage (×1000)**



(g) Transistor current

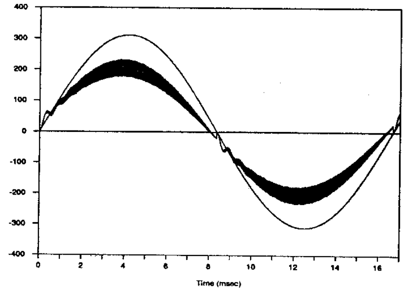


Fig.8 Input voltage and input current

Fig.7 Waveform of each part at 20 KHz view

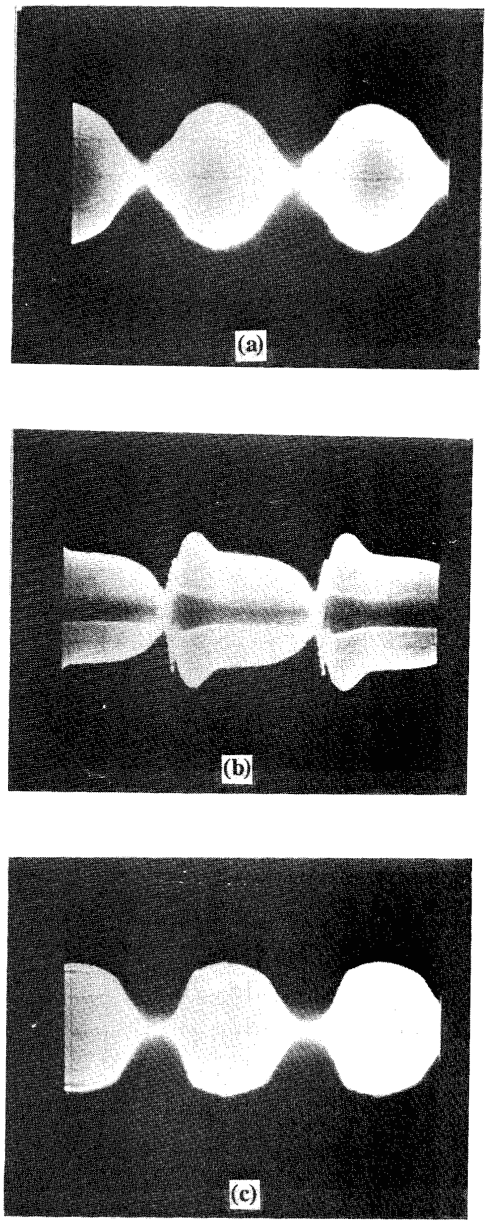


Fig.9 Waveform of each part; With view of 60 Hz basis

(a) Resonant capacitor voltage v_r: 500V/div; 2ms/div

(b) Lamp voltage v_l: 100V/div; 2ms/div

(c) Lamp current i_l; 1A/div; 2ms/div

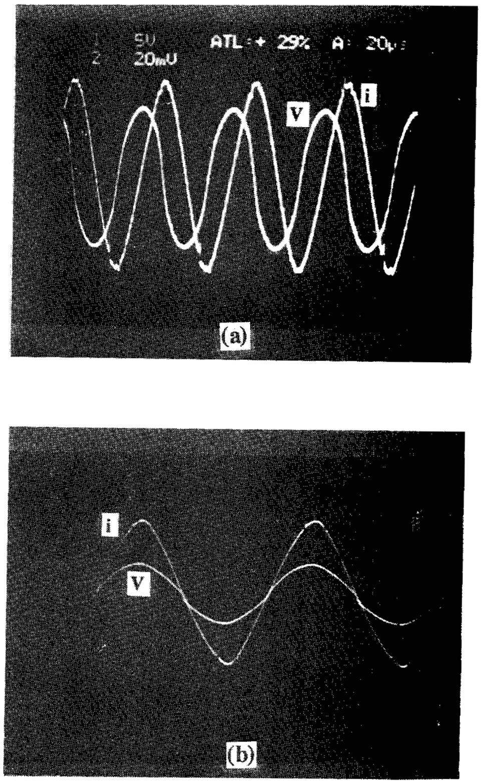


Fig.10 Waveform of each part; With view of 20 KHz basis:

(a) Resonant capacitor voltage and resonant inductor current: 500V/div; 2A/div; 20μs/div;

(b) Lamp voltage and lamp current: 200V/div; 1A/div; 10μs/div

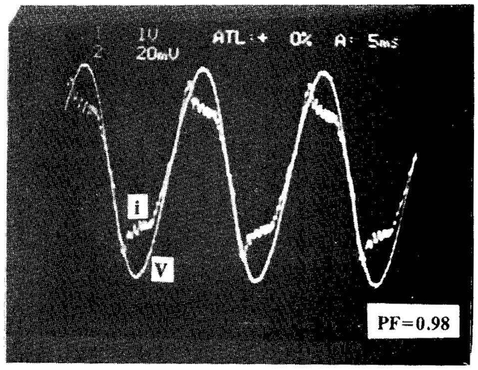


Fig.11 Input voltage and input current waveform: 100V/div; 1.5A/div; 5ms/div

The resonant capacitor voltage v_c is plotted in Fig. 6 (c). It is shown that its envelop forms almost a sine wave as given in equation (6), which is modulated with about 20 kHz resonant sinusoidal voltage. Resonant inductor current i_L and load voltage v_L are also plotted in Fig. 6 (d), 6 (e), respectively. These form the sinusoidal wave which is modulated with about 20 kHz sinusoidal waveform, too.

Intermediate input current i_i is shown in Fig. 6 (f). The thick, dark part of this figure is zoomed in as shown in Fig. 7 (e). The larger the input filter inductor L_i is, the smaller the dark area is. So, a trade-off exists between the value of L_i and its cost in the condition that the input power factor keeps near unity. We can see the deviation from the exact sinusoidal waveform at Fig. 6 (f). This is the repetitional transient response due to the abrupt change of v_i. Transient state is repeated every half period of 60 Hz sinusoidal input. This, however, brings about no serious problem in the steady state as the input voltage does not get changed abruptly but get changed continuously, and is zero at the starting point of transient response. The transistor collector-emitter voltage v_Q and the collector current i_q are also plotted in Fig. 6 (g) and (h), respectively. Fig. 6 (g) shows that the transistor voltage stress rises up to about 1,000 volts. The requirement of high voltage switching element is the demerit of the proposed circuit. But, in the proposed circuit, the switching loss becomes small due to the zero voltage switching operation.

The operation on the frequency 20 kHz basis is shown in the following figures. Figure 7 (a) shows the resonant capacitor voltage v_c, and Fig. 7 (b) shows the resonant inductor current. As might be expected, they are sinusoidal waveforms. The voltage v_Q of transistor collector-emitter voltage is given as shown in Fig. 7 (f) in which the zero voltage switching is clearly shown. The current i_Q of transistor collector current is also indicated as shown in Fig. 7 (g). Load voltage and load current waveforms are plotted in Fig. 7 (c) and (d), respectively. Also the input current waveform i_i is given in Fig. 7 (e).

Input current is plotted in parallel with the input voltage as shown in Fig. 8. It shows the input power factor is close to unity. These simulation results shows that the suggested ballast circuit operates well in the given operating condition.

V. EXPERIMENTAL RESULTS and DISCUSSIONS

Experiment is done for the 175 watt metal halide lamp which is one of the most popular in out-door lighting. The values of the components are the same as those used in the simulation except the actual lamp instead of simplified model resistor .

Resonant voltage v_c across the capacitor C_r is given as shown in Fig. 9 (a). Fig. 9 (b) shows the voltage across the lamp and Fig. 9 (c) shows the current flowing through it. The voltage has such shape because the lamp shows negative resistance characteristic when the current exceeds 1 A.

Resonant voltage and resonant current is indicated as shown in Fig. 10 (a) on 20 kHz basis. The voltage and the current of the load is shown in Fig. 10 (b) also on 20 kHz basis. They are almost a sinusoidal waveform. We can see from it that the voltage-ampere characteristic of the metal halide lamp is nearly pure resistive at a given operating condition.

Input Power Factor

Output part including the load itself has very poor power factor because large reactive impedance is cascaded to the lamp, the smaller resistive impedance compared to reactive impedance. Measured value of it was only $\cos\theta = 0.22$.

But, suggested ballast has nearly unity input power factor without regard to that of load part. Main idea is described as follows.

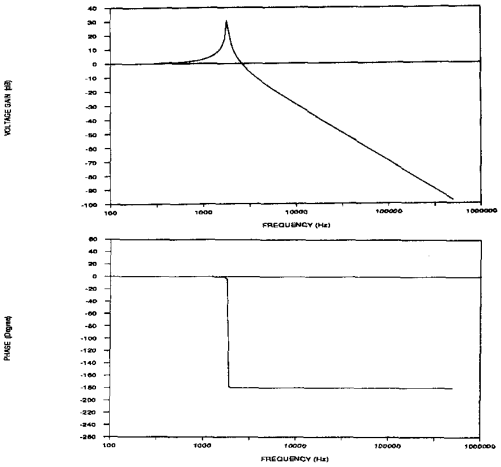


Fig.12 Frequency response of the model

Describing Laplace equation of the circuit shown in Fig. 3 can be written as

$$\frac{V_c}{V_s} = \frac{1}{L_i C_{eq} s^2 + \frac{L_i}{R} s + 1} \qquad (9)$$

Also its frequency response is plotted in Fig. 12. The voltage gain V_c / V_s is unity (0 dB) at point A at which the frequency is 120 Hz, and -50 dB at point B at which the frequency is 20 kHz, as shown in Fig. 12. This implies that L_i is shorted and C_{eq} is open because the impedance of L_i is relatively small and the impedance of C_{eq} is relatively very large for 120 Hz. Moreover, it means that we can approximate the whole circuit as pure resistive load. This is shown in Fig. 13. Therefore, the suggested circuit has unity power factor regardless of the load.

Experimental result shows that the power factor is more than 0.98 as shown in Fig. 11. The reason why it is not exactly unity may be explained by the electric characteristic of the lamp. Negative resistance of the lamp at around 1 A results such a distorted current waveform. This caused the ballast to deviate from unity power factor.

Luminous Efficacy

One of the major motivations of developing electronic ballast circuit is to improve light efficacy. It is well known that the luminous efficacy improves by 15-20 % when the lamp operates at several kHz.[2] For higher efficiency, suggested circuit adopts zero voltage switching. In addition, the resonant component values are properly designed to minimize the conduction loss. Suggested ballast circuit showed the improvement of the luminous efficacy by 9 % compared to the conventional magnetic ballast. The primary factor of loss was still due to the switching loss of the transistors. As the transistors used in the experiment were manufactured for the use of high voltage, its switching speed was rather slow. Higher efficacy is expected with faster switching devices.

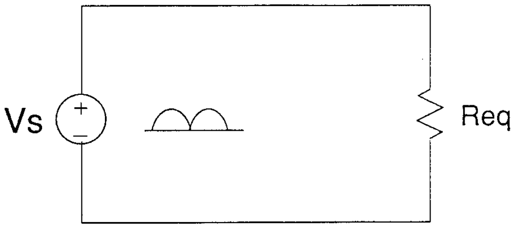


Fig.13 Simplified model of suggested ballast Fig.10

VI. CONCLUSION

This paper has suggested an electronic ballast for metal halide lamp. The ballast is basically a high frequency type. The achievement of unity power factor with high frequency resonant operation has been proposed and realized with prototype electronic ballast.

In order to minimize the switching loss, the ballast employs the zero voltage switching scheme in which the switching instants are synchronized with the voltage zero crossing points. For a base driver, self-oscillation scheme is taken advantage of. Therefore, base driver and controller part consist of only one leg of transformer, two resistors and two capacitors, which makes ballast more compact, lighter and more reliable.

Summing up the various features of the ballast, we can see the following advantages:

- unity input power factor and low harmonics on ac line side
- minimum number of switching devices
- high operating frequency
- low acoustic noise
- small size and light weight
- improved luminous efficacy
- extremely simple driver and controller

A prototype ballast for 175 watt metal halide lamp has been fabricated and tested in the laboratory and all the features of the ballast have been amply verified.

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