IEEE Power Electronics Specialists Conference, PESC-97, 39-45, St. Louis, 1997.

A MHz Electronic Ballast for Automotive-Type HID Lamps

Michael Gulko and Sam Ben-Yaakov*

Power Electronics Laboratory
Department of Electrical and Computer Engineering Ben-Gurion University of the Negev
P. O. Box 653, Beer-Sheva 84105, ISRAEL
Tel: +972-7-6461561; FAX: +972-7-6472949
Email: sby@bguee.bgu.ee.ac.il

Abstract - The compatibility of the Current Sourcing Push Pull Resonant Inverter (CS-PPRI) with the driving requirements of HID lamps designated for automotive headlight applications was investigated theoretically, by simulation and experimentally. The study reveals that a based ballast (CS-PPRI) complies with the automotive requirement of very fast warm up. The experimental ballast was run under Zero Voltage Switching (ZVS) at a nominal switching frequency of 1.29MHz while the pre-ignition switching frequency was 124KHz. Warm up time to 80% after cold ignition was about 10 seconds.

I. INTRODUCTION

High Intensity Discharge (HID) lamps and in particular Metal Halide Discharge (MHD) lamps are considered to be one of the most effective light sources [1]. These lamps have high electrical to lumen efficiency (efficacy), long life, good color rendition and good focusing capability when the arc is made short. These favorable characteristics, and in particular the very high brightness and color temperature of commercial HID lamps, make them good candidates for sophisticated applications such as automotive headlights. Indeed, some auto makers are already offering a HID lamp option to replace the conventional 'halogen' type headlights. Unfortunately, application of HID lamps in such demanding environments is far from being straightforward due to the many peculiarities of these light sources. The main difficulty with present day HID lamps is their need for special electrical circuits, electronic ballasts, to drive them [2, 3, 4].

The conventional design of an automotive HID lamp ballast involved two stages [5, 6]: a DC-DC converter to boost the battery voltage to the value required by the lamp (around 80V) and a DC-AC full bridge inverter that converts the DC bus to a low frequency square wave (in the range of 50-500Hz). This two stage design is further complicated by the need to pump high power to the lamp during warm up.

The nominal (electrical) power required to drive a headlight HID lamp is 35W [5, 6]. Assuming a nominal lamp voltage of 80V, the nominal current is about 0.44A. To ensure quick rise to nominal light intensity, the power level during warm up should be about 75W [5] which is more than twice than the nominal power. However, since the lamp voltage during warm up is low (about 20V), the current drive during warm up should reach about 7-8 time the nominal current, i.e. about 3-4 A. Considering the fact that the warm up time lasts few seconds, the ballast must be designed to current levels which are much higher than the nominal ones.

The objective of this study was to examine and evaluate the potential application of the Current-Sourcing Push-Pull Parallel-Resonance Inverter (CS-PPRI) topology [2] as a ballast for low wattage HID lamps designated as automotive headlights [5, 6]. Special attention was paid to three major points:

1. To permit the application of an external igniter (rather than using a multiresonance ignition scheme [2]) so that ignition pulses of very high voltage can be realized.
2. Ensuring soft switching of the inverter during ignition, warm up and normal operation.
3. Exploring the capability of the inverter to deliver high power to the lamp during ignition.

The operating frequency of the ballast was chosen to be above 1 MHz to overcome the acoustic resonance problems [2, 3, 4]. The study includes analytical investigation, simulation and an experimental evaluation of a 1.5 MHz ballast designed for a 35W automotive MHD lamp.

II. BALLAST TOPOLOGY

The proposed ballast (Fig. 1) is built around a CS-PPRI [2] and includes two switches (Q_1, Q_2) with inherent anti-parallel diodes (D_1, D_2), an input inductor (L_{in}) , integrated-magnetics element (T_2), resonant capacitor C_r and a serially connected ignition transformer (T_{ig}) with a secondary inductance of L_{ig}. A simplified equivalent circuit of the inverter is given in Fig. 2. The inverter operates in two modes: a voltage-source mode that is in effect prior to ignition and a current-source mode that prevails as soon as the lamp ignites and during steady state operation. The operating switching frequency of the ballast during the voltage-source mode and the current-source mode is designated f_{svs} and f_{scs} respectively. The two mode operation is facilitated by applying different resonant frequencies of the circuit. The low resonance frequency (f_{rvs}), which is

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* Corresponding author

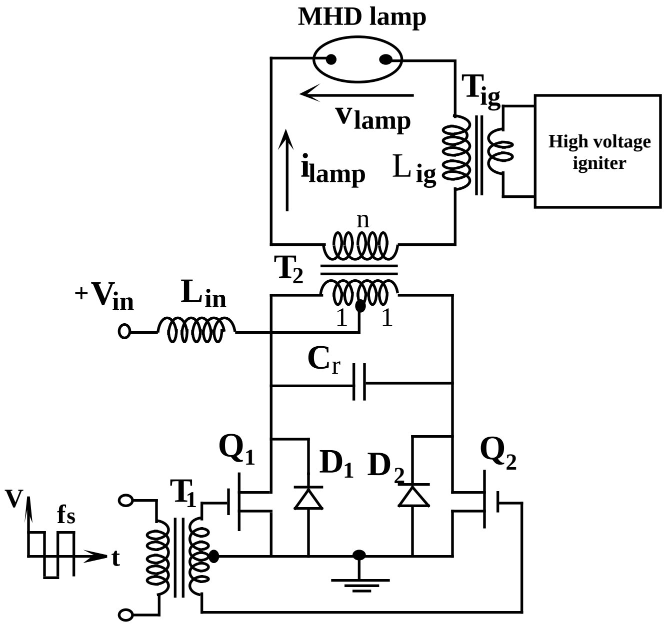


Fig. 1. The proposed electronic ballast for automotive HID headlight lamps.

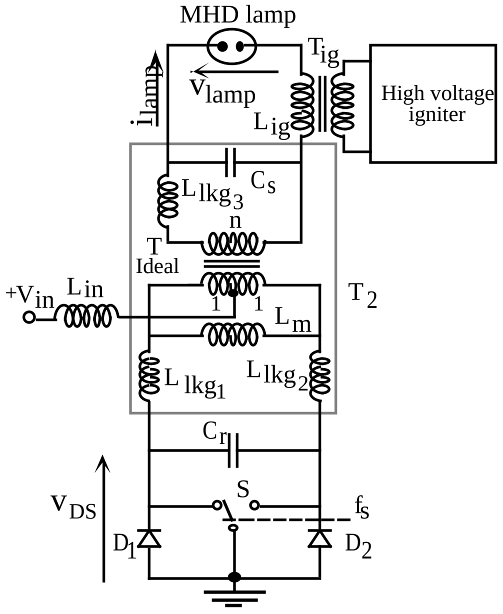


Fig. 2. Simplified equivalent circuit of the proposed ballast and leaky transformer representation of T_2.

applicable prior to ignition, is mainly controlled by the input inductance (L_{in}), the magnetizing inductance of T_2 primary (L_m) and the resonant capacitor C_r plus a stray capacitor C_s reflected to the primary (Fig. 2). The post ignition high frequency resonance (f_{rcs}) is controlled by T_2 leakages, the igniter's inductance L_{ig} reflected to the primary and the resonant capacitor C_r (Fig. 2). The difference between the modes, as discussed below, is affected by the lamp being ignited or extinguished.

II.1 *Voltage-Source Mode*

Prior to ignition (voltage-source mode), the lamp's resistance is very high, practically an open circuit. Consequently, the equivalent circuit of Fig. 2 can now be approximated by the equivalent circuit of Fig. 3a. In this case the secondary of T_2 is practically disconnected and since the leakages are assumed to be much smaller than L_m, they can be ignored. In the high frequency range, the effect of distributed capacitances across and between the windings may became significant. Fig. 3a shows an equivalent circuit in which these distributed capacitances are represented approximately by the lumped capacitor C_s across the secondary transformer terminals. During this mode of operation the inverter is controlled by low switching frequency f_{svs}. The circuit of Fig. 3a is basically the Push-Pull Parallel Inverter described earlier in connection with a DC-DC resonant transformer [7].

To insure a reliable starting of the HID lamp a sufficient pre-ignition open circuit voltage must be obtained. Applying the derivations given in [7], the approximate peak voltage of the resonant tank (V_{DSpk}) during voltage-source mode was found to be:

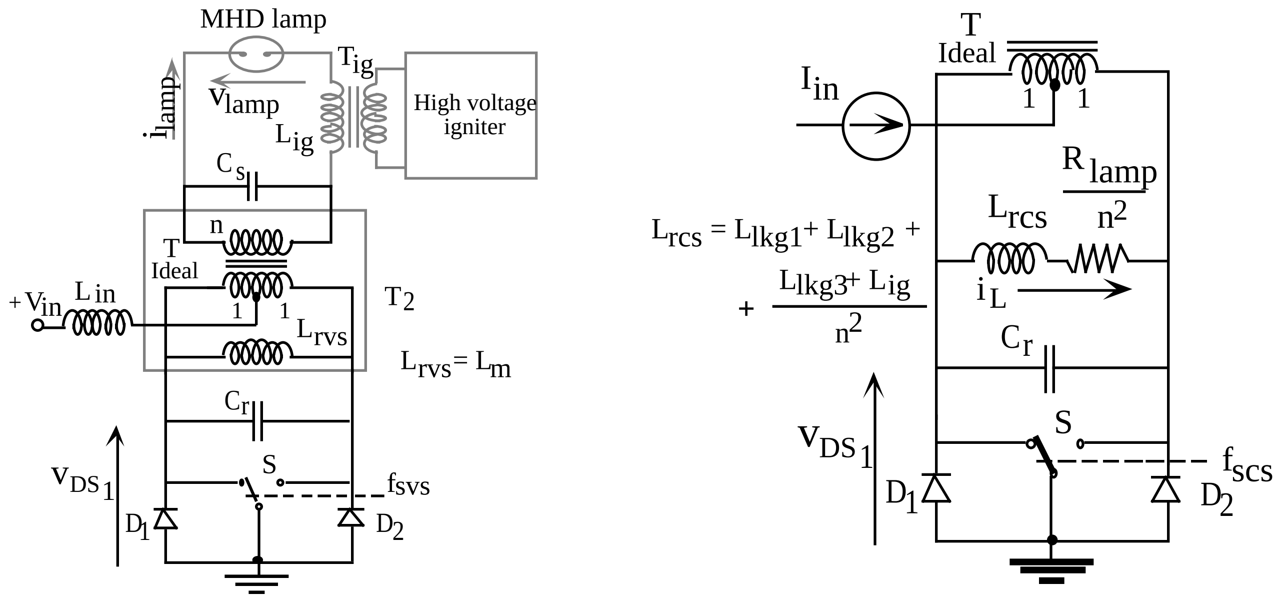
$$V_{DSpk} = \pi V_{in}\frac{T_s}{2T_\lambda} = \frac{\pi^2 V_{in}\sqrt{1+b}}{\vartheta_\lambda}\,\frac{f_{ovs}}{f_{svs}} \qquad (1)$$

where:
f_{svs} - switching frequency during voltage-source mode.
V_{in} - input voltage.
$\vartheta_\lambda = \omega_{rvs} T_\lambda$
T_λ − quasi-resonant period [7].
$\omega_{rvs} = 2\pi f_{rvs}$
$f_{rvs} = \dfrac{1}{2\pi\sqrt{(L_{rvs}||4L_{in})(C_r+n^2C_s)}} = f_{ovs}\sqrt{1+b}$ - the resonant frequency during voltage-source mode.

$f_{ovs} = \dfrac{1}{2\pi\sqrt{L_m(C_r+n^2C_s)}}$ - the natural resonant frequency during voltage-source mode.
n is the turn ratio of T_2.
C_s - stray capacitor across the secondary of T_2 (Fig. 3a).
$b = \dfrac{L_m}{4L_{in}}$

The relationship between the quasi-resonant period (T_λ) and the frequency ratio ($\frac{f_{ovs}}{f_{svs}}$) was derived from [7] and found to be:

$$\frac{f_{ovs}}{f_{svs}} = \frac{\left[\vartheta_\lambda - 2\mathrm{Tan}(\frac{\vartheta_\lambda}{2})\right]}{\pi\sqrt{(1+b)^3}}\,b \qquad (2)$$



(a) (b)

Fig. 3. Simplified equivalent circuit of the proposed ballast: (a) Pre-ignition (voltage-source mode); (b) Post-ignition (current-source mode).

The above equations can be used to explore the dependence of the resonance period (T_λ) on the switching frequency (f_{svs}) and inductance ratio (b) (Fig. 4). To retain ZVS condition of the inverter, the switching frequencies (f_{svs}) should be below the resonant frequency (f_{rvs}):

$$f_{svs} < f_{rvs} \qquad (3)$$

As shown in Fig. 4, the dashed area marks the operating points that do not fulfill the ZVS conditions of (3).

Examination of Fig. 3a reveals that the pre-ignition output open circuit voltage (V_{pk2}) is the peak voltage of the resonant tank (V_{DSpk}) reflected to the secondary of the T_2:

$$V_{pk2} = nV_{DSpk} = nV_{in}V^*_{pk2} \qquad (4)$$

where V^*_{pk2} is the normalized pre-ignition output open circuit voltage:

$$V^*_{pk2} = \frac{V_{pk2}}{nV_{in}} = \frac{\pi^2\sqrt{1+b}}{\vartheta_\lambda}\,\frac{f_{ovs}}{f_{svs}} \qquad (5)$$

This relationship is depicted in Fig.5. It is evident that by controlling the switching frequency such that $\frac{f_{ovs}}{f_{svs}} > 1$ the desirable pre-ignition open circuit voltage can be obtained (Fig. 5).

II.2 *Current-Source Mode*

Once the lamp is ignited, the secondary impedance drops and the load reflected to the primary now dominates the behavior. In practical cases, the impedance of the reflected load plus inductances will be much lower than L_m. Consequently, the equivalent circuit is now reduced to that of Fig. 3b. As can be seen the lumped capacitor (C_s) is heavily damped by the low impedance of the operating HID lamp. The input inductor (L_{in}) is replaced by a (DC) current source. The latter is justified by the fact that in the proposed design:

$$L_{in} > 4\,L_{rcs} \qquad (6)$$

where L_{rcs} is the resonant inductance in the current source mode. Hence, the AC current component through L_{in} will be low and therefore the input current during a resonance cycle can be considered constant. The resonant frequency is now controlled by C_r and L_{rcs}

$$L_{rcs} = L_{lkg1} + L_{lkg2} + \frac{L_{lkg3} + L_{ig}}{n^2} \qquad (7)$$

(see Fig. 2 for notations).

In this case, the reflected load is in series with the resonant inductor L_{rsc} which conforms to the CS-PPRI topology [2].

The analytical results of [2] are summarized in Fig. 6 for the expected range of operation. The function of the ballast during current-source mode, as discussed below, is characterized by two distinct periods: the warm up period and the steady-state period.

II.2.1 *Warm Up Period*

The warm up period is a time required for the HID lamp to achieve its nominal power after it has been ignited. To facilitate quick warm up, the inverter should be capable of delivering high current for few seconds. During this period the lamp voltage is about 15-20V and the required power is

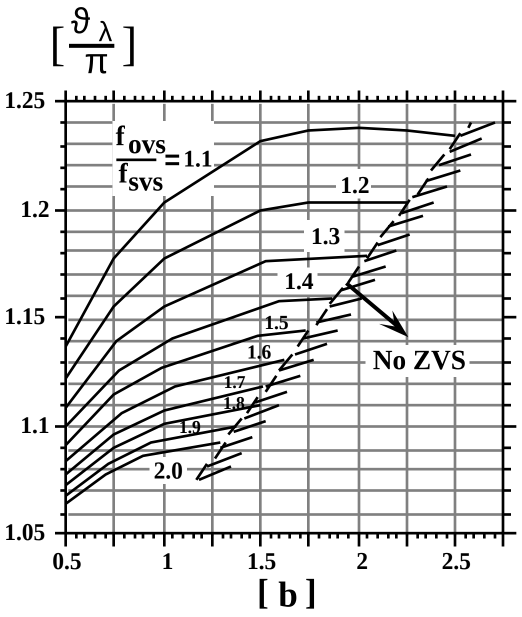


Fig. 4. The normalized quasi-resonant period ($\frac{\vartheta_\lambda}{\pi} = 2f_{rvs}T_\lambda$) as a function of the inductance ratio $b=\frac{L_m}{4L_{in}}$ with the normalized switching frequency (f_{ovs}/f_{svs}) as a parameter.

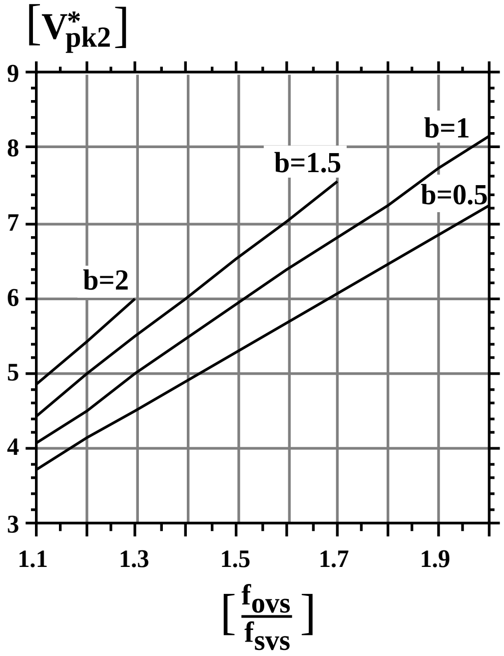


Fig. 5. Normalized pre-ignition output open circuit voltage (V^*_{pk2}) (equation 5) in voltage-source mode as a function of the normalized switching frequency (f_{ovs}/f_{svs}) with the ratio $b = \frac{L_m}{4L_{in}}$ as a parameter.

higher than nominal. Consequently, the equivalent lamp resistance ($\frac{v_{lamp}}{i_{lamp}}$) at warm up is mush lower than the nominal one. Examination of Fig. 6 reveals two very important features of the CS-PPRI topology:

1. Current sourcing characteristics are only slightly dependent on the load resistance.
2. The relationship between the (normalized) output current to (normalized) switching frequency for warm up period (R^*=0.01-0.03) can be approximated by a linear relationship:

$$I^*_{load_W} = -0.8 + 3.3\,\frac{f_{ocs}}{f_{scs}} \qquad (8)$$

where $I^*_{load_W}$ is the rms normalized lamp current (I^*_{load}) during warm up:

$$I^*_{load} = \frac{nI_{load}}{\frac{V_{in}}{Z_{rcs}}} \qquad (9)$$

R^* is the normalized lamp resistance in the current-source mode:

$$R^* = \frac{R_{lamp}}{n^2 Z_{rcs}} \qquad (10)$$

I_{load} - rms lamp current.
R_{lamp} - equivalent lamp resistance.

$Z_{rcs} = \sqrt{\frac{L_{rcs}}{C_r}}$ - characteristic impedance of the $L_{rcs}C_r$ resonant circuit in the current-source mode.

$f_{rcs} = f_{ocs}\sqrt{1-\left(\frac{R^*}{2}\right)^2}$ - the resonant frequency in the current-source mode.

$f_{ocs} = \frac{1}{2\pi\sqrt{L_{rcs}C_r}}$ - the natural resonant frequency in the current-source mode.

As can be seen, Fig. 6 and equation (8) imply that the inverter is operating as a current source and the magnitude of the output current is controlled by the driving switching frequency(f_{scs}) during warm up period. These two features are highly compatible with the warm up requirement of HID lamps pointing to the possibility of meeting extremely demanding warm up sequences. One would need of course to adjust the power handling capabilities of the switches and anti-parallel diode to permit high warm up current. This issue was also investigated in this study by examining the transistor's rms current of the switches (I_{Qrms}) and the average current of the anti-parallel diodes (I_{Dav}). The results shown in Fig. 7 in a normalized form defined by:

$$I^*_{Qrms} = I_{Qrms}\frac{Z_{rcs}}{V_{in}} \qquad (11)$$

$$I^*_{Dav} = I_{Dav}\frac{Z_{rcs}}{V_{in}} \qquad (12)$$

It was found that the expected power losses are approximately proportional to the current boost ($\frac{f_{ocs}}{f_{scs}}$). It is thus clear that to accommodate a very high warm up current, one will have to select low R_{dson} transistors. However, the situation is eased by two factors: the transistors are at the low voltage side and the fact that the warm up time lasts only few seconds; so the problem of heat removal is not that severe.

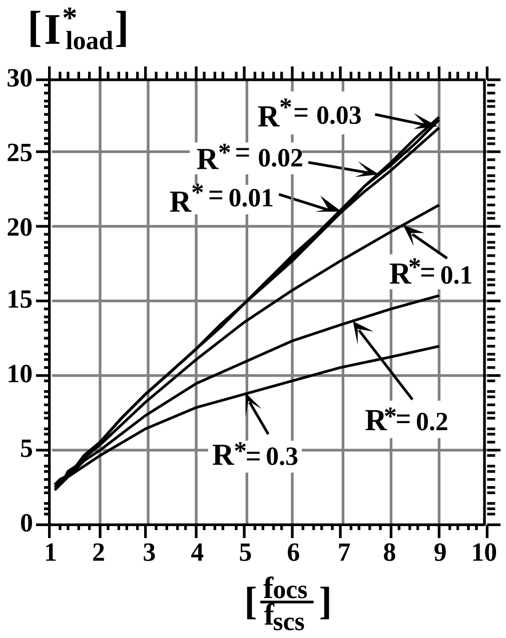


Fig. 6. Normalized output current (I^*_{load}) during current-source mode as a function of the frequency ratio (f_{ocs}/f_{scs}) with the normalized load resistance (R^*) as a parameter.

II.2.2 *Steady-State Period*

Once the HID lamp achieves its nominal power it enters the steady-state operation. In this condition the normalized lamp resistance (R^*) will be much higher than the corresponding value of warm up. But even in this case, the inverter behaves as a current source (Fig. 6). Examination of the expanded graph (Fig. 8), relevant to this operation period, reveals that in this condition the inverter output current is also controllable by switching frequency (f_{scs}).

III. EXPERIMENTAL RESULTS

The design parameters of the experimental ballast were as follows: V_{in} = 12V, L_{in} = 10μH, L_m = L_{rvs} = 100μH (during voltage-source mode), C_r = 5.1nF, C_s 40pF, L_{rcs} = 0.8μH (during-current source mode), n = 10, R_{lamp} = 250Ω (PHILIPS D2S-35W), $I_{lamp_{rms}}$ = 0.37A; Q_1, Q_2 - IRF540; Igniter peak voltage = 15kV; Input current during warm up 12 A.

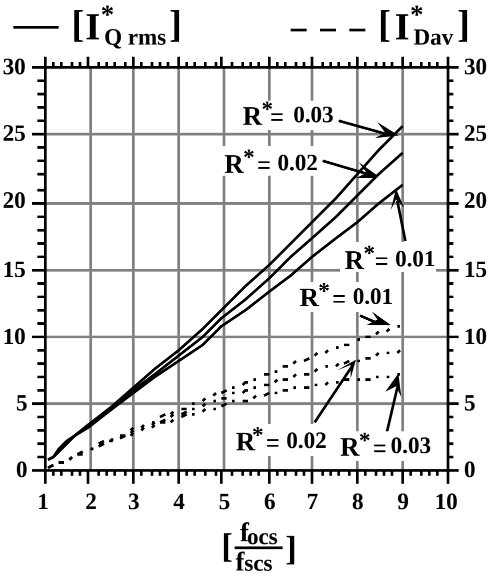


Fig. 7. Normalized rms transistor current (I^*_{Qrms}) (equation 11) and normalized average diode current (I^*_{Dav})) (equation 12) during warm up period as a function of the normalized switching frequency (f_{ocs}/f_{scs}) with the normalized load (R^*) as a parameter.

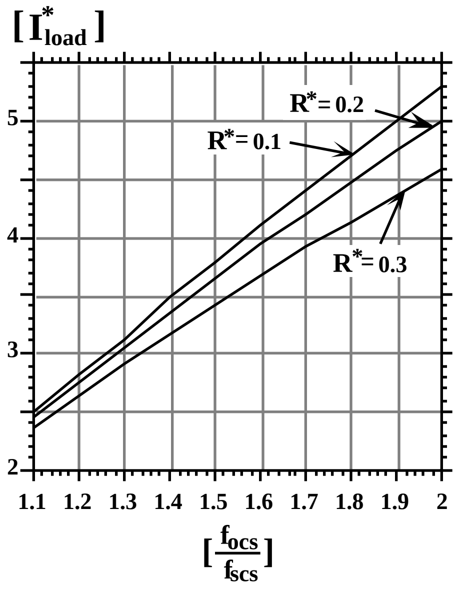
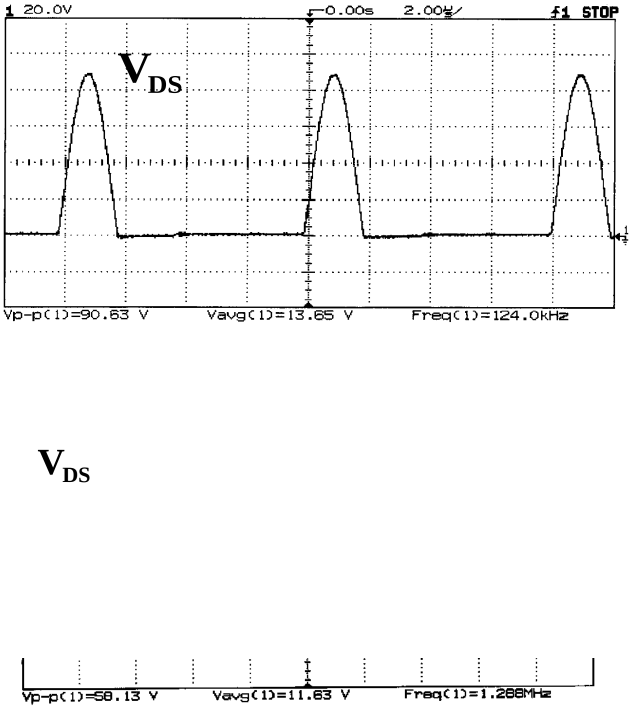


Fig. 8. Normalized output current (I^*_{load}) during steady-state period as a function of the frequency ratio (f_{ocs}/f_{scs}) with the normalized load resistance R^* as a parameter.

The drain-source voltage waveforms (Fig. 9) were found to be smooth and indicative of ZVS. The lamp voltage and current (Fig. 10) were smooth with some distortion which are attributed to the low damping of the circuit. Start up sequence was controlled manually by first fixing the switching frequency to about 124KHz and after ignition increasing it slowly to the nominal value of 1.29MHz. Under these conditions the time required to reach 80% of nominal output light intensity is about 10Sec (Fig. 11).

The experimental inverter was free of the acoustic resonance problem during warm up and at nominal operating conditions. At nominal operating conditions (35W, 1.29MHz) the arc was observed to be straight and stable. Light intensity was also stable during start up as the switching frequency was swept toward 1.29MHz.



(b)

Fig. 9. Drain-source voltage (V_{DS}) of experimental ballast: (a) At pre-ignition period (voltage-source mode); (b) At steady-state period (current-sourcing mode). Vertical scales: 20V/div. Horizontal scales: (a) 2µS/div; (b) 200 nS/div. Switching frequencies: (a) f_{SVS} = 124KHz; (b) f_{SCS} = 1.29MHz. Lamp: PHILIPS D2S-35W.

Design guidelines.

The following procedure is suggested for the practical design of the proposed MHz electronic ballast for an automotive-type HID lamp. It is assumed that the following parameters are given: input voltage to the driver (V_{in}), rms lamp current ($I_{lamp(rms)}$), nominal lamp power (P_{lamp}), required lamp power during warm up (P_W) and recommended pre-ignition output open circuit voltage (V_{pk2}).

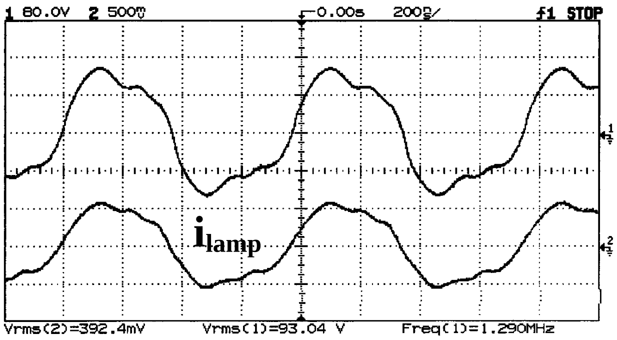
1. Select the switching frequency (f_{SCS}) for steady-state current-source mode according to the transistors and magnetic material available.

2. Calculate the apparent lamp resistance (R'_{lamp}):

$$R'_{lamp} = \frac{P_{lamp}}{\eta I^2_{lamp(rms)}}$$

where η - the efficiency of the ballast (0.8-0.85).

3. Choose (R^*) to be in the range 0.1 to 0.3. The current sourcing nature of the ballast is effective when the normalized load (R^*) is less than 0.3 (see Fig. 8).



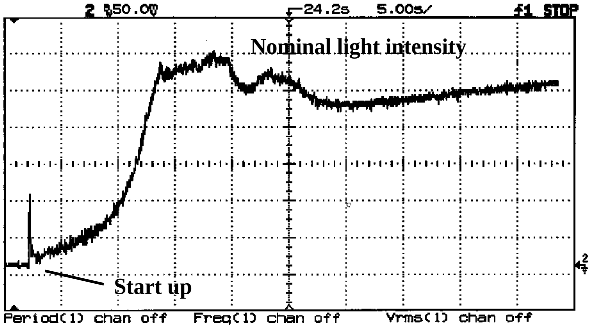


Fig. 11. Experimental output light intensity of HID lamp (PHILIPS D2S-35W) versus time at cold start up. Horizontal scale: 5 Sec/div.

4. Select the ratio for steady-state current-source mode (f_{OCS}/f_{SCS}) to be in the range 1.1 to 1.5. It is recommended to limit the ratio (f_{OCS}/f_{SCS}) to no more than 1.7, since a large ratio will increase conduction losses.

5. Calculate the natural resonant frequency (f_{OCS}) from the ratio (f_{OCS}/f_{SCS}).

6. Select I^*_{load} for steady-state current-source mode from Fig. 8 for the chosen R^* and the ratio (f_{ocs}/f_{scs}).

7. Calculate (L_{rcs}):

$$L_{rcs} = \frac{\left(\frac{I^*_{load}V_{in}}{I_{lamp(rms)}}\right)^2 \frac{R^*}{R'_{lamp}}}{2\pi f_{ocs}}$$

8. Calculate (n): $n = \frac{I^*_{load}V_{in}}{2\pi f_{ocs}L_r I_{lamp(rms)}}$

9. Calculate (C_r): $C_r = \frac{1}{(2\pi f_{ocs})^2 L_{rcs}}$

10. Calculate the rms output current (I_{load_W}) during warm up:

$$I_{load_W} = \frac{P_W}{V_{load_W}}$$

where V_{load_W} is the lamp voltage during warm up. As discussed above (see section II.2.1), V_{load_W} 15-20V.

11. Calculate the normalized output current $(I^*_{load_W})$ during warm up:

$$I^*_{load_W} = \frac{nI_{load_W}}{\frac{V_{in}}{Z_{rcs}}}$$

where $Z_{rcs} = \sqrt{\frac{L_{rcs}}{C_r}}$

12. Select the ratio f_{ocs}/f_{scs} during warm up from Fig. 6 for the calculated $I^*_{load_W}$ and R^*=0.01-0.02 (see section II.2.1).

13. Calculate the switching frequency (f_{scs_W}) during warm up from the selected ratio f_{ocs}/f_{scs} in step 12. The calculated switching frequency (f_{scs_W}) is the switching frequency of the voltage-source mode: $(f_{scs_W}) = (f_{svs})$.

14. Calculate the normalized pre-ignition output open circuit voltage (V^*_{pk2}):

$$V^*_{pk2} = \frac{V_{pk2}}{nV_{in}}$$

15. Choose frequency ratio (f_{ovs}/f_{svs}) to be in the range 1.2 to 1.7.

16. Select the inductance ratio b for voltage-source mode from Fig. 5 for the calculated V^*_{pk2} and chosen frequency ratio (f_{ovs}/f_{svs}).

17. Calculate the natural resonant frequency (f_{ovs}) from the chosen ratio (f_{ovs}/f_{svs}) (step 15), where $f_{svs} = f_{scs_W}$.

18. Calculate magnetizing inductance (L_m):

$$L_m = \frac{1}{(2\pi f_{ovs})^2(C_r + n^2 C_s)}$$

where C_s is the estimated stray capacitance at the secondary.

19. Calculate input inductance (L_{in}): $L_{in} = 4bL_m$

IV. CONCLUSIONS

The present study suggests that the CS-PPRI can potentially meet the requirement for warm-up and ballasting of HID lamps in automotive headlight applications. The results of this study can be used to design a ballast that can meet any particular warm up sequence. The penalty for a high warm up current is of course higher transistor and diode stresses. This is ameliorated to some extent by the fact that the transistors are placed in the low voltage side. Considering the fact that the realization of CS-PPRI is much economical than the conventional two stage topology, it could be a cost effective solution in automotive applications and other low voltage HID lamp ballasting applications.

V. ACKNOWLEDGMENT

This research was supported in part by a grant from the Israel Science Foundation.

REFERENCES

[1] J. P. Frier and M. E. Gazley Frier, *Industrial Lighting Systems*, McGraw-Hill Book Company, 1980.

[2] M. Gulko and S. Ben-Yaakov, "Current-sourcing push-pull parallel-resonance inverter (CS-PPRI): theory and application as a discharge lamp driver," *IEEE Trans. on Industrial Electronics,* 451, pp. 285-291, 1994.

[3] J. W. Denneman, "Acoustic resonances in high frequency operated low wattage metal halide lamps," *Philips Journal of Research* , Vol. 38, No. 4/5, pp. 263-272, 1983.

[4] H-J. Faehnrich and E. Rasch, "Electronic ballasts for metal halide lamps,"*Journal of the Illuminating Engineering Society,* pp. 131-140, Summer, 1988.

[5] F. Goodenough, "Novel DC-DC converter keeps power constant," *Electronic Design*, No. 1, pp. 51-62, April, 1996.

[6] C. Diazzi, F. Martignoni, P. Nora, R. Quaglino and T. Placke, "A power BCD chipset for automotive HID lamp ballast systems," *Proc. PESC-96* (Baveno, Italy), June, 1996, pp. 1766-1772.

[7] G. Ivensky, A. Abramovitz, M. Gulko and S. Ben-Yaakov, "A resonant DC-DC transformer," *IEEE Trans. on Aerospace and Electronic Systems,* Vol. 29, No. 3, pp. 926-934, July, 1993.