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Modelling and Simulation of Modified Flyback Converter for HID Lamp

Hannah Monica Anoop, S. Paul Sathiyan

Abstract**—*****This paper presents an electronic ballast for High Intensity Discharge lamp. The modified flyback converter is used to produce Low-Frequency Square-Waveform inorder to avoid acoustic resonance. The converter has the advantages of only two active switches for current control and a single choke. The design of the converter is presented. The converter is simulated in PSIM and the simulation results are shown.***

Index Terms— Acoustic Resonance (AR), High Intensity Discharge (HID), Low-Frequency Square-Waveform (LFSW), Power Control (PC), Power Factor Correction (PFC).

I. INTRODUCTION

HID lamp needs a current source for proper operation [7]. Buck converter was widely used [5], [6] because of its advantages like high efficiency, operation in continuous or discontinuous conduction mode etc. But for low power applications, the relatively more number of switches to produce output voltage inversion does not make a good option. So, flyback has been proposed for low power applications [2-4] which can produce output voltage inversion with relatively less number of switches at comparable efficiencies[2-3]. Integration of Power Control (PC) and Power Factor Correction (PFC) stages is done by sharing the active switches. The Modified flyback converter has the advantages of having less number of active switches (two) compared to three switches in [2], [3]. It does not need a high-side driver as in [2] which reduces the cost and complexity. In [4] the lamp is on the top of two capacitors which make the sensing of lamp current difficult [1]. The converter also has the advantage of sensing the lamp current with sensing resistors, op-amp and filter capacitors which makes it cost-effective.

II. CONVERTER AND ITS OPERATION

Stage 1[Fig. 2(a)]: A steady state is assumed, where C_2 voltage is the sum of E and the load voltages, reverse biasing (blocking) D_4. S_1 conducts and S_2 remains opened.

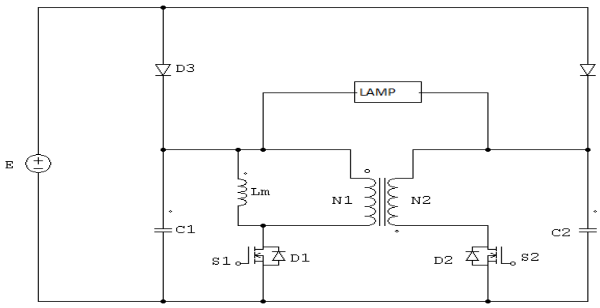

Fig. 1. Modified flyback converter

C_1 voltage is applied to the flyback primary, N_1. Thus, primary is charged with energy squarely proportional to the current through S_1, supplied from C_1.

Stage 2 [Fig. 2(b)]: S_1 is still closed and with S_2 opened, when C_1 voltage is equal to the voltage of the input voltage source E (C_2 remaining with lamp plus E voltages), voltage E is directly applied to the flyback primary N_1. Choke continues to be charged, but with the energy from the voltage source E.

Stage 3 [Fig. 2(c)]: S_1 is opened. The energy stored in the magnetic core is transferred to the capacitor C_2 through current flowing by the anti-parallel diode of S_2, D_2.

Stage 4 [Fig. 2(d)]: C_1 voltage is the sum of E and the load voltages, reverse biasing (blocking) D_3. S_2 conducts and S_1 remains opened. C_2 voltage is applied to the flyback secondary, N_2. Thus, secondary is charged with energy squarely proportional to the current through S_2, supplied from C_2.

Stage 5 [Fig. 2(e)]: S_2 is still closed and with S_1 opened, when C_2 voltage is equal to the voltage of the input voltage source E (C_1 remaining with lamp plus E voltages), voltage E is directly applied to the flyback secondary N_2. Choke continues to be charged, but with the energy from the voltage source E.

Stage 6 [Fig. 2(f)]: S_2 is opened. The energy stored in the magnetic core is transferred to the capacitor C_1 through current flowing by the anti-parallel diode of S_1, D_1.

III. DESIGN CONSIDERATIONS

A. Flyback converter

Current through the primary of the flyback transformer is given by,

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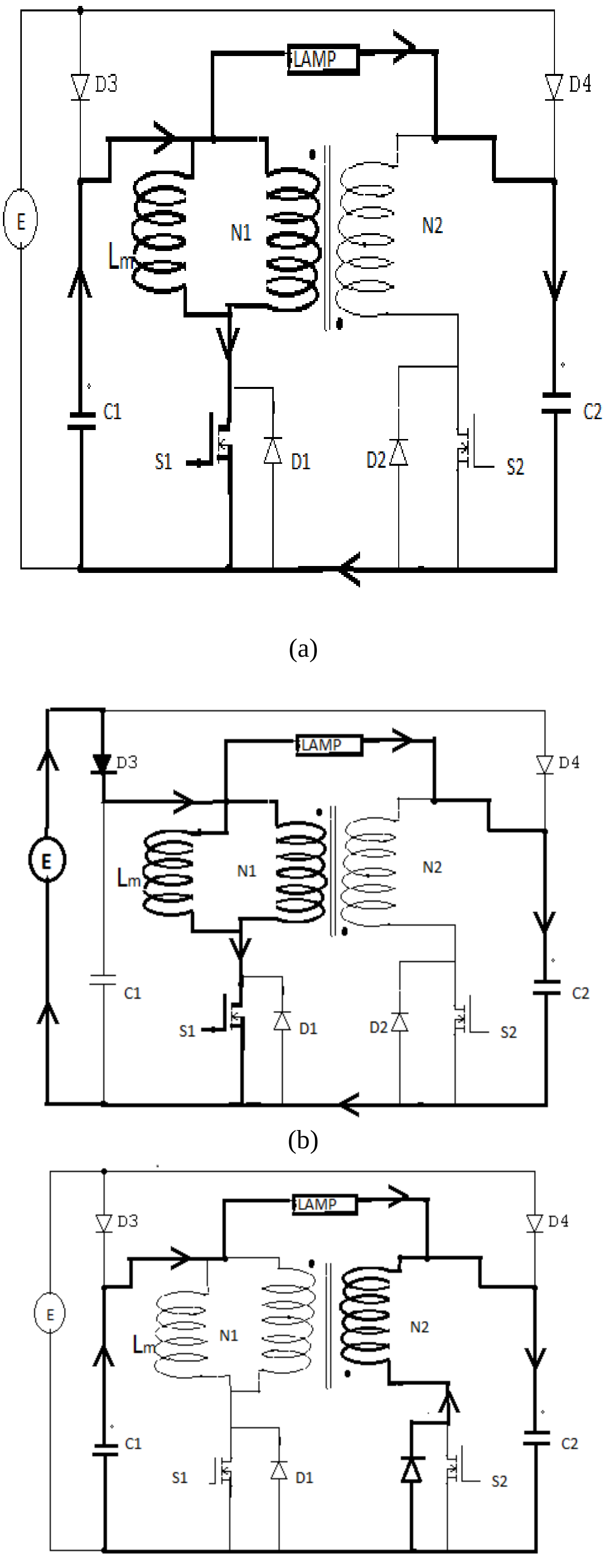
* Correspondence Author (s)
Hannah Monica Anoop, Electrical and Electronics Engineering, Karunya University, Coimbatore, India.
S. Paul Sathiyan, Electrical and Electronics Engineering, Karunya University, Coimbatore, India.

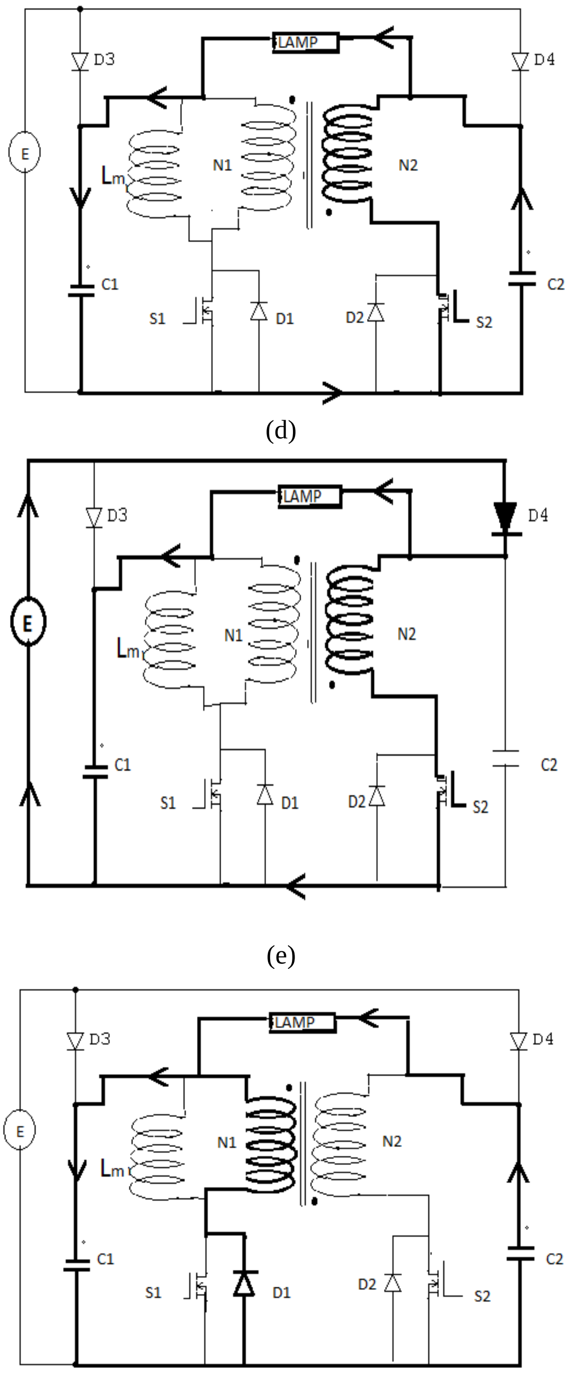


(a)

(b)

(c)

Fig. 2. Operation of modified flyback converter



(d)

(e)

(f)

$$i_P(t) = \frac{E}{L_P} t_1 \quad (1)$$

The peak value for one complete period is given by,

$$i_{P\_p} = \frac{E}{L_P} dT_S \quad (2)$$

The mean value for one complete period is given by,

$$i_{P\_m} = \frac{E d^2 T_S}{2L_P} \quad (3)$$

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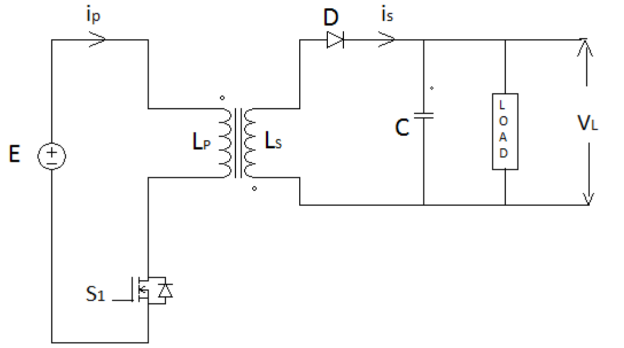

Fig. 3. Flyback converter

Current through the secondary of the flyback transformer is given by,

$$i_S(t) = \frac{V_L t_2}{L_S} \quad (4)$$

The peak value for one complete period is given by,

$$i_{S\_p} = \frac{i_{P\_p}}{n} \quad (5)$$

The time is determined by,

$$t_2 = \frac{L_S i_{S\_p}}{V_L} = \frac{n d T_S E}{V_L} \quad (6)$$

The mean value for one complete period is given by

$$i_{S\_m} = \frac{1}{2} i_{S\_p} \frac{t_2}{T_S} = \frac{E^2 d^2 T_S}{2 V_L L_P} \quad (7)$$

B. Modified flyback converter

Duty cycle for the boundary condition is given by;

$$D = \frac{E + V_L}{2.E + V_L} \quad (8)$$

The average current through the switches;

$$I_{SW} = \frac{E.D^2}{2.Lm.f_s} \quad (9)$$

As steady state voltage, E is constant and average current through capacitors is zero

$$I_{SW} = \left(\frac{P_{Lamp}}{E} + \frac{P_{Lamp}}{V_L}\right).\frac{1}{\eta_{FLY}} \quad (10)$$

Equating the above equation for current,

$$L_M = \frac{E^2 D^2 \eta_{FLY}}{2.f_s.P_{Lamp}}.\left(\frac{V_L}{E + V_L}\right) \quad (11)$$

C. Model

Applying the flyback current equation to the equivalent circuit in figure 3;

$$I(t) = \frac{E^2 d(t)^2}{2.L_m.f_s}\left(\frac{1}{E + v_L(t)}\right) \quad (12)$$

From the equivalent circuit;

$$C_o.\frac{dv_L}{dt} + \frac{v_L(t)}{Z_{Lamp}} = \frac{E^2 d(t)^2}{2.L_m.f_s}\left(\frac{1}{E + v_L(t)}\right) \quad (13)$$

By introducing small signal perturbations,

$$C_o \frac{d\hat{v}_L(t)}{dt} + \frac{\hat{v}_L(t)}{Z_{Lamp}} = -\frac{E^2 D^2}{2.L_m.f_s}\frac{1}{(E + V_L)^2}\hat{v}_L(t) + \frac{E^2 D}{L_m.f_s.(E + V_L)}\hat{d}(t) \quad (14)$$

Converting into s-domain,

$$C_o s\,\hat{v}_L(s) + \frac{1}{Z_{Lamp}}\hat{v}_L(s) = -k_1\hat{v}_L(s) + k_2\hat{d}(s) \quad (15)$$

Where,

$$k_1 = \frac{E^2 D^2}{2.L_m.f_s}\frac{1}{(E + V_L)^2} \quad (16)$$

$$k_2 = \frac{E^2 D}{L_m.f_s.(E + V_L)} \quad (17)$$

Now,

$$\frac{\hat{v}_L(s)}{\hat{d}(s)} = \frac{k_2.\hat{z}_{Lamp}}{1 + (k_1 + C_o.s).\hat{z}_{Lamp}} \quad (18)$$

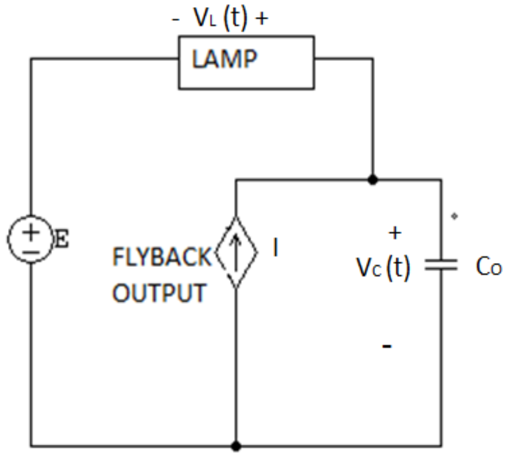

Fig. 4. Equivalent circuit of modified flyback converter

Dividing by impedance of the lamp;

$$\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{k_2}{\frac{1}{\hat{z}_{Lamp}} + (k_1 + C_o.s)} \quad (19)$$

$$\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{k_2}{\frac{s + p}{k_o(s + z)} + (k_1 + C_o.s)} \quad (20)$$

$$\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{\frac{k_2}{C_o}(s + z)}{s^2 + s\left(z + \frac{1}{C_o}\left(k_1 + \frac{1}{k_o}\right)\right) + \frac{1}{C_o}\left(\frac{p}{k_0} + k_1 z\right)} \quad (21)$$

For stable open-loop operation the condition to be satisfied is,

$$\left(z + \frac{1}{C_o}\left(k_1 + \frac{1}{k_o}\right)\right) > 0 \quad (22)$$

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$$C_o = C_1 = C_2 < \left(k_1 + \frac{1}{k_o}\right).\frac{1}{-z} \quad (23)$$

Small signal modeling of Discharge Lamp
From [8];

$$Z_{Lamp}(s) = \frac{v_L(s)}{i_L(s)} = k\frac{s+z}{s+p} \quad (24)$$

A dc step input is given to perturb lamp operation
So the lamp current is given by

$$i_L(s) = \frac{\frac{V_{DC}}{s}}{Z_{Lamp}(s)} = \frac{V_{DC}}{k}\frac{(s+p)}{s(s+z)} \quad (25)$$

In order to find out the dynamic effect of lamp alone, a dc voltage source is considered with a resistive ballast as shown in fig. 5

$$i_L(s) = \frac{\frac{\hat{V}_i}{s}}{R_b + Z_{Lamp}(s)} \quad (26)$$

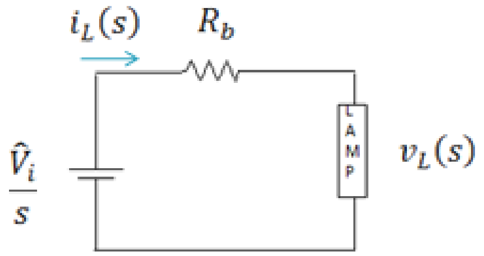

Fig. 5. Equivalent circuit of lamp-ballast system

$$i_L(s) = \frac{\frac{\hat{V}_i}{s}}{R_b + k\frac{s+z}{s+p}} \quad (27)$$

$$i_L(s) = \frac{\frac{\hat{V}_i}{s}(s+p)}{R_b s + R_b p + ks + kz} \quad (28)$$

$$i_L(s) = \frac{\hat{V}_i}{s}\frac{(s+p)}{s(R_b+k) + R_b p + kz} \quad (29)$$

$$i_L(s) = \frac{\hat{V}_i}{s}\frac{(s+p)}{(R_b+k)\left[s + \frac{R_b p + kz}{R_b + k}\right]} \quad (30)$$

$$i_L(s) = \frac{\hat{V}_i}{(R_b+k)}\frac{(s+p)}{s\left[s + \frac{R_b p + kz}{R_b + k}\right]} \quad (31)$$

Taking the inverse laplace transform;

$$\frac{A}{s} + \frac{B}{\left[s + \frac{R_b p + kz}{R_b + k}\right]} = (s+p) \quad (32)$$

We get the values of A and B as;

$$A = \frac{p(R_b+k)}{(R_b p + kz)} \quad (33)$$

$$B = \frac{k(z-p)}{(R_b p + kz)} \quad (34)$$

$$i_L(s) = \frac{\hat{V}_i}{(R_b+k)}\left[\frac{p(R_b+k)}{(R_b p + kz)}\frac{1}{s} + \frac{k(z-p)}{(R_b p + kz)}\frac{1}{\left(s + \frac{R_b p + kz}{R_b + k}\right)}\right] \quad (35)$$

$$i_L(s) = \frac{\hat{V}_i p}{(R_b p + kz)}\frac{1}{s} + \frac{\hat{V}_i}{(R_b+k)}\frac{k(z-p)}{(R_b p + kz)}\frac{1}{\left(s + \frac{R_b p + kz}{R_b + k}\right)} \quad (36)$$

Taking the inverse to obtain the lamp current in time-domain;

$$\hat{\imath}_L(t) = L^{-1}\{i_L(s)\} \quad (37)$$

$$\hat{\imath}_L(t) = \frac{\hat{V}_i p}{(R_b p + kz)} - \frac{\hat{V}_i}{(R_b+k)}\frac{k(p-z)}{(R_b p + kz)}exp\left(-\frac{R_b p + kz}{R_b + k}t\right) \quad (38)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i p}{(R_b p + kz)} - \frac{\hat{V}_i}{(R_b+k)}\frac{k(p-z)}{(R_b p + kz)} \quad (39)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i p}{(R_b p + kz)} - \frac{\hat{V}_i k\, p}{(R_b+k)(R_b p + kz)} + \frac{\hat{V}_i k\, z}{(R_b+k)(R_b p + kz)} \quad (40)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i p}{(R_b p + kz)}\left[1 - \frac{k}{(R_b+k)}\right] + \frac{\hat{V}_i k\, z}{(R_b+k)(R_b p + kz)} \quad (41)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i p}{(R_b p + kz)}\left[\frac{R_b}{(R_b+k)}\right] + \frac{\hat{V}_i k\, z}{(R_b+k)(R_b p + kz)} \quad (42)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i}{(R_b p + kz)(R_b+k)}(R_b p + kz) \quad (43)$$

$$\hat{\imath}_L(t=0) = \frac{\hat{V}_i}{(R_b+k)} \quad (44)$$

$$\hat{\imath}_L(t=\infty) = \frac{\hat{V}_i p}{(R_b p + kz)} \quad (45)$$

$$\hat{\imath}_L(t=t_1) = \frac{\hat{V}_i p}{(R_b p + kz)} - \frac{\hat{V}_i}{(R_b+k)}\frac{k(p-z)}{(R_b p + kz)}exp \quad (46)$$

IV. SIMULATION RESULTS

The converter is simulated in simulation software PSIM version 9.0.3

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TABLE I. SIMULATION VALUES

Components	Simulation values
Swithces,S_1,S_2	Ideal
Diodes,D_3,D_4	Ideal
Input voltage, E	200 V
Inductor, L_m	243µH
Capacitors, C_1,C_2	8.7 µF

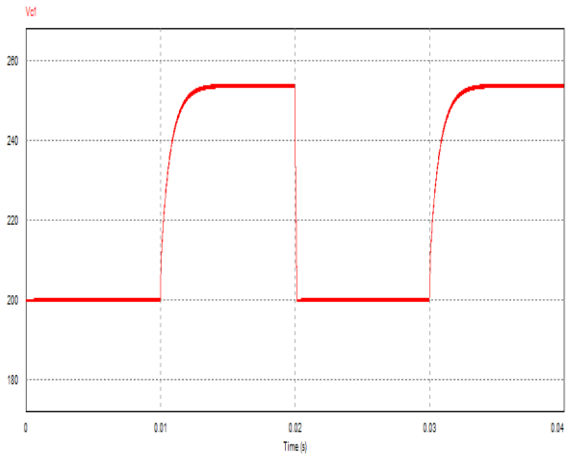

Fig. 6. Voltage across capacitor C_1

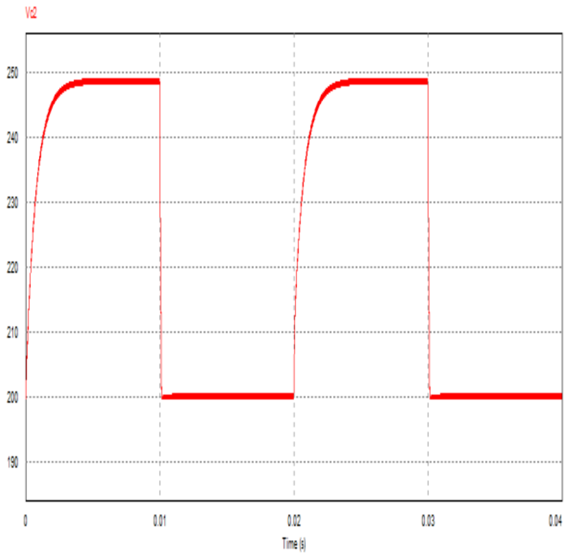

Fig. 7. Voltage across capacitor C_2

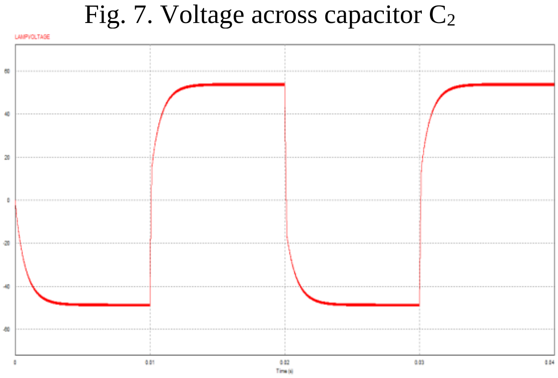

Fig. 8. Lamp voltage

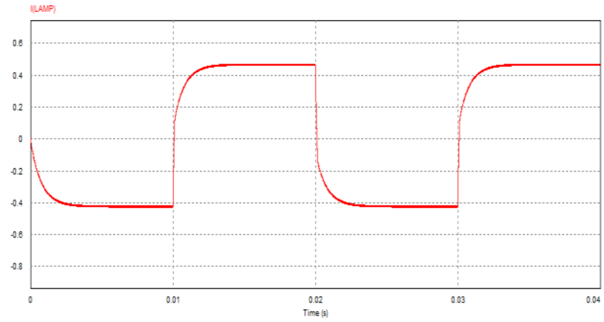

Fig. 9. Lamp current

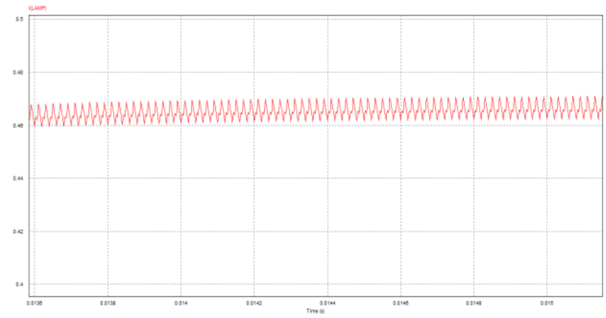

Fig.10. Ripple in lamp current with $C_1= C_2=8.7$ µF

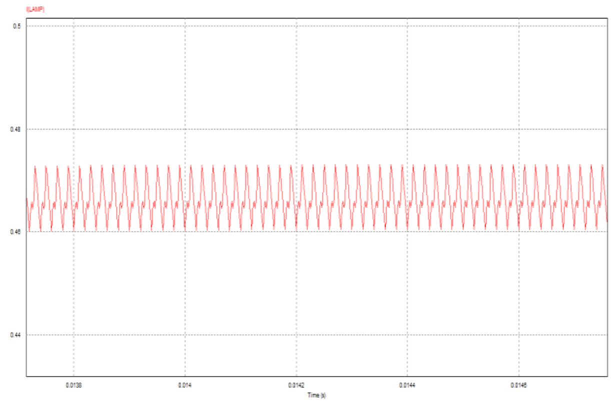

Fig.11. Ripple in lamp current with $C_1= C_2=6$ µF

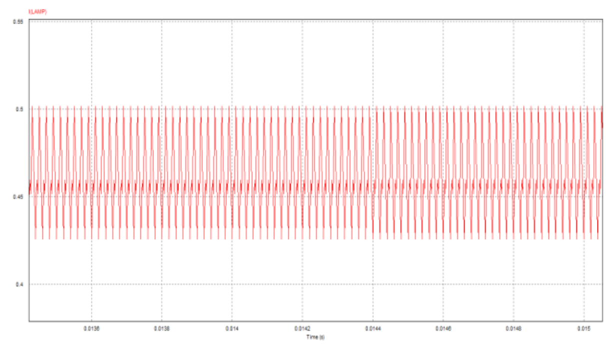

Fig. 12. Ripple in lamp current with $C_1= C_2=1$ µF

V. CONCLUSION

The paper herein has presented the advantages and problems associated with HID lamp. The lamp needs a ballast for smooth operation. An electronic ballast which supplies the lamp with a Low-Frequency Square-Wave using high frequency switching. Only two active switches are used which reduces the cost of the electronic ballast.

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The size and weight of the ballast is also reduced with the reduction in the number of components. The components of the electronic ballast are also been designed. There is an increase in the magnitude of the ripple in the lamp current with the reduction in the value of capacitors. As the number of active switches are only two, the cost is reduced and the switching losses are also reduced. This modified flyback converter is simulated and shown.

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Hannah Monica Anoop has received her B.tech degree in Electrical and Electronics Engineering from JNTU, Andhra Pradesh. She is currently pursuing her M. tech in Power Electronics and Drives in Karunya Univeristy.

S. Paul Sathiyan is working as Asst. Professor in Karunya University. He has done his Diploma in Electrical and Electronics Engineering with Honors. He received his B. tech degree in Electrical and Electronics Engineering from Manonmaniam Sundaranar University. He received his M. tech degree in Power Electronics and Drives from Karunya Univeristy. He is currently pursuing his PhD from Karunya Univeristy. His area of research is Adaptive Cruise Control for Vehicles. He has more than six years of teaching experience and has delivered three lectures. He has published six papers in journals and three papers in conferences.

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