

# Integrated Two Stage LED Driver

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**Abstract**— In this paper, an integrated two stage converter is proposed as a high power factor offline driver for power LED lamps. The circuit uses two inductors and two capacitors as energy transferring elements which provides high quality, high efficient driver to the lamps. The advantage of this converter is that it uses only one MOSFET as switch. With a careful design of the converter, film capacitors may be used, thus avoiding low life-rating electrolytic capacitors in the whole converter. The main feature of this circuit is that have a galvanic isolation between the source and the load is provided. A design example for a 70W converter supplied from a 230V/50 Hz mains is shown.

**Index Terms**—Continuous Conduction Mode, Discontinuous Conduction Mode, Duty Cycle, Electrolytic capacitors, film capacitors, LED driver, Pulse Width Modulation

## I. INTRODUCTION

Nowadays the energy-inefficient incandescent lamps and mercury-based tubular and compact fluorescent lamps are replacing as LED lamps. In electronics, an LED circuit is an electrical circuit used to power a light-emitting diode (LED). The circuit must provide sufficient current to light the LED at the required brightness, but must limit the current to prevent damaging the LED. The voltage drop across an LED is approximately constant over a wide range of operating current; therefore, a small increase in applied voltage greatly increases the current. That is, an LED driver is a self-contained power supply that controls the amount of current and voltage supplied to an LED light.

An LED constant current driver monitors the loop current of each LED and automatically adjusts the generated DC voltage output to the minimum value needed to produce the highest forward voltage. As mains power is Alternating Current (AC) and Light Emitting Diodes run on Direct Current (DC), this current needs to be converted by a rectifier. Some LED lamps have inbuilt rectifiers so can be used with iron-core transformers. If there is no inbuilt rectifier then the LED light needs to be used in conjunction with an LED specific driver as they all have rectifiers as standard. Some LED Drivers use Pulse Width Modulation (PWM) in conjunction to enable the LED light to become dimmable.

Very simple circuits are used for low-power indicator LEDs. More complex, current source circuits are required when driving high-power LEDs for illumination to achieve correct current regulation. As the technology improves,

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numerous types of switching converters have been developed as power

supply to LEDs. The numerous types of switching converter include boost, buck, buck-boost, and Cuk converters.

Here a two stage buck boost and fly-back converter is provided as a driver to the LED lamps which has high power factor, long life and high efficiency. The advantage of fly-back converter is providing isolation between input and load side.

## II. INTEGRATED TWO STAGE CONVERTER

Fig-1 shows the electrical diagram of the Integrated Two stage Converter.

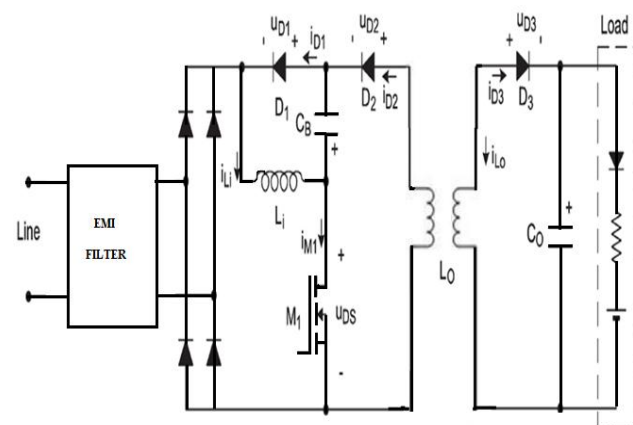


Fig -1: Integrated two stage converter

This converter is similar to two buck-boost converters in cascade.  $L_i$ ,  $D_1$ ,  $CB$ , and  $M_1$  form the input buck-boost converter and  $L_o$ ,  $D_2$ ,  $D_3$ ,  $Co$ , and  $M_1$  form the output buck-boost converter. A reversing polarity is produced by the first converter in the capacitor  $CB$ . It is corrected by the second converter, giving a positive output voltage with respect to ground.

Since the input inductor  $L_i$  is operated in discontinuous conduction mode (DCM), the average current through the line will be proportional to the line voltage, giving a near unity power factor. The output inductance  $L_o$  can be operated either in continuous conduction mode (CCM) or DCM. Although the operation in DCM has the advantage of providing a bus voltage across  $CB$  independent of the duty cycle and output power, it presents the disadvantage of requiring a higher value of the output capacitance  $Co$  to achieve low current ripple through the load. Because the current ripple is lower in CCM, the output inductance  $L_o$  is operated in this mode to have a reduced value for  $Co$ .

The operation of the fly-back stage in CCM with a duty cycle lower than 0.5 reduces the low-frequency ripple voltage since it is multiplied by the buck-boost converter voltage ratio. Thus, it will be possible to use a film capacitor to implement  $C_o$ , thus having a higher life rating and better efficiency than using electrolytic capacitors.

Different modes of operation of this converter within a switching period are shown in Fig-2. Important waveforms are shown in Fig-3.

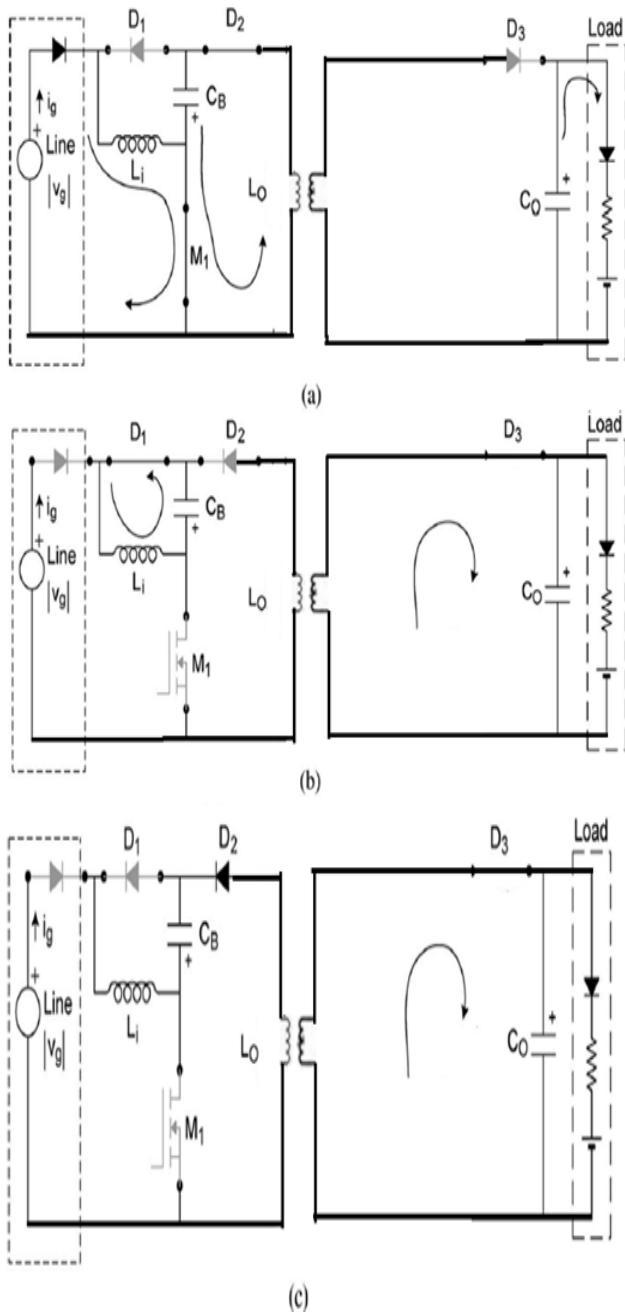


Fig- 2: Different modes of operation of the Integrated two stage Converter (a) Mode I:  $0 < t < DT_s$  (b) Mode II :  $DT_s < t < DT_s + t_1$  (c) Mode III :  $DT_s + t_1 < t < T_s$

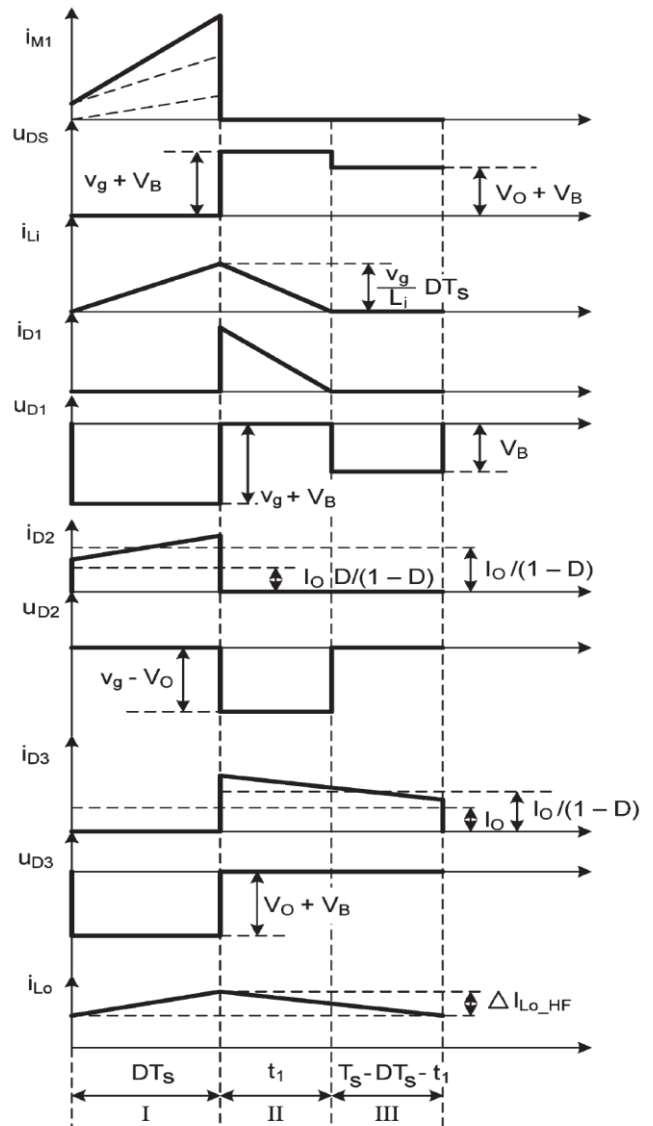


Fig- 3: Important waveforms of the integrated two stage converter within a high frequency switching period

The operation of this converter is divided into three modes.

**MODE 1:  $0 < t < DT_s$**

When the switch is turned on, the input inductor  $L_i$  begins to charge to rectified voltage  $V_s$ . The bus capacitor  $C_B$  which was previously charged to  $V_s$  is discharged so that the primary of the fly-back transformer is charged with bottom positive polarity. The output capacitor supplies the load current.

**MODE 2:  $DT_s < t < DT_s + t_1$**

When the switch is turned off,  $L_i$  is discharged through diode  $D_1$ . Opposite polarity voltage is induced in the secondary of the fly-back transformer so that the diode  $D_3$  is forward biased and it supplies the load. At the end of this mode,  $L_i$  is completely discharged.

**MODE 3:  $DT_s + t_1 < t < T_s$**

There will be no current flow in the input side. Since diode  $D_3$  is forward biased, the secondary of the fly-back transformer still supply the load.

III. ANALYSIS AND DESIGN OF INTEGRATED TWO STAGE CONVERTER

In this section, an integrated two stage converter is analysed when operated from the main voltage and a simulation prototype has been developed using MATLAB/SIMULINK. Considering the lamp formed by 60 LW W5SG power LEDs by Osram in a series array, the load rating current is 350 mA, with an output power of 70W and a total luminous flux of 1500 lm. The load was tested at the laboratory to obtain the following model parameters:  $V = 170 \text{ V}$  and  $R = 87 \Omega$  [4]. The equivalent load resistance at nominal power is  $R = 577$ . The selected switching frequency is 50 kHz. The line voltage is 230 Vrms with a 50-Hz line frequency. The converter must admit at least 10% line voltage variation, assuring constant current through the load.

Let the line voltage be a sinusoidal waveform given as

$$v_g(t) = V_g \sin \omega_L t \tag{1}$$

A. Line current and Input power

The current  $i_g$  is the input current through  $L_i$  during the time interval  $0-DT_s$ , and is modulated by the rectified line voltage as shown in Fig-5, where  $D$  is the transistor duty cycle and  $T_s$  is the switching period.

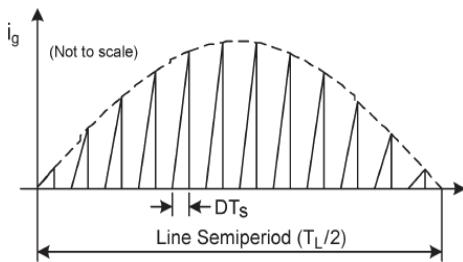


Fig- 5: Input Current Waveform

The input current averaged at line frequency can be calculated as

$$\langle i_g \rangle = \frac{1}{T_s} \int_0^{DT_s} i_{g\_peak} \sin \omega_L t dt = \frac{D}{2} \frac{V_g}{L_i f_s} \sin \omega_L t \tag{2}$$

where  $i_{g\_peak}$  is the instantaneous peak current in each switching period,  $V_g$  is the peak line voltage,  $f_s$  is the switching frequency and  $\omega_L$  is the line angular frequency. Thus  $i_g$  is a sinusoidal waveform that will provide an input power factor close to unity.

Taking into account that both input waveforms are sinusoidal, the average input power  $P_g$  can now be calculated as,

$$P_g = \frac{1}{2} V_g \langle i_g \rangle_{peak} = \frac{D^2 V_g^2}{4 L_i f_s} \tag{3}$$

where  $\langle i_g \rangle_{peak}$  is the averaged input current peak value.

B. Output voltage and Bus voltage

The output power  $P_o$  is

$$P_o = \frac{V_o^2}{R} \tag{4}$$

where  $V_o$  is the output voltage and  $R$  is the static equivalent resistance of the LED load, which is obtained by the ratio

between the LED voltage and current dc values at each operating point.

$$R = \frac{V_{LED}}{I_{LED}} = \frac{V_\gamma + R_\gamma I_{LED}}{I_{LED}} = \frac{V_\gamma}{I_{LED}} + R_\gamma \tag{5}$$

where  $V_\gamma$  and  $R_\gamma$  are the voltage and resistance parameters of the LED lamp equivalent circuit.

The output voltage  $V_o$  for the ideal converter is calculated by equating input power  $P_g$  and output power  $P_o$ . Assuming 100% efficiency, by equating equations 3 and 4,  $V_o$  is finally obtained as

$$V_o = \frac{D V_g}{2 \sqrt{K}} \tag{6}$$

where  $K$  is a non dimensional factor given by

$$K = \frac{f_s L_i}{R} \tag{7}$$

The bus voltage  $V_B$  can be calculated by using the voltage conversion ratio for this converter.

$$V_B = \frac{1-D}{D} V_o = \frac{(1-D) V_g}{2 \sqrt{K}} \tag{8}$$

The limit duty cycle  $D_{limit}$  can be obtained from the voltage conversion ratio in the DCM-CCM boundary

$$D_{limit} = \frac{1}{1 + \frac{V_g}{V_B}} \tag{9}$$

When the actual duty cycle is lower than the limit value, the input stage will operate in DCM.

C. Reactive components

The input inductance  $L_i$  can be obtained using equation 3 and assuming 100% efficiency

$$L_i = \frac{D^2 V_g^2}{4 P_o f_s} \tag{10}$$

By choosing a duty cycle of 40%, a value  $L_i = 1.2 \text{ mH}$  is obtained. Now,  $L_i$  is selected to be  $0.4 \text{ mH}$  when the operation of  $L_i$  in discontinuous mode for the whole line voltage range is checked.

The bus capacitor  $C_B$  is the voltage applied to the second stage. The current through this capacitor is given by the currents through diodes  $D1$  and  $D2$ . In these diodes, only the current through  $D1$  is modulated by a rectified line frequency, as shown in Fig-6. In order to calculate the bus ripple, the low frequency component of the current through  $D1$  must be obtained.

(19)

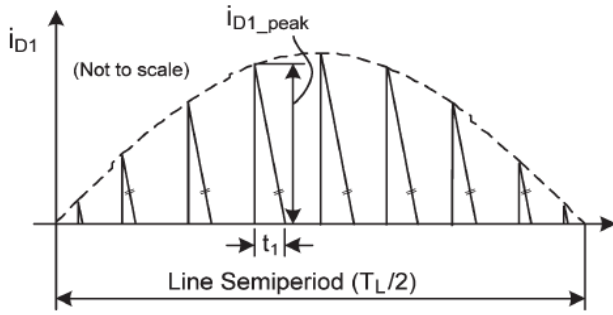


Fig- 6: Current waveform through Diode D1

From Fig-6, the average current through D1 is obtained as

$$\langle i_{D1} \rangle = \frac{1}{T_s} \frac{i_{D1\_peak} t_1}{2} \quad (11)$$

where  $i_{D1\_peak}$  be the D1 peak current in each switching period and  $t_1$  be the time needed by this current to reach zero from its peak point. Both values are changing after double the line frequency and have the following values:

$$i_{D1\_peak} = \frac{V_g}{L_i} D T_s \quad (12)$$

$$t_1 = \frac{D V_g T_s}{V_B} \quad (13)$$

Using equations 12 and 13 in equation 11, the D1 average current is obtained as

$$\langle i_{D1} \rangle = \frac{D^2}{2V_B f_s L_i} V_g^2 = \frac{D^2}{2V_B f_s L_i} V_g^2 \sin^2 \omega_L t \quad (14)$$

$$\langle i_{D1} \rangle = \frac{D^2 V_g^2}{2V_B f_s L_i} \left( \frac{1}{2} - \frac{1}{2} \cos 2\omega_L t \right) \quad (15)$$

The low-frequency ac component circulating through D1 and CB is given as

$$\langle i_{D1} \rangle_{ac} = \frac{D^2 V_g^2}{2V_B f_s L_i} \cos 2\omega_L t \quad (16)$$

Now, the low-frequency peak-to-peak ripple voltage across capacitor CB,  $\Delta V_{B\_LF}$  can be obtained as,

$$\Delta V_{B\_LF} = 2 \langle i_{D1} \rangle_{ac\_peak} X_{C_B} \quad (17)$$

$$\begin{aligned} &= 2 \frac{D^2 V_g^2}{4V_B f_s L_i} \frac{1}{2\pi(2f_L) C_B} \\ &= \frac{D^2 V_g^2}{8\pi V_B L_i C_B f_s f_L} \end{aligned} \quad (18)$$

where  $\langle i_{D1} \rangle_{ac\_peak}$  is the peak value of the low-frequency current through diode D1, obtained from equation 16, and  $f_L$  is the line frequency. The necessary bus capacitance is then calculated from equation 18 as follows

$$C_B = \frac{D^2 V_g^2}{8\pi V_B L_i \Delta V_{B\_LF} f_s f_L}$$

Let the maximum bus peak-to-peak ripple voltage is selected to be 10%; it gives 30 Vpp approximately. By equation 19,  $C_B = 80 \mu F$  is obtained.

The low-frequency voltage ripple at the output is,

$$\Delta V_{O\_LF} = \frac{D}{1-D} \Delta V_{B\_LF} \quad (20)$$

The low-frequency ripple current through the LED load produced by this ripple voltage is given as:

$$\Delta I_{LED\_LF} = \frac{\Delta V_{O\_LF}}{R_y} = \frac{D}{1-D} \frac{\Delta V_{B\_LF}}{R_y} \quad (21)$$

As long as the flyback converter operates in continuous mode, the LED current ripple at low frequency depends only on the bus voltage ripple and the bus capacitance CB. Co has no effect on this low frequency ripple.

Assuming the turns ratio of fly-back transformer to be 1:1, Lo and Co can be calculated as follows.

Output voltage ripple,

$$\Delta V_{O\_HF} = \frac{\Delta Q}{C_o} \quad (22)$$

$$\Delta Q = I_o D T_s \quad (23)$$

$$C_o = \frac{D I_o}{\Delta V_{O\_HF} f_s} \quad (24)$$

The voltage and current ripples in the LED load are related by the dynamic resistance as follows:

$$\Delta V_{LED} = \Delta I_{LED} R \quad (25)$$

Using equation 25 in 24,  $C_o = 40 \mu F$  is obtained for a .2% current ripple at high frequency.

Average current through Lo,

$$I_{L_o} = I_{D_2} + I_{D_3} \quad (26)$$

$$= \frac{I_o D}{1-D} + I_o = \frac{I_o}{1-D} \quad (27)$$

Taking average voltage across Lo=0,

$$\frac{L_o \Delta I_{D_2}}{D T_s} = V_B \quad (28)$$

$$\frac{L_o \Delta I_{D_3}}{t_{off}} = V_o \tag{29}$$

$$\Delta I_{L_{O\_HF}} = \Delta I_{D_2} + \Delta I_{D_3} = \frac{2DV_B}{L_o f_s} \tag{30}$$

$$L_o = \frac{2DV_B}{\Delta I_{L_{O\_HF}} f_s} \tag{31}$$

where  $\Delta I_{L_{O\_HF}}$  is the high-frequency peak-to-peak current ripple,  $\Delta V_{o\_HF}$  is the high-frequency peak-to-peak output voltage ripple, and  $I_o$  is the dc current through the LED load. Selecting a maximum ripple voltage of 4.2%, this is around 10 Vpp.  $L_o$  is calculated for a 50% current ripple. Using equation 31, a value  $L_o = 7$  mH is obtained.

An EMI filter is formed by a 20-mH common-mode inductance and a 2-mH differential-mode inductance with two 100 nF across the input and the output of the filter [1]. The filter was used to avoid high-frequency current circulating through the line and to avoid distortion in the input current.

#### IV. SIMULATION

Simulation is done in MATLAB/SIMULINK.

The simulation diagram of integrated two stage converter is shown in Fig-7. A buck boost converter operating in discontinuous mode provides the required power factor correction. In order to provide the dc voltage regulation as well as the galvanic isolation a fly-back converter is placed in the output stage. The operation of fly-back converter is similar to that of buck boost converter.

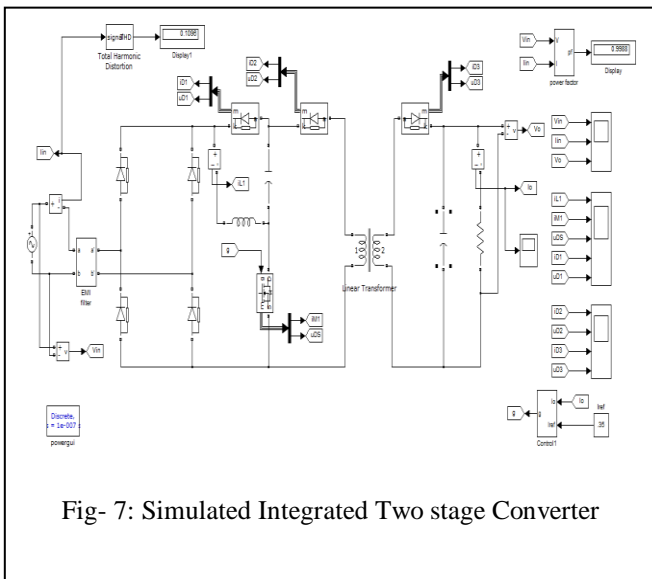
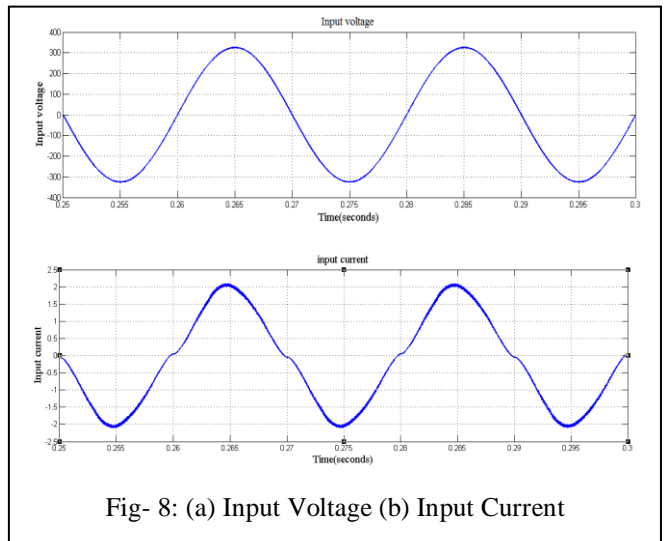


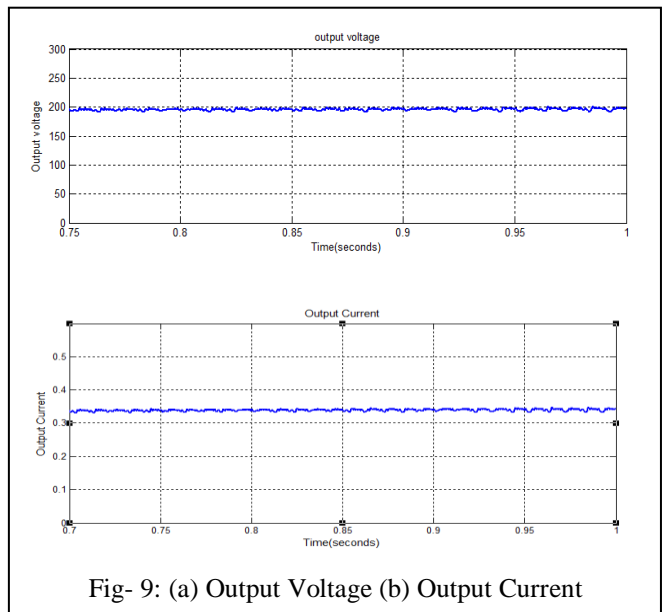
Fig- 7: Simulated Integrated Two stage Converter

#### X. 3.3 SIMULATION RESULTS

##### A. Simulation results



From Fig- 8, it is observed that the input current is almost sinusoidal and follows the input voltage. The power factor therefore is very high of about 99 %.



The output voltage and current are almost steady at about 200V and 0.35A respectively. This can be seen from Fig- 9. From the figure, it can be seen that there is certain ripple in the output voltage and current; actually it can be deliberately added in order to reduce the value of capacitance and make use of film capacitors.

### V. EXPERIMENTAL SETUP

Due to practical difficulties of making the hardware section of the LED driver with EMI filter, here an integrated two stage converter is experimentally verified without EMI filter. The output voltage is maintained to be 24 V. The switching frequency is 50 KHz.

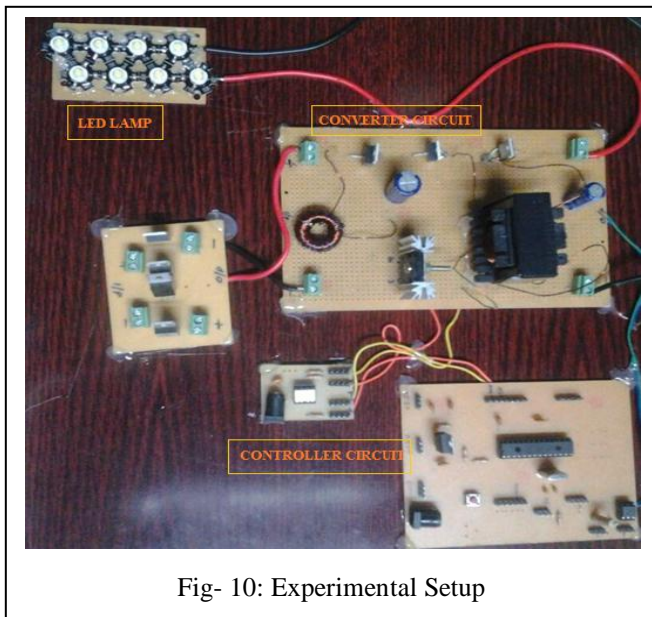


Fig- 10: Experimental Setup

The experimental set up is shown in Fig-10. There are basically three sections for the circuit; the converter section, controller section and the load LED matrix. It also consists of regulator IC LM 317 to provide the Vcc to dsPIC and MOSFET gate driver IC.

The converter circuit consists of the cascaded buck boost circuit. Supply is taken from mains and it has a diode bridge rectifier to obtain dc input to the converter circuit. dsPIC is used to shape the gate pulses which is given to the gate of MOSFET through gate driver IC. The output voltage is fed back to the feedback circuit which provides the analog pulse to the ADC input of dsPIC. Also this circuit is provided with regulator IC to provide the required voltage to gate driver IC and dsPIC. The load consists of 8 LEDs in series with the rating 3 V and 1 W. So the current through the load is 0.33A and voltage across it is 24V.

#### A. Experimental Results

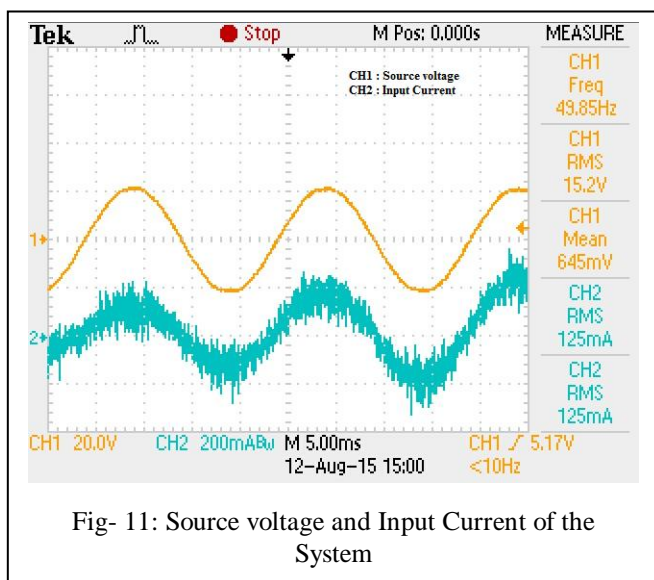


Fig- 11: Source voltage and Input Current of the System

The source voltage and input current of the system is shown in Fig-11. Here the line voltage can be varied up to 70 V rms. If the voltage is greater than this, then the switching losses will increase and the output voltage decreases. The distortion in the input can be reduced using an EMI filter in the input. But it increases the complexity of the circuit. From the figure, we can see that input current and voltage are in phase. Hence the input power-factor is very high.

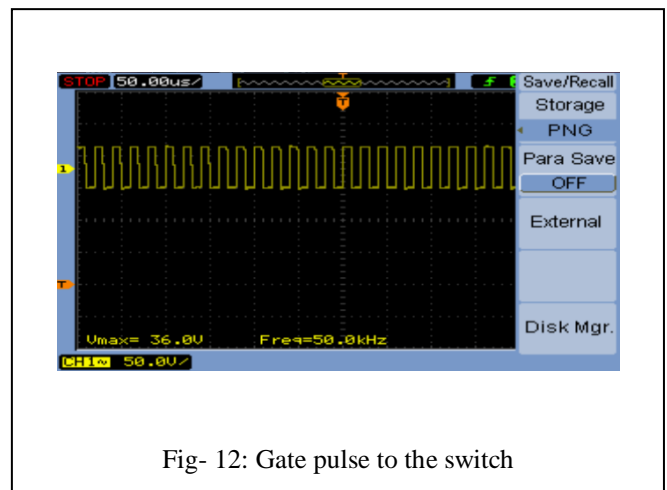


Fig- 12: Gate pulse to the switch

Fig-12 shows the gate pulse to the switch. This is of 50 KHz frequency. The duty cycle is regulated to get the required voltage in the output.

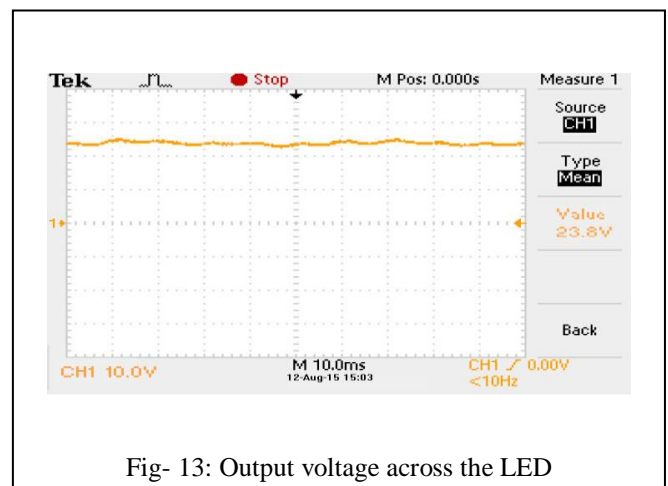


Fig- 13: Output voltage across the LED

From Fig- 13, it can be seen that the output voltage is obtained to be 24 V. Certain ripple in the output can be deliberately added in order to reduce the value of output capacitance.

### VI. CONCLUSIONS

The main thrust of the thesis is to provide a highly efficient driver for power LED lamps with high power factor. Since the input buck-boost stage is operating in DCM, it has got

very high power factor. This converter can stably maintain the output voltage and current to the required level. The closed loop control is implemented using a microcontroller. With a careful design of the converter, the bus capacitor can be made low and thus it is possible to use film capacitors, which reduces the size, weight and cost of the circuit, thus avoiding the low-life-rating electrolytic capacitors in the whole converter.

By providing fly-back converter, it can be used for medical applications where isolation is essential. Though isolation increases the cost, it is a safety aspect that cannot be neglected in certain applications.

In this paper, the converter was implemented to obtain only one lighting level. It can be extended for street lighting application where more than two lighting levels are used. The low dimming level can be implemented by reducing mean current through the LED lamp.

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