PRIMARY SIDE REGULATED LED DRIVER FOR SOLID STATE LUMINAIRE

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ABSTRACT

This Paper deals with the practical implementation of 30W LED power driving circuit for solid state luminaire. In this project work, flyback converter topology is implemented using controller IC FL7733A. It has integrated PWM controller with primary side regulation technique. The approach provides constant current and constant voltage output with single-stage active power factor correction, and benefits like higher efficiency, wide operating voltage range, overvoltage protection, overcurrent protection & overtemperature protection with minimum components. This paper consists of test report of the actual hardware prototype built to drive a solid-state luminaire of 30 high brightness LEDs operating under 37V with 715 mA load. Finally experimental results showed that proposed LED power driving circuit is suitable for the indoor and outdoor lighting applications.

Keywords — Flyback converter, FL7733A, Integrated PWM controller, regulation, wide operating voltage range, hardware prototype, solid state luminaire.

I. INTRODUCTION

About 25% of total electrical power generated is consumed for residential, commercial, and industrial lighting applications throughout the world [1]. Hence development of green technology is highly demanded as energy crises and the environmental issues are considered on priority. As energy consumption by illumination equipment is significantly high, there is a need to implement cost effective and energy saving solution over traditional lighting sources. LEDs has many merits over conventional lighting sources i.e., light in weight, energy saving, small size, high luminous efficiency, environmental friendliness (harmful elements such as lead and mercury is added) and longer life time span about 10,000 hours [3]. The implementation of LED driver is based on constant current at the output side, so it is prime important to develop driving circuit for LED which are connected in different series and parallel combination, can be termed as string [2]. Switch mode power supply in various configurations can be used for LED power driving. In recent years, single stage, two stage and integrated-stage topologies are developed to reduce losses and cost [3].

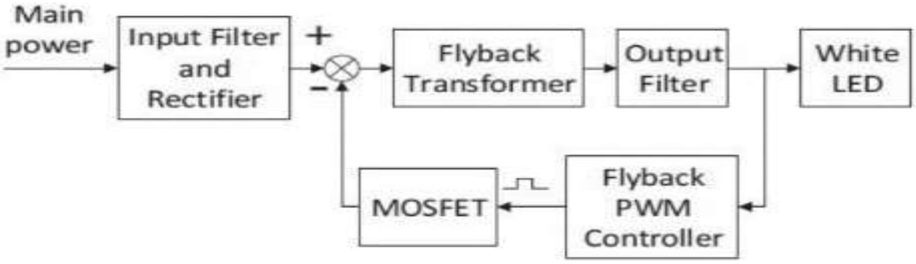


Fig.1 Block diagram of LED flyback controller [1]

In general-purpose LED lighting, non-isolated and isolated PFC (power factor corrected) LED driving topologies are used. From a safety point of view, isolated converter topologies are preferred as shown in Fig.1. In this type, a high frequency transformer is used known as flyback transformer which provides isolation between power circuit, controller & LED load. Researchers are working to develop single-stage PFC converter-based topologies with improved power quality. In low power applications, single stage buck and flyback PFC converter topologies are most suitable because of low component count and cost [4]. But high voltage stress across the MOSFET switch experiences ringing effect in flyback converter. When the peak and average current of flyback is relatively high, the energy loss of switch will be increased. RCD snubber circuit is required to improve turn-off capability and RC is used for overvoltage spike suppression. Generally, the conversion efficiency of Buck converters decreases as the voltage conversion ratio decreases, and the efficiency of Boost converters is found to decrease as the voltage conversion ratio increases. It is very important to achieve high efficiency power conversion within a wide voltage range, especially for the power systems fed by renewable energy and batteries [5]. In practice, the topology of LED driver can be selected according to the requirements-indoor or outdoor use, including performance parameters like power factor, harmonic distortion, cost, galvanic isolation, lifetime, temperature, and applications. For indoor applications, such as general-purpose lighting, ballasts (luminaire assembly) should be compact, low cost, and with reduced number of components. Ballast is common term used for all type of lamp drivers [6]. A buck regulator topology has the lowest number of components and hence has a low cost. Being a single stage switched mode LED driver, a non-isolated buck topology is recommended for low power applications [13]. Limitation of buck converter topology circuit is isolation is not employed. So, it cannot be used for outdoor (e.g., street light) applications. An isolated buck converter or combination of buck and flyback converter with quasi resonant topology with improved performance can be implemented for outdoor applications [14]. Flyback converter is the most used circuit for low to medium output power applications. This topology is basically used where the output voltage needs to be isolated from the input main supply [2]. Generally, input to the circuit is unregulated DC voltage which is obtained from the utility AC voltage after rectification and filtering. To maintain the desired output voltage a fast-switching device like a MOSFET is used. Basically, transformer is used for voltage isolation purpose as well as for better matching between input and output voltage and current requirement [2].

The proposed work consists of an active Power Factor Correction (PFC) controller for use in single stage flyback topology. Primary-side regulation and single-stage topology minimize cost by reducing external components such as the input bulk capacitor and secondary side feedback circuitry. Operating frequency is proportionally changed by the output voltage to guarantee discontinuous current mode (DCM) operation. Accordingly, the circuit is assembled using IC 7733A and tested to verify its current stability over input voltage range [7]. Constant current makes the stability in the brightness of all LEDs which are connected in the string.

This paper is divided into five different sections. In section I, basic introduction about LED power driving topology is discussed. In section II, operating principle of flyback-based LED power driving circuit with methodology of proposed project work is presented. In section III, proposal of primary side regulated LED driver with isolation is explained. In section IV, experimental results are discussed with test report of 30W LED power driving circuit & their related graphs are also being plotted.

II. METHODOLOGY OF PROPOSED FLYBACK CONVERTER

LED driving circuit with flyback topology is operating in discontinuous conduction mode to utilize the full energy. The basic principle of a flyback converter shown in Fig. 2. with the inductor divided to form a transformer. When the switch is closed, the primary of the transformer is directly connected to the input voltage source. The primary current and magnetic flux in the transformer increases, storing energy in the transformer. The voltage induced in the secondary winding is negative, so the diode is reverse-biased, output capacitor supplies energy to the output load. When the switch is opened, the primary current and magnetic flux drop. The secondary voltage is positive, forward-biasing the diode, allowing current to flow from the transformer. The energy from the transformer core recharges the capacitor and supplies the load. The operation of storing energy in the transformer before transferring to the output of the converter allows the topology to easily generate multiple outputs with little additional circuitry, although the output voltages must be able to match each other through the turn's ratio. Also, there is a need for a controlling rail which must be loaded before the load is applied to the uncontrolled rails, this is to allow the PWM to open up and supply enough energy to the transformer. The basic circuit of flyback converter (see Fig.2) works in three modes [8].

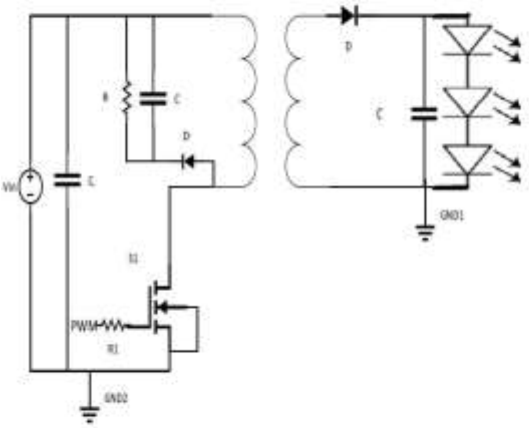


Fig.2 Principle of flyback Topology [8]

Mode I: When switch ‘S1’ is on, the primary winding of the transformer gets connected to the input supply. During this time , the diode ‘D’ connected in series with the secondary winding get reverse biased due to the induced voltage in the secondary. It is given by

$$\text{Vin} = L_{pri} \times \frac{d}{dt} i_{pri}$$

Where L*pri* is inductance of primary winding, i_{pri} is current through primary winding
Vin is input voltage (output from rectifier), At the end of Mode-1, the energy stored in the primary winding is

$$\frac{\text{Lpri X I}^{2}\text{pri}}{2}$$

At the end of mode I, peak primary current reaches to Ip(pk), given by equation
Ip(pk) = i_{pri} Vin x D x T /L_{pri}
The secondary current of Ise (pk) is given by
Ise (pk) = (Np/Ns) x Ip(pk), where Np is number of turns of primary winding, Ns is number of turns of secondary winding.

Mode II: When Switch turns off, the current in the primary winding drops suddenly, the voltage across the primary winding reverses. The diode becomes forward biased. The secondary winding, while charging the output capacitor (parallel to the load), starts transferring energy from the magnetic field of the fly back transformer to the output in electrical form. If the off period of the switch is kept large, the secondary current gets sufficient time to decay to zero and magnetic field energy is completely transferred to the output capacitor and load. Flux linked by the windings remain zero until the next turn-on of the switch, and the circuit is under discontinuous flux mode of operation. Alternately, if the off period of the switch is small, the next turn on takes place before the secondary current decays to zero. The circuit is then under continuous flux mode of operation. The primary and secondary windings of the flyback transformer do not carry current simultaneously.

Mode III: After magnetic field energy transferred to the output, the secondary winding emf, and current fall to zero and stops conducting. In this condition, the output capacitor, continues to supply voltage to the load. This part of the circuit operation has been referred to as Mode III of the circuit operation. Thus, during discontinuous mode, MOSFET is OFF; diode is OFF. The output capacitor continues to provide uninterrupted voltage to the load which are power LEDs. To achieve electrical isolation to improve safety & better matching between input and output voltage & current requirement, flyback converter is widely used in LED drivers. However, RCD snubber is needed to avoid high voltage spikes from the main switch which are due to leakage inductance resonates with the parasitic output capacitance of the MOSFET [11].

III. PROPOSAL OF PRIMARY SIDE REGULATED LED DRIVER WITH ISOLATION

The proposed LED power driver circuit consist of a electromagnetic interference (EMI) filter as a surge protection circuit, bridge rectifier, filter, external MOSFET, AC-DC PWM controller, RC snubber circuit, isolation transformer and output block as shown in Fig.3. The output of this converter is connected to five parallel strings (channels) of six series LEDs each. Accordingly, the driving circuit is fabricated and tested to verify output voltage and current stability. The standard test report is generated for 37V dc output voltage,0.715 load current.

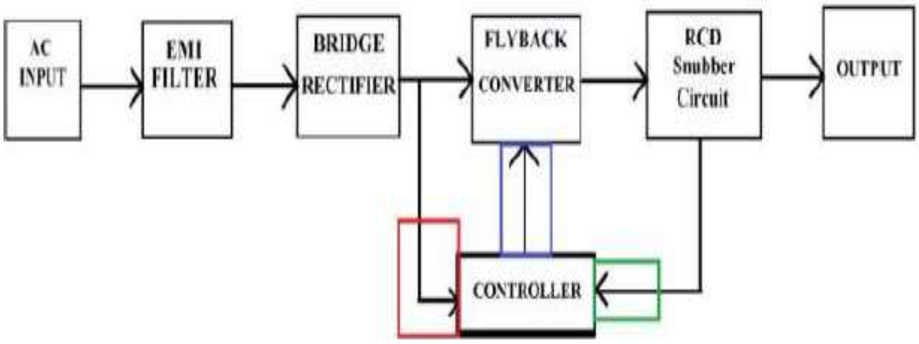


Fig.3 Block Diagram of proposed LED Power Driving Circuit [9]

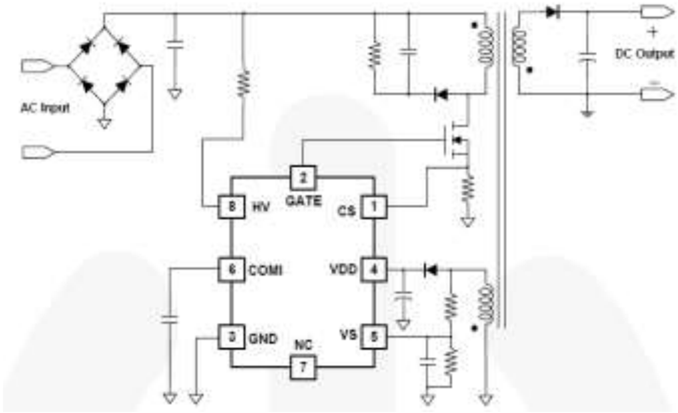
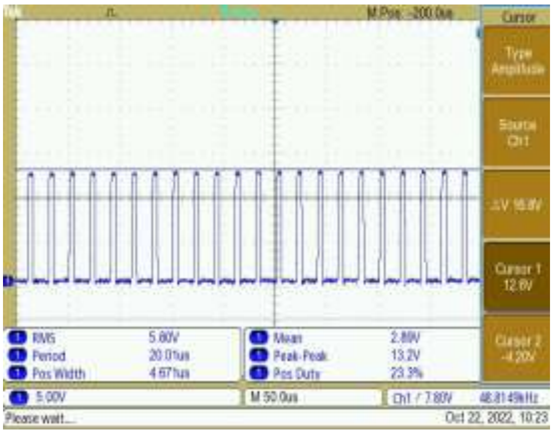


Fig.4 Application circuit of primary side regulated flyback type LED driver [10]

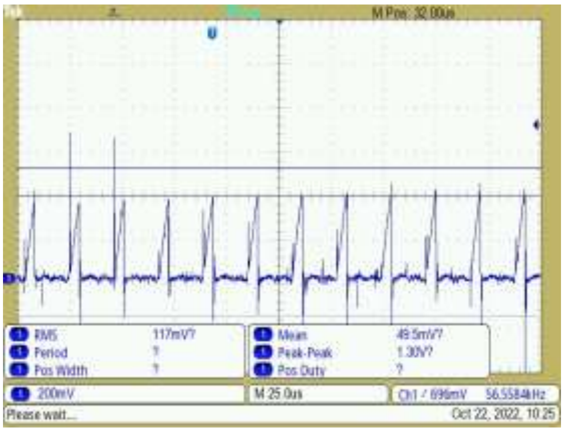
The AC input is supplied from the socket 230V based on India’s electrical supply to each socket. The function of EMI filter is an unwanted electrical signal that can create interference in the electronic devices by radiated emission or conducted. It is noise travel along the electrical conductor and noise travel through the air as magnetic field. The function of the bridge rectifier is to convert the AC input voltage to DC input voltage to the entire system. The rectifier is integrated diode bridge which is available as a single four terminal module (KBP210G). It is used to achieve superfast recovery time for high efficiency. The function of the flyback converter is to convert the DC input voltage to low level of DC output voltage. Flyback converter have isolation between the primary side and secondary side and no direct connection between both, so the high voltage is separate to one side and low voltage to another side. Hence the topology is termed as flyback converter [9]. The function of the RCD snubber circuit is to limit the peak voltage on the drain of MOS field effect transistor. The functions of the controller are to drive the MOSFET, current sensing (pin1) and voltage feedback (pin5). the red color block in Fig.3 is current sensing (pin8) from bridge rectifier, blue color block is sending duty cycle to flyback converter (pin2) and green color block is to receive the voltage feedback from the RCD snubber circuit. This circuit consists of resistor in parallel with capacitance and a series diode. This circuit absorb the current in the leakage inductor by turning on the diode. Refer Fig.4, Auxiliary winding is added to transformer to detect the output voltage and discharge time information for constant current regulation. This winding is connected to voltage sense (pin5) of the controller FL7733A through potential divider resistor. At start up, VDD reaches to 16V when VDD capacitor charges through high voltage at pin 8. As the output voltage increases ,the auxiliary winding becomes dominant VDD supply current source. During current mode switching with flyback topology, output current is determined by output voltage. Hence output voltage increases linearly irrespective of line voltage variation. Load short circuit protection is enabled internally after 15 millisecond which can be set by COMI (pin 6) capacitor (2.2μF).

In flyback topology or buck-boost topology, constant current turn on time and constant frequency in discontinuous conduction mode (DCM) operation gives high power factor and low harmonic distortion [10]. Output current can be determined by peak drain current and inductor current discharge time. The peak drain current sensed by CS (pin1). Output current calculation is compared with internal precise voltage reference to generate error voltage which determines the MOSFET's turn on time. To maintain constant current regulation over the entire input voltage range, a line compensation resistor of 470 Ω is inserted between CS pin and source terminal of MOSFET. The voltage across compensation resistor is dependent on current flow out of CS pin for MOSFET turn on and it is proportional to input voltage as shown in Fig.5



RMS 5.80V
Period 20.01us
Pos Width 4.67us
Mean 2.89V
Peak-Peak 13.2V
Pos Duty 23.3%
5.00V M 50.0us Ch1 ⁄ 7.80V 48.8149kHz
Please wait... Oct 22, 2022, 10:23

Fig.5 Waveforms of PWM signal at pin 2



RMS 117mV?
Period ?
Pos Width ?
Mean 49.5mV?
Peak-Peak 1.30V?
Pos Duty ?
200mV M 25.0us Ch1 ⁄ 696mV 56.5584kHz
Please wait... Oct 22, 2022, 10:25

Fig.6 Current sense waveform at pin1

Fig. 5 shows the switching frequency & gate voltage waveform. The duty cycle is given by D= Ton/T where D is duty cycle, Ton is on time of MOSFET and T is total time ($T_{on}+T_{off}$). Operating frequency is 48.8149KHz. MOSFET gate threshold voltage is 2.89 V. To maintain discontinuous current mode across a wide range of output voltage, the switching frequency is linearly adjusted by the output voltage, output voltage is detected by auxiliary winding and resistance divider connected across Vs pin of IC FL 7733. The frequency control lowers the primary rms current with better efficiency in full load condition. In case of short LED condition (SLP), the secondary diode is stressed by high current as shown in Fig.4, When Vs pin voltage is lower than 0.3 V due to short circuit condition, cycle by cycle current limit level changes to 0.2 V from 1.0 V and SLP is triggered if the Vs voltage is less than 0.3 V for next four switching cycles. Internally inside FL7733A, SLP block consist of a comparator, sample and hold circuit. In a sensing resistor short circuit condition, V_{cs} (Voltage across CS pin) level is almost zero and pulse by pulse current limit becomes ineffective. In this controller, if V_{cs} level is less than 0.1V in the first switching cycle, the GATE output is stopped by current mode sensing resistor short protection method. During start up, VDD capacitor must be charged to 16V through internal JFET to enable the controller action. When output diode or secondary winding are shorted, switch current with extremely high di/dt can flow through the MOSFET even by minimum turn on time. When CS voltage across sensing resistor is higher than 1.35V, the over current protection comparator output shuts down GATE switching. The controller has temperature -sensing circuit which shuts down PWM output if the junction temperature exceeds 150^0C.

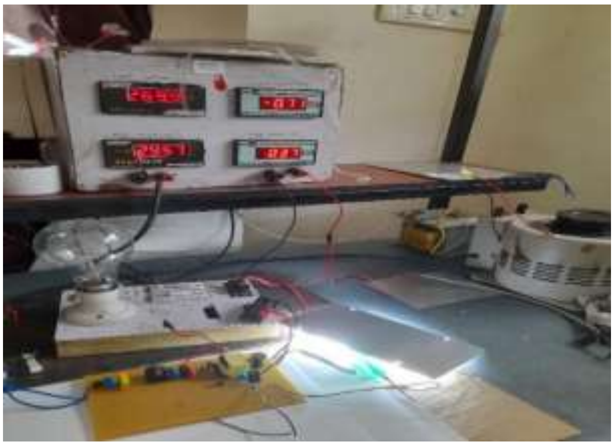


Fig.7 Experimental setup

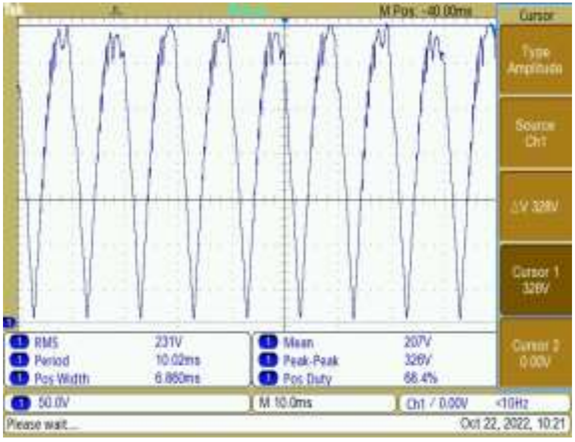


Fig.8 Rectifier output

Table 1: Test Report of proposed LED driver

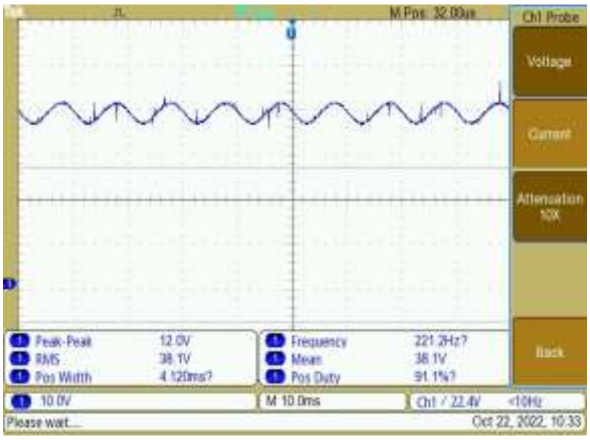
Input voltage (Volts)	170	230	270
Input current (Amp)	0.174	0.131	0.113
Input Power (Watts)	29.58	30.00	30.66
DC Output Voltage (Volts)	36.00	37.00	37.00
Output Current (Amp)	0.714	0.715	0.716
Output Power (Watts)	26.27	26.45	27.01
Efficiency (%)	88.81	88.16	88.09
Power factor	0.97	0.98	0.96
Athd* (%)	6.2	6.4	6.18
Vthd# (%)	2.75	3.63	2.77

*Athd is Total Harmonic distortion with reference to load current, #Vthd is Total Harmonic distortion with reference to output voltage.

With the help of experimental set up shown in Fig.7, test report of proposed scheme is presented in Table 1.LED power driving circuit is assembled and tested with 30 light emitting diodes. The measurements are carried out on SONIT DPM101 meter.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Following graphs are obtained on digital storage oscilloscope.Fig.8 shows pulsating waveforms are obtained with 207 V average output voltage of rectifier which is applied to HV pin. Instead of electrolytic capacitors, plastic film capacitor is recommended to the output side of rectifier. Plastic film capacitors handles large voltage, offer high stability, long shelf life, low equivalent series resistance, low self-inductance, and a high ability to absorb power surges. Rectifier output waveforms is modified due to feedback detection and PWM controller. Fig.6 shows output voltage waveform across external current sensing resistor R2 (pin 4 and pin 8). Depending upon current variation the duty cycle also changes and MOSFET conducts accordingly.



Peak-Peak 12.0V
RMS 38.1V
Pos Width 4.120ms?
Frequency 221.2Hz?
Mean 38.1V
Pos Duty 91.1%?
10.0V
M 10.0ms
Ch1 / 22.4V <10Hz
Please wait...
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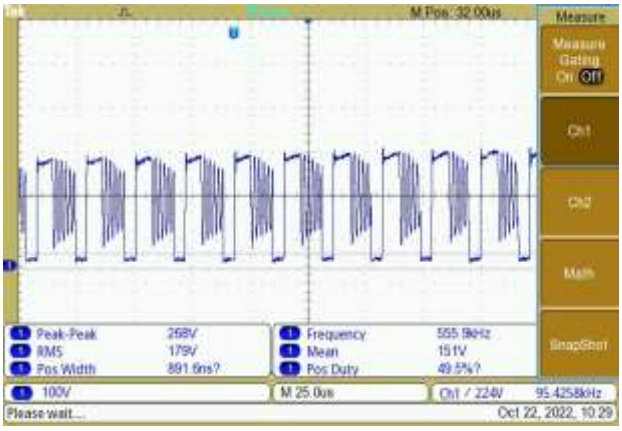
Fig.9 voltage waveform across 30 Watts load



Peak-Peak 298V
RMS 179V
Pos Width 891.6ns?
Frequency 555.9kHz
Mean 151V
Pos Duty 49.5%?
100V
M 25.0us
Ch1 / 224V 95.4258kHz
Please wait...
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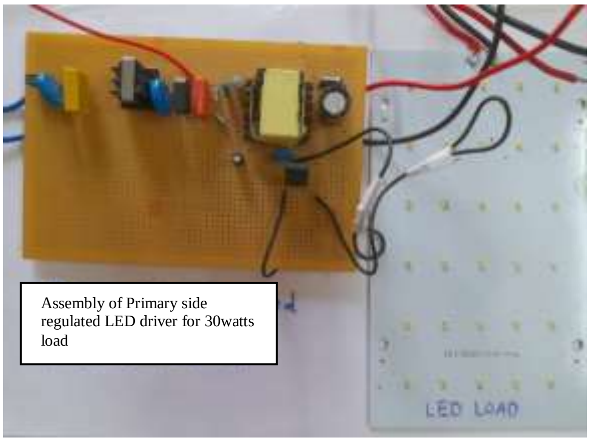
Fig.10 Voltage VDS across Internal MOSFET

Fig. 11 Lab setup for obtaining the waveforms



Assembly of Primary side regulated LED driver for 30watts load

Fig.12 Component side of LED Driver board

Following graphs are obtained after analysis of the test report from Table1

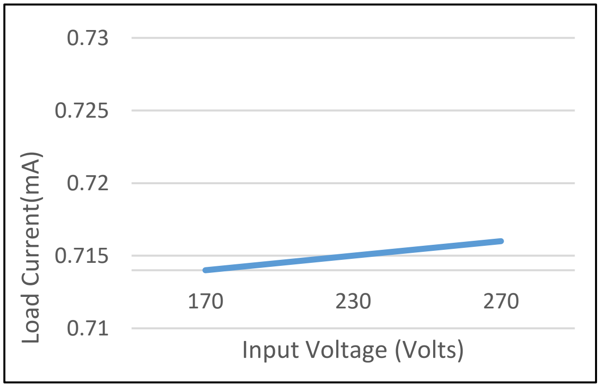


Fig.13 Output current (I_O) Vs Input Voltage (V_{in})

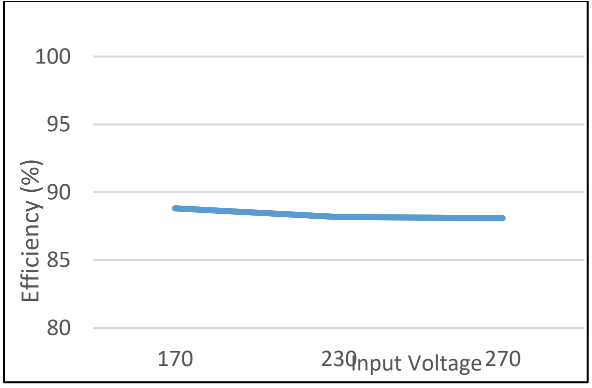


Fig.14 Efficiency (%) Vs Input Voltage (Vin)

Fig.13 shows Output current (Io) Vs Input Voltage (Vin) response. This load regulation curve shows that output LED current is almost remains constant for input voltage range of 170 to 270 V ac. Fig.14 shows Efficiency (%) Vs Input Voltage (Vin) curve which shows that efficiency of proposed LED driver circuit is 88.16% for 230 V input voltage. Efficiency almost remains constant over the range of 170 to 270 V ac. In Fig.5, reponse shows that power factor changes from 0.96 to 0.98 over the input voltage range from of 170 to 270 V ac.Ideally the value should be equal to 1 ,but due to output side flyback transformer , it is lagging power factor.

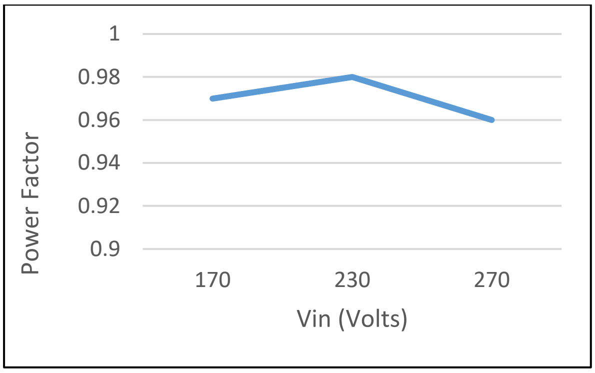


Fig.15 Power Factor Vs Input Voltage (Vin)

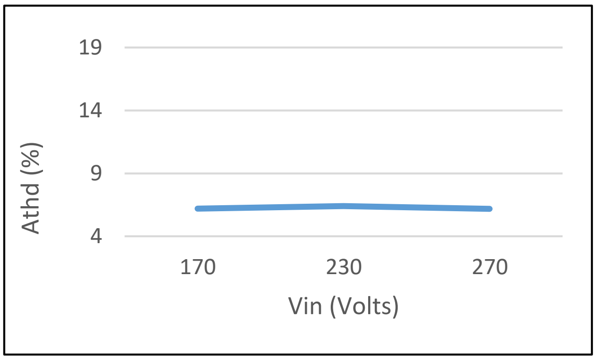


Fig.16 Athd (%) Vs Input Voltage (Vin)

Fig.16 shows current based total harmonic distortion curve which points towards high value at 230V. The results are within the acceptable limits and indicates the proposed scheme is best suited for lighting applications. In addition to above analysis, temperature inside the LED luminaire is also an important parameter for consideration. The LED junction temperature Tj estimation model can be written as follows

$$T_j = T_b + R_{\mathrm{th}} \frac{(P_E - P_L)}{n}$$

In above equation, Tb is the temperature measured at the base of the LED luminaire, Rth is the thermal resistance between the LED junction and the luminaire base, and PE and PL are the electrical and optical power from and to the LEDs, respectively. n is the count of LEDs present in the LED light engine [15]

V. CONCLUSIONS

An LED power driving circuit with having improved power factor for lighting applications has been presented in this paper. The primary side regulated flyback converter-based topology with PWM controller is used to satisfy present standard requirements. For improving isolation and safety, step-down secondary side feedback is avoided by using controller IC FL7733. This is primary side regulated PWM controller which is used in this implementation. The methodology minimizes the turn on time fluctuation, improves the power factor and low THD over universal line voltage range. The proposed scheme has been implemented successfully and tested for verifying the performance parameters viz,wide operating voltage range 90 to 300V, high step down ratio from 230V to 37 V, constant current with better luminance level. The proposed topology works as a good solution to implement low-cost, high-power factor LED driving circuit for lighting applications. To mention, scope for improvement in the circuit of primary side regulated flyback converter methodology may be the reduction in components, size, and control methodology [11].Hence integrated buck-flyback converter (IBFC) topology can be considered to investigate the possibility of efficiency improvement by redesigning the components and using another constant current LED driver in quasiresonant mode [12].

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