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Design and Development of Compact LED Driver For Long Life with PWM Dimming Functionality

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Abstract: Solid state lighting like Light Emitting Diode (LED) lamps are eco-friendly, mercury-free, more energy efficient, able to ignite instantly and have longer lifetime, superior efficacy performance. Commercial / residential LED lamps should achieve high power factor greater than 0.9 according to Energy Star Criteria for Solid State Lighting Luminaries and harmonics of the input current should meet the IEC 61000-3-2 Class C standard. Large output capacitance is required at the output of the LED driver circuit to balance the energy difference between the input pulsating AC power and output DC power delivered to the LED load and minimize the low frequency LED output current ripple. There is a mismatch between the lifetime of electrolytic capacitors (5000 hours) and the LED (1,00,000 hours) that affects lifetime of overall LED system. A compact single-switch AC/DC high power factor electrolytic capacitor-less LED driver with integrated PFC circuit and step-down voltage conversion circuit is proposed here. Simulation and hardware models were developed on a 12-W LED lamp. A remote controlling technique is used to provide different dimming level function for even the non-dimmable LED lamps. The LED driver system also operates with high power factor of 0.95 in accordance with Energy Star Criteria for Solid State Lighting Luminaries and low Total Harmonic Distortion of 21% which is within the limits of IEC 61000-3-2 Class C standards.

***Keywords**: Current Ripple, Electrolytic Capacitor, Light-Emitting Diode (LED), Power Factor, Total Harmonic Distortion*

I. INTRODUCTION

This document is a template. For questions on paper guidelines, please contact us via e-mail. An LED bulb consists of an array of light-emitting diodes (LED) that are integrated or built into a lamp or light bulb and is utilized to create artificial light. LED lamps have a longer lifespan compared to incandescent lamps. They can provide large savings in energy and cost. They have higher efficiency than Compact Fluorescent Lamps (CFLs) and high bright LEDs manufactured by Cree and other companies can produce light greater than 400 lumens per watt. Residential LED lighting can cut down energy utilization by 90% (with respect to incandescent lamps) and 55% (on comparison with Compact Fluorescent Lamps). LEDs are thermally sensitive devices and their performance is determined by ambient temperature or heat controlling properties. LEDs are also sensitive to operating voltage. They function with a voltage higher than threshold voltage and maximum value of output current shouldn't exceed the rating specified by manufacturers. Commercial / residential LED lamps should achieve high power factor [1] and harmonics of the input current should meet the IEC 61000-3-2 Class C standard [2].

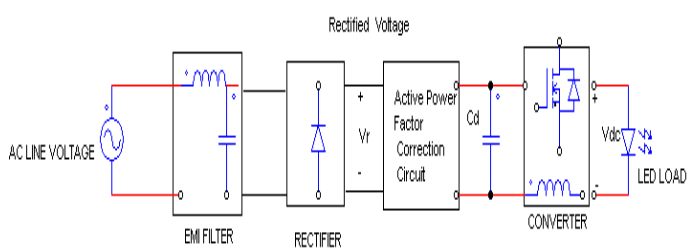

Fig.1. Dual stage LED driver with active power factor correction.

LED drivers can be a single-stage switch-mode DC/DC converter(i.e., buck, buck-boost or flyback) [3] or a two-stage converter that consists of a front-end boost converter [4] for power factor correction (PFC) and step down voltage conversion circuit as shown in Fig. 1. The two stage driver decreases energy storage capacitor (C_d) due to larger input impedance of the second stage DC/DC converter, but increases the number of circuit elements increasing size and cost of the driver circuit causing lower efficiency. Operation at high power factor with a sinusoidal AC-input current leads to pulsating input power. There is a need to compensate the energy difference between the fluctuating source power and the output DC power delivered to the LED load by incorporating large output capacitor. Visible flickering irritates human vision causing malaise, epileptic seizures, headaches etc [5] .

To reduce the LED driver size and cost, aluminium electrolytic capacitor is used as energy storage capacitor due to its high energy density. Operating life of aluminium capacitor is only 5000 hours compared with the lifetime of an LED lamp, which lasts 1,00,000 hours thus affecting the overall life of LED fixture [6]. Aluminium based electrolytic capacitors are susceptible to their operating temperature, ripple current, internal equivalent series resistance. They have low electromagnetic immunity, low overvoltage and overcurrent capabilities and are highly unreliable and susceptible to damage. Various LED driver solutions without electrolytic capacitors have been proposed before. In [7], flyback converter with a bidirectional buck-boost converter at the flyback's output was used to absorb the pulsating component of the LED current to eliminate low frequency component of the LED current and the output energy storage capacitor used in the conventional flyback converter. In [8], a modified flyback converter with an additional auxiliary winding and three switches was presented to provide constant current to the output. In [9], a coupled inductor PFC single-switch LED driver circuit is proposed but the switch suffers very high current and voltage stress as the switch needs to handle both PFC inductor current and LED current resulting in low efficiency. In [10], a valley-fill circuit was used to replace series capacitor of a conventional Single-Ended Primary-Inductor (SEPIC) converter to provide required energy to drive the LEDs. In [11], a electrolytic capacitor-less LED driver based on two flyback converters was proposed but it doesn't have the dimming feature to control brightness.

These LED driver circuits without electrolytic capacitor involves multiple stages or multiple switch topologies and use several high voltage film capacitors. This leads to complicated gate drive controllers and increases the cost of the overall circuit. A compact electrolytic capacitor-less LED driver with a remote controlled dimming functionality is proposed here. It is a single-stage single-switch topology that eliminates aluminium capacitors without increasing the number of switches or injecting input current harmonics to balance the energy at LED load.

II. THEORETICAL BACKGROUND OF THE PROPOSED CIRCUIT

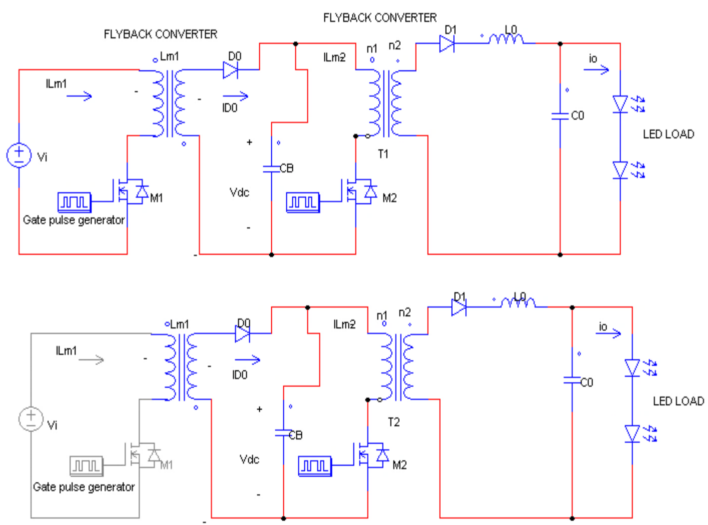

Fig. 2. Derivation of novel LED driver circuit

LED driver circuit is obtained by combining a discontinuous conduction mode (DCM) power factor corrector (flyback converter) and a continuous conduction mode (CCM) flyback converter into a single-stage single-switch topology as shown in Fig. 2. Capacitor is transferred from output to intermediate rectifier stage of the converter. It utilises an extra winding to feedback part of the energy to the energy storage capacitor and provide a close-to-sinusoidal input current. Three-winding transformer delivers isolation, input power factor correction and stores and provides the required energy to the output. Energy storage capacitance is reduced, which allows film capacitor instead of conventionally used electrolytic capacitors. Secondary side of flyback converter is used as the DCM power factor corrector consisting of D_0, C_B, and L_{sec} (secondary of L_m), where the voltage across capacitor C_B is boosted from the rectified voltage (V_r). Current flowing through D_0 follows the low frequency voltage envelope provided by the difference between V_r and V_{dc}. Output stage is an isolated flyack converter that consists of L_m, L_{tri} (tertiary winding of L_m), M, $D_1$and an output filter (L_o and C_o). L_f and C_f form the input electromagnetic interference (EMI) filter. The final LED driver circuit is given in Fig. 3.

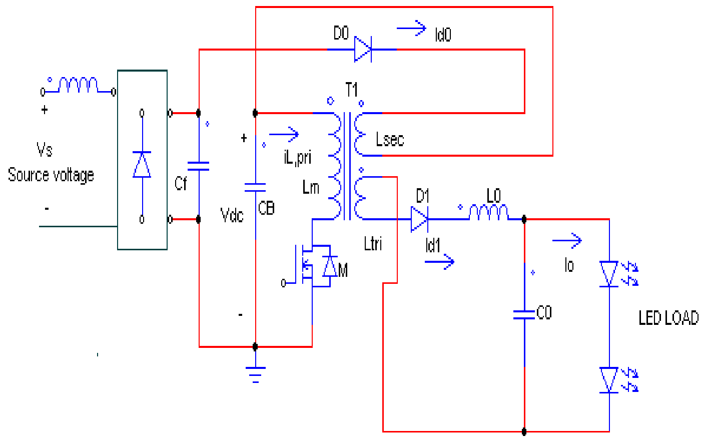

Fig. 3. Proposed isolated LED driver circuit with flyback converter

A. Circuit Operating Principles

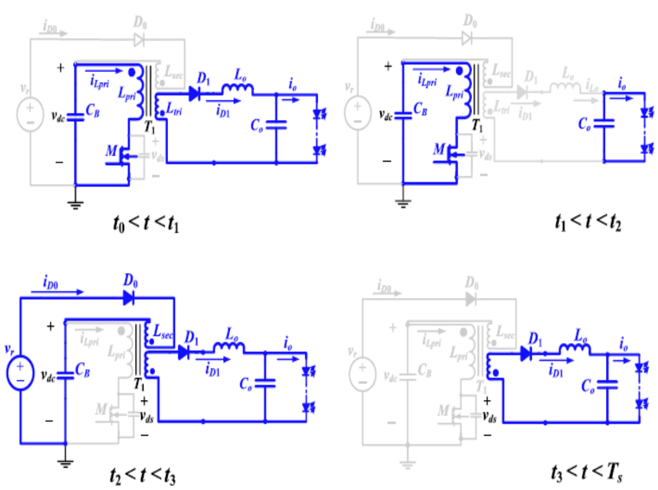

Fig. 4. Operating stages of the LED driver

[Stage 1: $t_o < t < t_1$]: The various working stages of the driver circuit are shown in Fig. 4. When the gate pulse is applied to turn ON the MOSFET switch (M), current i_{Lpri} flows through C_B and M and the current i_{D1} discharges its energy through D_1 and C_o. This stage ends when i_{D1} drops to zero.

[Stage 2: $t_1 < t < t_2$]: At t_1, D_1stops conducting and the output capacitor C_o discharges its energy to the load. The switch (M) still conducts and rising part of the current i_{Lpri} is decided solely by the voltage across capacitor C_B.

[Stage 3: $t_2 < t < t_3$]: When the gate pulse (V_G) is withdrawn, MOSFET stops conducting and the switch voltage (v_{ds}) increases. Due to reversal of polarity between transformer windings, D_0 and D_1turns ON and due to the step-down voltage function of the flyback output stage, i_{D1} increases linearly. As V_{dc} is boosted from the rectified voltage, i_{D0} reduces linearly. This stage ends when i_{D0} decreases to zero.

[Stage 4: $t_3 < t < T_s$]: At t_3, due to the DCM operation of the PFC, i_{D0} reduces to zero and D_0 stops conducting but the output inductor (L_o) provides energy to the LED load. The voltage and current waveforms are indicated in Fig. 5.

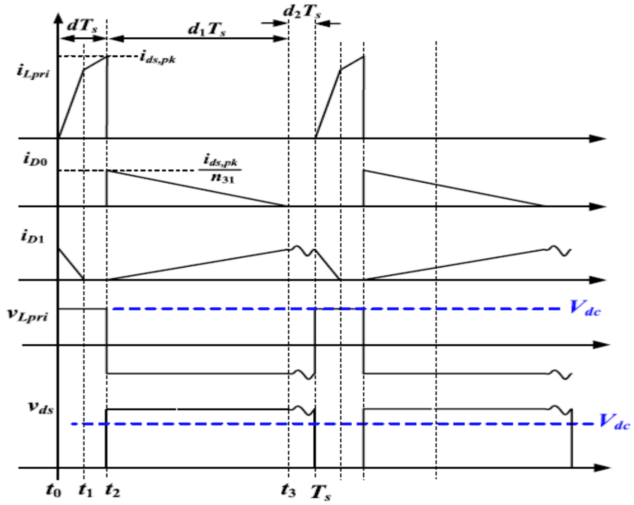

Fig. 5. Key Waveforms of the pulsating current LED driver

III. DESIGN OF THE DRIVER CIRCUIT

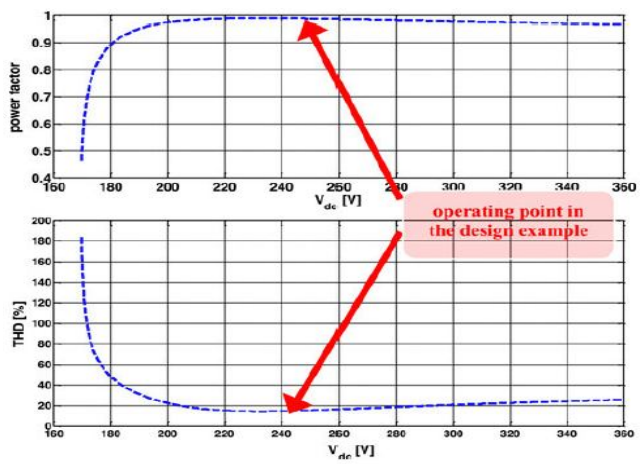

Fig. 6.Variation of input power factor and input current THD with capacitor voltage

To authenticate the working of the circuit, the circuit was first simulated in PSIM on a 12-W LED lamp with input voltage of 120V_{rms} and switching frequency of 62 kHz. Output load consists of ten series-connected LEDs with an average current of 0.35 A which gives a total output power of close to 12 W. Driving LED with pulsed-current improves the constancy of the luminous power of the LED while high DC current leads to saturating luminous level [12].

As input voltage is 120 V_{rms}, peak input volage V_p is 170 V using $V_p = 1.414 * V_{rms}$. The optimized input current shape occurs at a ratio of V_p/V_{dc} between 0.6 and 0.8. A ratio of

$\beta = V_p/V_{dc} = 0.7$ is chosen to give $V_{dc} = 245$ V as shown in Fig. 6. V_p must be lesser than V_{dc} as β influences the input power. Power factor reduces as V_{dc} nears V_p. As V_{dc} rises, β drops and power factor rises. Further reducing β actually drops the power factor slightly. As β decreases, shape of the input current becomes more like a square waveform and input power factor drops. Therefore the minimum power factor that can be achieved, when the input current becomes a pure square shape is 0.9.

With V_{dc} = 245 V and an efficiency of 0.85, C_B is calculated to be 2.7µF. L_o is then designed to be 1.5mH with $n_3 = n_1$. Capacitor (C_o) of 2uFacts as output filter added by reducing the high frequency LED output current ripple.The input EMI filter components L_f and C_f are designed to be 1.3mH and 47nF. Since the presence of C_f can introduce a phase shift between the line voltage and the line current and will then affect the input power factor, the capacitance of C_f should not be too large in the actual design.

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IV. SIMULATION MODEL AND RESULTS

The proposed LED driver was simulated in PSIM 9 by selection of components from the Elements library in PSIM toolbar. The PSIM simulation model is given in Fig.7.

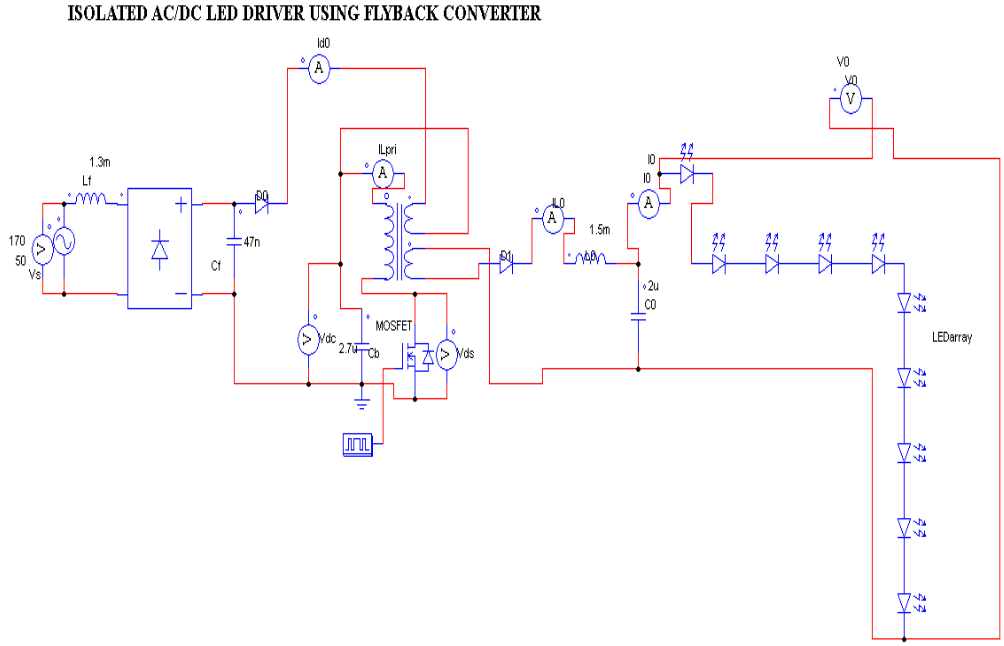

Fig.7. PSIM simulation model of the proposed LED driver circuit

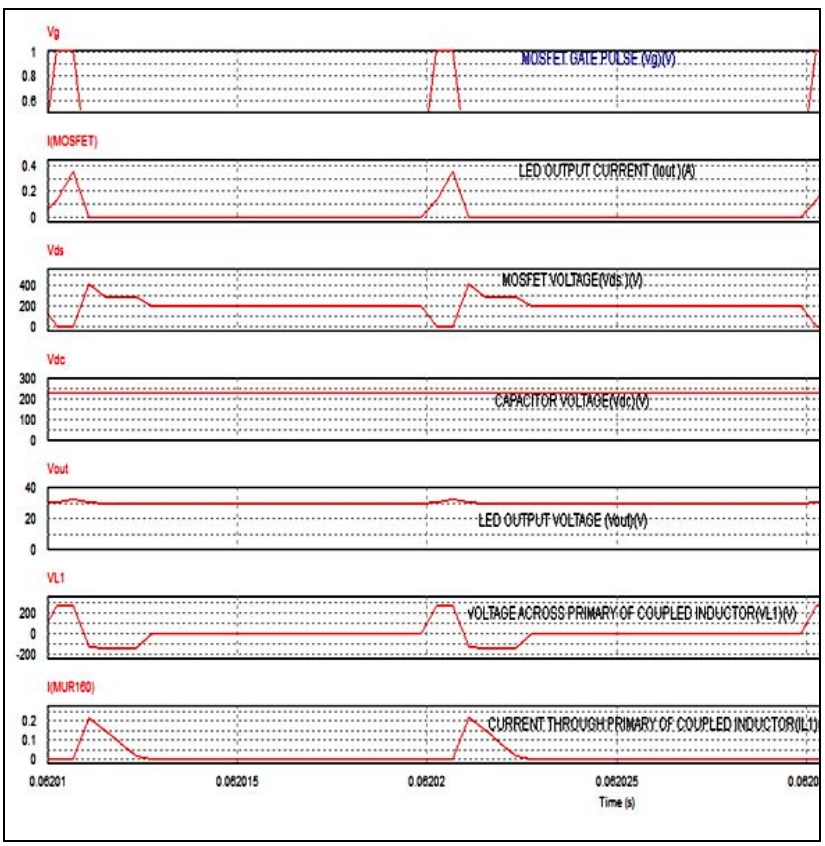

Fig.8. Key waveforms of the PSIM simulation model

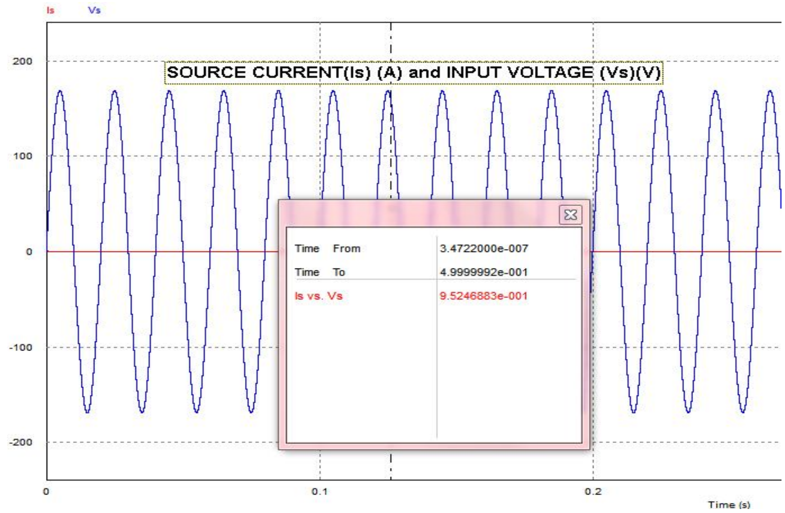

Fig. 9. Power factor determination at the source side

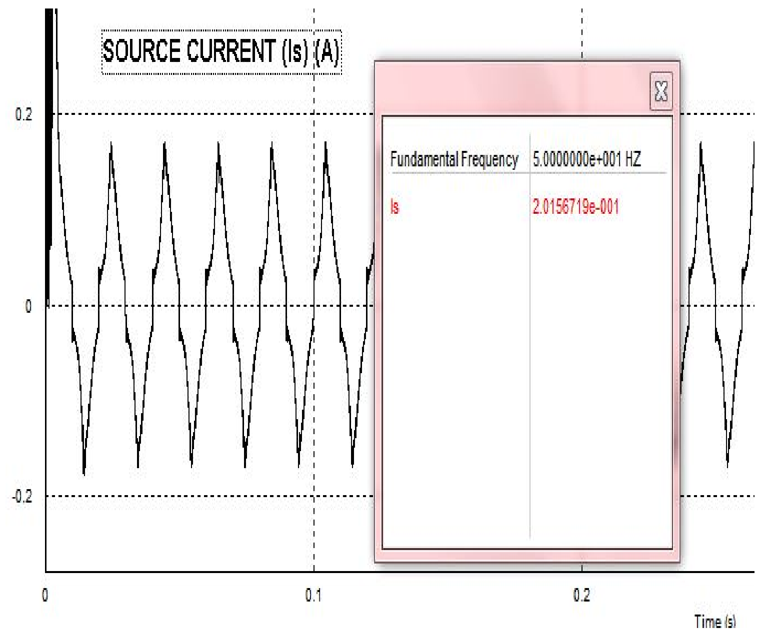

Fig. 10. Total harmonic distortion determination of source current.

The waveforms of the MOSFET switching pulse, diode current, primary winding voltage, capacitor voltage, LED output current, MOSFET switch voltage, and LED output voltage are shown in Fig. 8. The LED output current was achieved as 0.4A and the LED output voltage as 85V for a duty ratio of 40%. The capacitor voltage is determined as 200V and the maximum voltage stress as 320V. It can be seen that the input current is almost in phase with the input voltage with a input power factor of 0.952 as in Fig. 9 at the input side in accordance with Energy Star Criteria for Solid State Lighting Luminaries and the Total Harmonic Distortion of the input current is 20.15% which is within the limits of IEC 61000-3-2 Class C standards as given in Fig. 10**.** The source current is almost sinusoidal with a value of 0.18A and the source voltage is 170V.

V.HARDWARE DEVELOPMENT

A compact and reliable high power factor electrolytic capacitor less LED driver circuit that offers high frequency pulsating current is designed and developed as a hardware prototype.

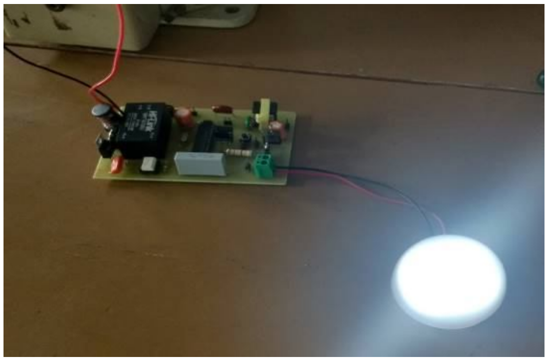

Fig. 12. LED bulb with full brightness

Fig. 13. LED bulb dimmed using remote control

Traditionally, AC to DC conversion is accomplished using a transformer and rectifier circuit. Use of transformers in transformer-based supplies and incorporating inductor/MOSFET/controller in switched power supplies are not feasible and affect the compactness of the overall circuit by increasing the size and weight especially for electrical appliances. A transformer less power supply using zener diode provides 12V for the TLP250 MOSFET driver circuit. The 12V from the transformer less power supply is acts as input to the 7805 voltage regulator IC which converts the 12V to 5 V to provide 5V DC supply to the ATmega328/P microcontroller.

An input filter (inductor and capacitor), bridge rectifier IC (HD04D) and a filter capacitor of 47nF, 250V is placed for smoothening the DC voltage ripples and give a stable regulated DC voltage. The TLP250 driver circuit amplifies the low-voltage signal from ATmega328P controller to a large-voltage of 12V to trigger the gate of IRF840 power MOSFET. The main difference between TLP250 and other driver circuits like IR2111,SG3525A etc is the optical isolation between input stage and output stage of TLP250 TLP250 acts as a gate driver to switch ON the MOSFET and as a opto-coupler. A ultra- fast recovery diode MUR160 discharges the freewheeling current when the MOSFET switch stops conducting . The 3 winding flyback transformer is designed for a turns ratio of $N_1/N_2 = 2/5$ and $N_3 = N_1$ and magnetising inductance (L_m) of 0.75mH (referred to primary winding). A ferrite core is utilised because of high switching frequency of 62kHz and the input part ratings are 240V ,3A and an output ratings of 120V and 2A. Philips 12W LED lamp was used as the LED load. Atmega328P provides the trigger signal for the MOSFET. As the duty ratio becomes 40%, the conducting time of the MOSFET increase and the average LED output voltage rises causing higher luminous intensity as shown by Fig.12. As the duty period reduces to 10%, ON time of the MOSFET switch decreases and the average LED voltage decreases causing reduced brightness of the LED lamp as indicated in Fig. 13. An IR remote is used to provide dimming levels from 40% to 10%. IR sensor TSOP 31456 demodulates the IR signals received and provides it to the microcontroller Atmega328P which decodes the pulse and performs the dimming function according to the program.

Fig. 14. Flukemeter for Power quality parameters measurement

As a final investigation, a flukemeter is used to measure the power factor and the Total Harmonic Distortion(THD) as shown in Fig. 13. The power factor was determined as 0.95 which is within the Energy Star Criteria for Solid State Lighting Luminaries and the total harmonic distortion as 23%.

VI. NOVELTY AND LIMITATIONS

The proposed driver has extended life and improved reliability due to absence of electrolytic capacitors. Harmonic content of the source current is 20% which is within the IEC 61000-3-2 Class C standard resulting in low Total Harmonic Distortion (THD). This can be seen from the simulation results of PSIM simulation model. The LED driver has high efficiency, lesser cost due to less components and compact size. It functions at a highinput power factor of 0.95 according to Energy Star Criteria for solid state lighting luminaries. A remote controller is used to implement PWM dimming to adjust the brightness level. Dimming is provided at four different stages and can dim even non dimmable lamps which are more commonly offered inthe market. Extra dimming levels can be added. It requires extra magnetic component in the form of an inductor and needs two more fast recovery diodes than the flyback converter. However, those are standard fast-recovery diodes and the overall cost of the circuit will not be much higher than the standard flyback converter.

VII. CONCLUSION

A compact low cost LED driver with PWM dimming for dimmable and non-dimmable LED bulbs was successfully realized. With the integrated PFC stage in the proposed circuit, close to unity power factor can be achieved in the circuit. The derivation of the driver topology, its working stages and the circuit characteristics have been explained in this paper. The DCM operation of coupled inductor provides PFC and high frequency pulsating current to the LED lamp. Simulation models in PSIM and hardware of the driver circuit was developed to authenticate the novelty of the circuit by implementing a 12W, 230 V_{rms} model. If the driver circuit is developed and manufactured as a Surface Mounted Device (SMD) circuit, it can substitute prevailing LED drivers for in industrial, commercial and domestic lighting applications. Much higher levels of efficiency will become the standard and it will integrate greater levels of complexity in terms of power monitoring and performance. More integration of Systems on Chips (SOC's) will decrease the size, while sustaining reliability of the circuit.

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