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Design of Low-Cost AC-Direct Driverless LED Luminaries with Non – Perceptible Flicker

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Abstract:- Design considerations for a low cost and efficient Light Emitting Diode (LED) luminaries involve numerous compromises. Factors such as efficiency, power factor and flicker Index all present a compromise against each other. It is conventional to employ suitable means that make for a low cost and efficient LED luminaire. In this paper, a driverless AC-Direct LED luminaire with non-perceptible flicker, improved power factor, with acceptable total harmonic distortion (THD) characteristics is designed. With a flicker index of 0.2, it outperforms most AC luminaires employing high voltage switching chips, which have a typical flicker index usually greater than 0.3. The efficiency is 88%, as against 80% achieved by most AC LED light engines. The design has a THD of 18.79% and power factor of 0.92, this meets Energy Star requirements for consumer products.

Keywords:- *LED Luminaire, Flickerless LED, Driverless, Low Cost, AC-Direct.*

I. INTRODUCTION

Globally, lighting forms a major part of energy consumption worldwide. Lighting consumes about 25% of the world's total electric energy [1]. Efficient lighting with energy saving has become very vital. Consequently, current light sources are expected to be designed to be highly efficient, environmentally friendly, energy saving, and should be able to deliver the required visual preference [2].

Light Emitting Diode (LED) provides all the aforementioned properties, and with advancements in technology, they are being deployed in mobile products and backlighting of Liquid Crystal Display) LCD panels [3]-[4]. Generally, LED lighting are majorly deployed in applications that require low-brightness illumination (e.g the screen backlights of laptops and mobile phones), and high-brightness illumination (which includes general lighting, vehicle lighting, and backlighting of large television panels) [5]-[6]. LED-based Solid State Lighting (SSL) is a promising energy saving technology to replace incandescent halogen, fluorescent tube, and Compact Fluorescent Light (CFL) in the lighting industry. LED's when compared to the aforementioned technologies has a longer life span, about 50,000 operational hours compared to 1000 – 2000 hours for incandescent lamps and 5000 – 10,000 hours for CFL [7]. LED's also costs much less and has a higher luminosity than these other technologies when operating with the same power rating.

While LED's present both an economical and efficient solution to lighting problems, the best way to power them efficiently remains debateable. In the early stage, expensive light engines and converters were mainly used for driving LEDs. Most of these technologies depended on high voltage Integrated Circuit (IC) switching chips for matching the number of LED strings during a power line cycle with the instantaneous power line voltage [8]. The major problem associated with these LED drivers is that due to their poor design and performance they greatly reduce the durability and cost of the lighting system.

Demands for higher efficiency, lower cost, and reduced flicker content of the emitted light keeps increasing and spurring the implementation of improved techniques and products. By dividing the LED's into sections, AC direct driving techniques are employed to drive the LED's without need for a switching mode power supply (SMPS).

In this paper, a driverless LED luminaire with non-perceptible flicker, alongside improved power factor and total harmonic distortion (THD) characteristics is designed.

II. CHARACTERIZING PHOTOMETRIC FLICKER

The Photometric flicker is a common phenomenon among light sources. Conventional light sources ranging from incandescent lamps, High Intensity Discharge (HID), fluorescent, CFL, and LED's all experience some degree of flicker. Photometric flicker is a characteristic of the light source resulting from power sources drawn from AC mains. According to the Illuminating Engineering Society of North America (IES) Lighting Handbook, flicker is defined as: "the rapid variation in light source intensity" [9]. The effect of light sources with flicker over a period of time on human observers can be very hazardous. This could lead to physiological effects and can have neurological consequences. Light engines running on such rapid variations are recognized as contributing to headaches and migraines [10].

The adoption of driverless modules promising long life and quick return-on-investment in the market has been greatly plagued by high flicker. The Illuminating Engineering

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Society (IES) developed two metrics to quantify flicker as described in RP-16-10 (Nomenclature and Definitions for Illuminating Engineering) [11]. The more commonly utilized metric is percent flicker. The percent flicker helps to indicate the average amount of modulation in light output over a single on–off cycle. A Percentage flicker of 100% indicates that at some point in its cycle, no light is produced. A light source that is completely steady is said to have zero percent (0%) flicker.

The other metric is the flicker index. This ranges from zero to one. It accounts for the shape of the light's waveform and the duty cycle. A low value of percent flicker and flicker index is desirable for non-perceptible flicker. Note that recent findings indicate a new metric called Compact Flicker Degree (CFD). This helps in evaluating the performance of light engines that use higher frequencies (up to and beyond 2000Hz) for modulation of light [12].

Flicker is inherent in Conventional light sources. Incandescent lamps have a percentage Flicker of around 10~20% [13], while magnetically ballasted CFL lamps have a rather high flicker of 37 ~ 70%. Though modern electronically ballasted CFL lamps have lower Percent flicker of around 5% [13].

Presently, there is no clearly stipulated standard regarding the maximum acceptable flicker in LED lamps. The percent flicker specified by manufacturers stipulates that the percent flicker should be less than 30% in the 100Hz - 120Hz frequency range [13]. A stable LED driving current is required to achieve a flicker free operation. According to [13], there are two kinds of light flicker observable in LED lamps:

- AC line frequency related light fluctuation (usually at double the line frequency (100Hz for 50Hz line frequency and 120Hz for 60Hz line frequency).
- Random light intensity fluctuation (often caused by incompatibility between lamp and peripheral lighting components).

According to research, flicker above 75Hz is usually not noticeable by most individuals. Although, the perceptibility of flicker is not only related to frequency: it is also related to the intensity of the peaks and valleys of the light output (intensity modulation) and duration of these variations [13].

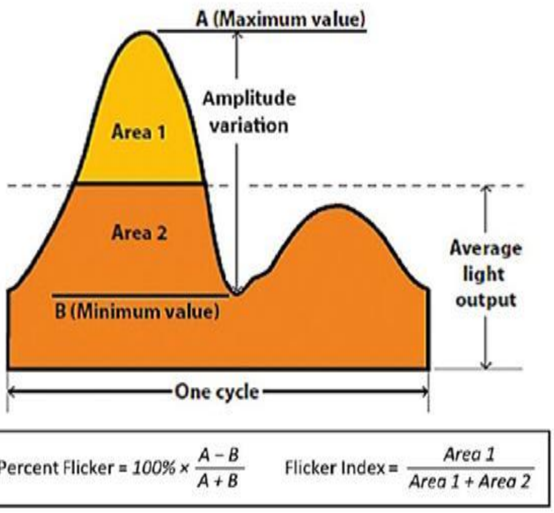

Fig.1 Figurative description of flicker Index [13].

III. TOPOLOGIES FOR THE DESIGN OF LED LUMINAIRE WITH NON-PERCEPTIBLE FLICKER

I. The *Basic Offline LED Driver*

The operation of a mains fed LED driver is used to illustrate the reason behind the 100Hz/120Hz perceptible flicker in offline LED lamps.

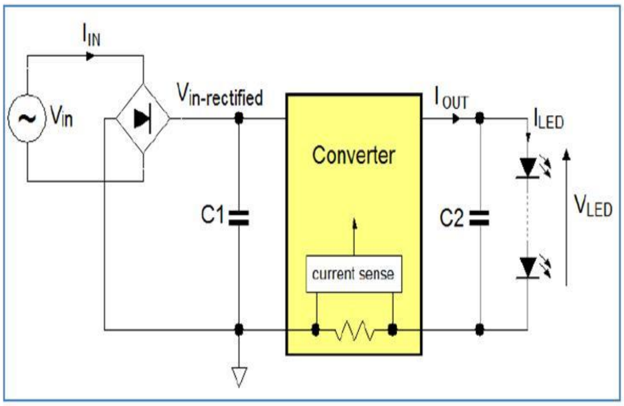

Fig. 2 Basic Offline LED Driver [13].

The converter for most single stage offline LED drivers consists of a Buck-Boost or flyback converter to convert the rectified line voltage into a suitable output voltage for driving the LED string.

In such a system shown in figure 2, flicker-free operation is achieved if the LED current I_{LED} is a stable DC current, and the LED voltage V_{LED} is fixed. Since the line voltage is sinusoidal, the circuit must contain a voltage buffer element that would help to transform the alternating current into DC voltage. This achieved using either of C_1 or C_2 as shown in figure 2. [13].

II. High Power Factor Applications

To design a system with high power factor that meets with the harmonic standards stipulated by IEC61000-3-2, the LED driver with an ac input incorporates Power Factor Correction (PFC) control [14]. A unity power factor implies that a pulsating power will be seen at the input side of the driver, while the output power is typically made constant to drive the LEDs. To balance out the instantaneous power difference between the pulsating input and the constant output an Electrolytic capacitor is usually employed for that.

From figure 3, for good power factor with low input harmonic current, the value of C_1 must be kept small and the converter must try to maintain a sine shaped input current as well, requiring a low bandwidth control loop. The voltage buffer element (C_2) is used to reduce the voltage ripple across the LED string. A large value of C_2 is required to achieve very small LED voltage ripple. The LED current ripple and flicker is usually determined by the voltage ripple along with the LED characteristics [13].

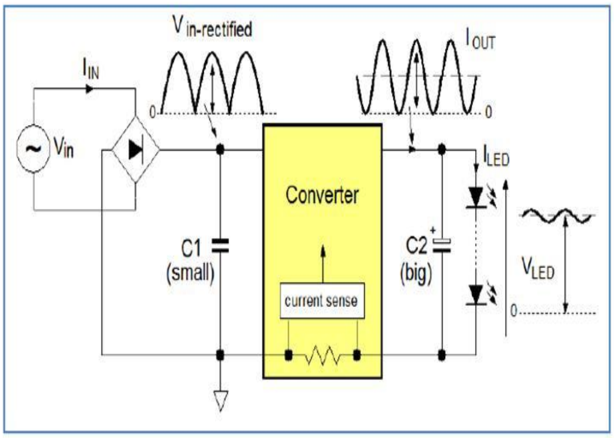

Fig.3 High power factor converter [13].

To control the flicker in a high PFC single stage LED driver, the following procedure is followed [13]:

i. Characterize the maximum acceptable flicker percentage requirement (about 30%)
ii. Establish the maximum LED current peak to peak variation (I_{PP}) from the Luminous Flux vs. forward current curve.
iii. Using the LED I/V curve, calculate the dynamic resistance (R_D) of the LED at the operation point.
iv. Calculate the maximum peak to peak voltage ripple (V_{PP}) across all the LED string, mathematically, it is:

$$(V_{PP}) = (I_{PP}) * (R_D) \quad (1)$$

v. Calculate the output capacitor value using equation (2):

$$C_{OUT} = \frac{(I_{PP})}{(V_{PP}) * 2\pi f} \quad (2)$$

Where:
(I_{PP}) is twice the average LED current and (V_{PP}) is the allowed peak to peak output voltage ripple across the LED string

f is twice the line frequency.

IV. DESIGN PARAMETERS FOR THE AC – DIRECT DRIVERLESS LED LUMINAIRE WITH NON-PERCEPTIBLE FLICKER.

The design parameters for the LED luminaire are chosen to match or exceed the photometric characteristics of a two feet (2 feet) fluorescent light or a Compact Fluorescent Light (CFL) down light luminaire at a reduced cost and higher efficiency. Important photometric characteristics of these light fixtures are compared in table 1.

TABLE 1
PHOTOMETRIC CHARACTERISTICS OF SOME LIGHT FIXTURES
*Source: Lamp manufacturers datasheet [15].

Characteristic	CFL Value	2 ft. Fluorescent Value	LED luminaire Value
Light Output (Lumen)	**670***	**950***	**1026***
Power (Watts)	**11**	**10**	**9**
Efficacy (lm/W)	**61**	**95**	**114**
Correlated Colour Temperature (CCT)	**4000K**	**4000K**	**4000K**

Two of the most important parameters in the design process of any LED-based luminaire is the number of LED's required to meet the design goals and the effective capacitance of the circuit.

The LED used for this design is Cree XLAMP MX-6 LED high brightness LED. Important parameters of the XLAMP MX-6 LED are shown in Table 2.

TABLE 2
IMPORTANT PARAMETERS OF THE XLAMP MX-6 LED

Part Number	Norminal CCT (K)	Norminal Drive Current (mA)	Typical Forward Voltage (V)	Typical Power (W)	Typical Efficacy (lm/W)
XLAMP MX-6	4000	300	3.3	1	114

To effectively determine the number of LED's needed, the inefficiencies contributed by the optical, thermal and electrical systems is estimated as follows.

- **Optical Loss**: Optical system efficacy is estimated by examining light losses due to Secondary Optics and fixture Light loss. Fixture light loss arises when the light source strikes the fixture housing before hiting the target. The efficiency of the fixture depends on the placement of the LED's, the fixture shape and material. The structure for the designed LED luminaire is such that the LED's emit optical light directionally, removing the need for reflectors; hence only secondary optical loss due to the diffuser placed over the LED's is considered. The generally accepted optical efficiency through the secondary optical element lies within 85% and 90%. An optical efficiency of 88% is assumed in this design.
- **Thermal Loss**: This is due to decrease in relative luminous flux output of the LED as junction temperature (T_j) rises. Most LED data sheets list typical luminous flux at T_j = 25°C, while most LED applications use higher temperatures. A Junction temperature T_j = 80°C is assumed which corresponds to a minimum relative flux of 80% from the LED's datasheet [15]. 85% relative luminous flux is the thermal efficacy estimate used in the design.
- **Electrical Loss**: Electrical loss is inherent in electrical devices, for the system designed; an efficiency of 88% is achieved. Most typical LED drivers has an efficiency between 80% and 90%.

The exact number of LED lumens that is required to achieve the design goals is calculated considering only the light efficiencies. Electrical efficiency does not affect the amount of light produced by the luminaire. This is calculated as shown below:

$$Actual\ Lumens = \frac{Target\ Lumens}{(Optical\ Efficiency)*(Thermal\ Efficiency)} \quad (3)$$

$$Actual\ Lumens = \frac{1026}{(88\%)*(85\%)} \simeq 1{,}372\ lm$$

The number of LED's required to produce this amount of lumen depends on the operating current. For the LED used (XLAMP MX-6 LED), the operating current is 300mA.

Therefore:

$$Number\ of\ LEDs = \frac{Actual\ Lumens\ Needed}{Lumens\ per\ LED} \quad (4)$$

$$= \frac{1372\ lm}{114\ lm} = 12.04\ LEDs$$

Thus a minimum of 12 LEDs of 114 lm @ 300mA operating current per LED wired in series are needed to satisfy the light output design goal.

The effective capacitance C_{eff} represents the combined capacitance of the Power Factor Corrector (PFC) circuit during the discharge period. The effective capacitance of the PFC circuit is given as:

$$Ceff = (C1//C3) + (C2//C4) \quad (5)$$

Different capacitor values yields different values of power factor and THD %. According to [16], the best combination of capacitors that yields the highest PF and lowest THD is when $C1 = C4 = C$ and $C2 = C3 = C/2$. Substituting this condition into equation () yields:

$$C_{eff} = 3C/4. \quad (6)$$

The Output Power (P_o), estimated Efficiency (η), normal discharge period (t_{normal}), holdup time requirement (t_{holdup}) and effective capacitance (C_{eff}) can be calculated from the following equation:

$$C_{eff} = \frac{2(P_o)(t_{holdup}+t_{normal})}{\eta(V_s^2-V_f^2)} \quad (7)$$

Where V_s and V_f are the designated initial and final voltage, respectively, in the entire discharge period.

The normal discharge period (t_{normal}) is 4ms for 50Hz AC, while the holdup time requirement (t_{holdup}) is 5ms. The circuit starts discharging at around two-third of input voltage and assume 15% voltage ripple during discharge, thus:

$$V_s = \frac{2}{3}\sqrt{2}\,(V_{RMS}) \quad (8)$$

$$V_s = \frac{2}{3}\sqrt{2}\,(230) = 216.84V$$

$$V_f = (1-0.15)V_s \quad (9)$$

$$V_f = (1-0.15)(216.84) = 184.32\text{V}$$

$$C_{eff} = \frac{2(P_o)(t_{holdup}+t_{normal})}{\eta(V_s^2-V_f^2)}$$

$$C_{eff} = \frac{2(9)(0.004+0.005)}{0.88(216.84^2-184.32^2)} = 14.11\mu f$$

$$C = \frac{4}{3}C_{eff} = 18.81\mu f$$

In the actual design, $20\,\mu f/250V$ electrolytic capacitor was used for C.

V. CONTROL CIRCUITRY OF DRIVERLESS AC – DIRECT LED LUMINAIRE WITH REDUCED FLICKER.

The harmonic input currents drawn from AC mains by the conventional bridge-diode rectifier with a large bulk capacitor connected to its output led to the passive power factor correction approach adopted in this design. The circuit employed in this work is as shown in Fig.4.

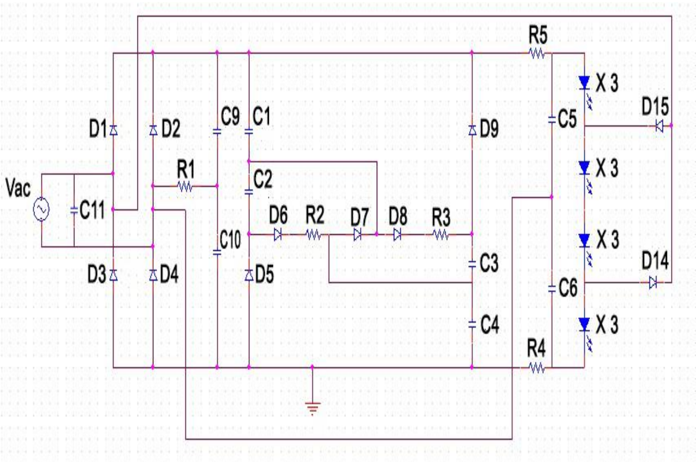

Fig.4 Circuit diagram for the driverless and flickerless LED Luminaire

Considering the circuit diagram in fig. 4, an improved valley fill circuit is introduced to replace the bulk electrolytic capacitor and hence make for better power factor correction. When AC voltage is applied to the circuit, in the first instance, the line voltage would be slightly higher than the voltage across either of (V_{C1} +V_{C2}), (V_{C3} +V_{C4}) or (V_{C1} + V_{C4}). Consequently, the bridge diode conducts and the Input current flows to the output load directly. With time, the line voltage rises slightly above the voltage sum, (V_{C1} + V_{C3} + V_{C4}) or (V_{C1} + V_{C2} + V_{C4}) and starts charging the capacitor pair with lower voltage first.

In this design, C_2 = C_3, therefore they will all charge up at the same time and the input current charges the capacitors and flows to the load the same time.

Unlike the conventional large bulk capacitor, the input current still flows to the load rather than remaining at the peak input voltage and preventing the input current from flowing as the input voltage decays. The PFC circuit allows the input current to still flow to the load because the valley-fill voltage stays around two-third of the peak input voltage. This lengthens the conduction time for bridge diodes compared to the conventional rectifier. When the input voltage decreases and falls below two-third of the input peak voltage, the input current stops flowing because the bridge diode is reverse-biased. At this point, the capacitor pairs discharges in series to provide the output current.

At the zero crossing level, the Line voltage changes direction but is lower than the valley fill voltage. Thus, the input current still flows through the path R_1-C_{10}-D_3. The whole charging/discharging cycle repeats at the next half line cycle when the input voltage is higher than the voltage sum of (V_{C1} +V_{C2}), (V_{C3} +V_{C4}) or (V_{C1} + V_{C4}).

Capacitors C_9 and C_{10} are introduced to increase the conduction time of the input current, they provide an alternate path for the input current to flow into the Valley fill circuit before the input line voltage rises above the Valley fill circuit voltage [16]. This helps to decrease the current distortion. Their values are chosen to be smaller than that of the capacitors in the PFC circuit. There are chosen after deciding the value of the effective capacitance of the circuit.

Resistor's R_2 and R_3 are introduced to reduce the inrush current into the PFC circuit and to also suppress current distortion by limiting and smoothing the peak diode charging current. The power dissipated by these resistors is only a fraction of the input power; therefore they wouldn't impact greatly on the efficiency of the system. For a hold up time of 5mS at 0.92 power factor, 20Ω resistors were used.

According to Yanchao Method for Single-Phase Rectifier [17], the distortion factor due to the waveform distortion has a similar property to reactive power. The input capacitor C_{11} was introduced to compensate this reactive power. It absorbs the harmonic distortion power so as to yield higher power factor and lower THD. The distortion factor is related to the THD as shown below:

$$Distortion\ Factor = \sqrt{\frac{1}{1+THD^2}} \qquad (10)$$

Where,

$$THD = \frac{\sqrt{\sum_{n\neq 1} I_{n\_RMS}^2}}{I_{1\_RMS}} \qquad (11)$$

These all relate to the power factor in the expression given below:

$$Power\ Factor = Displacement\ Factor \times Distortion\ Factor \qquad (12)$$

$$Distortion\ Factor = Cos\ (\theta_v - \theta_i) \qquad (13)$$

Where, θ_v and θ_i are the phase of the voltage and current respectively.

VI. EXPERIMENTAL RESULT

The proposed circuit was simulated and tested at a power level of 9W and input voltage of 230V (RMS). Simulation and experimental results are presented in Table 3. The waveform of the input voltage, the input current and the output voltage of the experimental circuit are shown in Figs. 5 and 7.

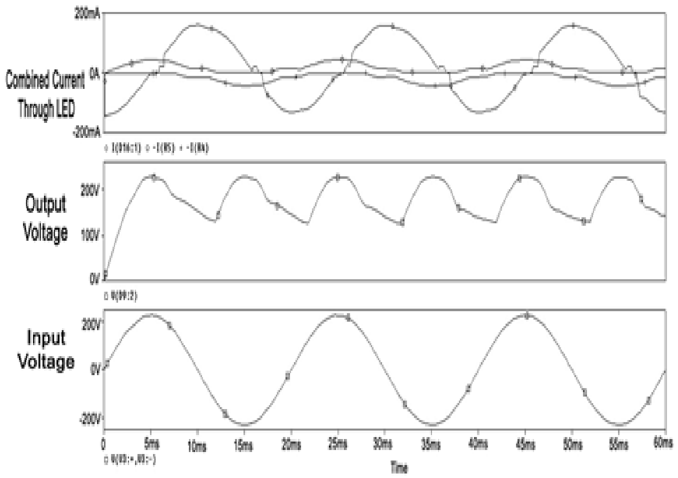

Fig. 5 Operating Waveforms of the circuit

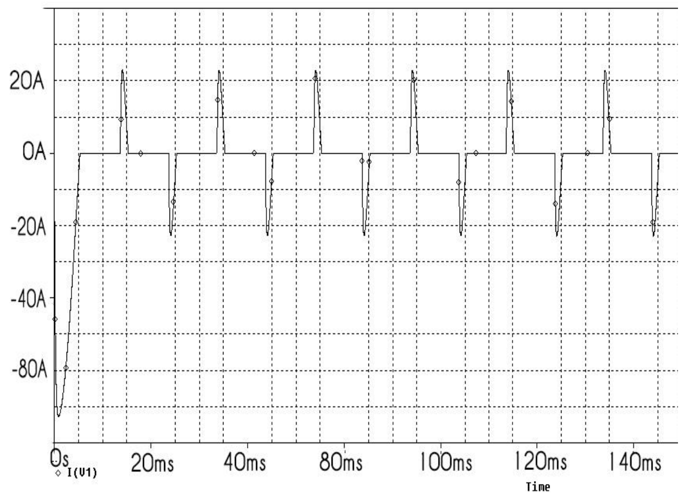

Fig. 6 Input current waveform of the conventional circuit

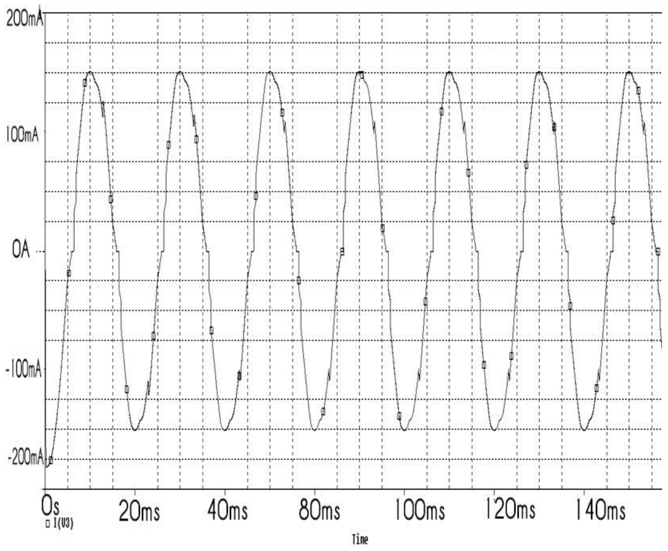

Fig. 7 Input current waveform of the PFC circuit

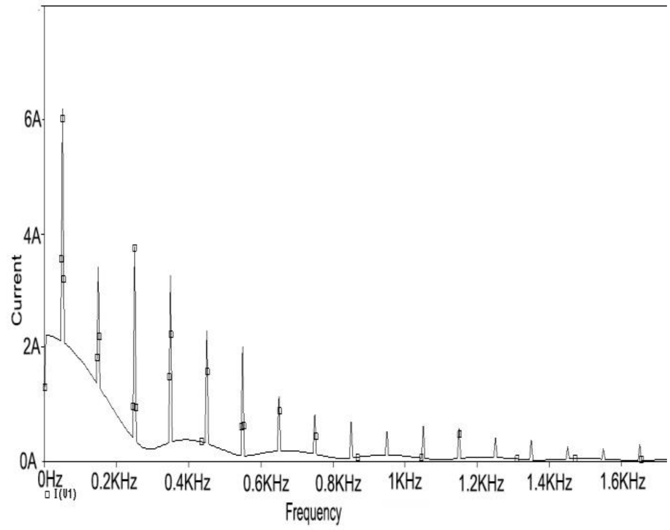

Fig. 8 Fourier analysis of the Conventional Circuit

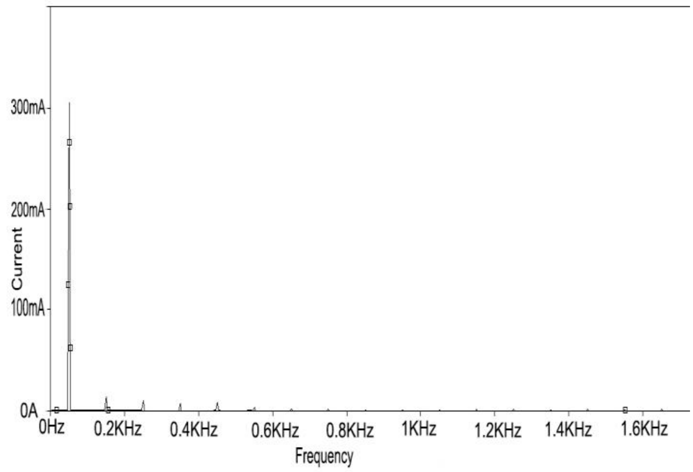

Fig. 9 Fourier analysis of the PFC Circuit

TABLE 3
SIMULATION AND EXPERIMENTAL RESULTS

Parameter	Simulation Value	Measured Value
Input Power	10W	10.18W
Input Voltage Range	170-230V(RMS)	170- 230V(RMS)
Output Power	9W	8.96W
Efficacy	-	114lm/w
Efficiency	90%	88%
Power Factor	0.95	0.92
Flicker Index	-	0.2

The LED strings are subdivided into four equal sub segments as shown in Figure 4. From figure 5, the top sub segment of the LED is shorted out during the positive half cycles, while the bottom sub segment is shorted out during the negative half cycles. When the input voltage turns positive, C_5 charges up through R_5, and C_6, which previously was charged to the negative peak of the line voltage, receives current passing through the lower three strings. This produces the first hump (of displacement current) seen in the combined LED current waveform in Fig. 5. When C_5 is charged sufficiently, galvanic current starts passing through R_4 leading to the second hump in the combined LED current waveform of Figure. 5. A complementary series of the described charging and discharging events happens during negative half cycles. C_5 and C_6 stops about half of the LED current from going through the resistors at all, which helps to boost the system efficiency to over 90% without the protection circuitry.

The frequency of the rectified voltage is twice the input frequency, the LED arrangement is such that it illuminates at twice the frequency of the input voltage alternately by the upper and lower strings. LED's from the upper string is located close to a corresponding LED from the lower string, so that the combination of the two produces light continuously. This arrangement makes for non-perceptible flicker even though individual elements of the array are only activated at a frequency of 50 Hz.

Fast Fourier Transform of the input currents of both the conventional circuit and the passive PFC circuit was performed and is shown in Fig. 8 and 9. From the analysis in Fig. 8 and 9, it is shown that even the fifth harmonic component of the conventional rectifier circuit contributes significantly to the input harmonic current and hence the main cause of low power factor and high THD. However, on application of the PFC, almost all the harmonic components are suppressed yielding a THD of 18.79% and power factor of 0.92. The reasons for THD reduction and power factor improvement in the PFC circuit were explained in section 5.

The output current waveform has a flicker index of 0.2, lower than is achievable by most light engines employing complex and expensive driver chips. The prototype has a Varistor and a current limiting resistor incorporated into it to enable protection of the device which reduced the efficiency to 88%, otherwise an efficiency of over 90% is achievable with this design depending on the values of the limiting resistors used.

The fixture housing was made of a light 22-gauge galvanized metal sheet. For the secondary optics; a frosted diffuser cover was printed with a 3D printer.

VII. CONCLUSION

This simple, low cost circuit outperforms most conventional AC LED products. Eventhough the active power factor correction approach has higher power factor and lower total harmonic distortion compared to the passive power factor correction approach, the shortfalls of such systems are higher cost, circuit complexity, poor efficiency, and Electromagnetic Interference (EMI) issues. The proposed circuit has no inductor, which is the bulkiest and largest component for conventional LED driver circuits employing the boost Power Factor Corrector (PFC) converter; this makes the circuit smaller when compared to existing ones. Switching loss associated with the circuit operation is also eliminated and hence permits the use of normal standard diodes, consequently reducing cost.

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