

LED-Lamp Design for Renewable Energy-Based DC House Application

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ABSTRACT

This paper describes the design of an LED lamp to be used in a DC house being supplied using a renewable energy source or in a DC Smart Grid. LED lamps are widely known for its low-electricity consumption. The DC house application is becoming more and more popular due to its advantage of using DC generated electricity, for example from a solar photovoltaic system, directly without having to invert it into AC voltage. However, LED needs a driver to activate and control it. Its mounting also needs certain precaution to anticipate the high heat from the LED. An appropriate heatsink is required before activating the LED. The laboratory results indicate that a 3-watt LED bulb lamp can produce an efficiency up to 93.16% with luminous efficacy 82.29 lm/W. These results prove that an LED bulb consumes less energy and can give an optimal brightness.

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1. INTRODUCTION

DC house application has been winning more and more interests to boost the use of electricity directly from renewable energy sources without having to involve many inverting power electronic devices [1]. It offers the possibility to benefit low-power low-voltage generated electricity without passing the AC power transmission and distribution systems [2]. Being integrated to form a DC microgrid system, it has been proven to cause significantly less power losses being compared to its AC counterpart systems [3-4]. The DC house system can take the benefit from the DC generation system [3-6]. It also provides its energy need itself through the conversion of various renewable energy sources such as photovoltaic, hydro, wind, and even human labor [2, 7].

The most important equipment which must be available in a house is the lighting system. LED-based lighting has been recently known as very efficient and of low-energy consumption. A LED is working on direct current (DC) voltage, so it is very suitable as the load in a DC-house. As the mains current is normally an alternating current (AC) at much higher voltage than the LED can accept, certain circuitry is sometimes needed to convert the mains AC into DC at the correct voltage, although some low-voltage LEDs are also available in the market. A LED light design being developed in [7] produced light bulb's efficiency until 85.63% with a voltage range between 24V-72V and power consumption of 13,44 watts. It also produced enough illumination levels for lighting at home. This paper presents a design of LED-lamp to be used in a DC house being supplied using a renewable energy source or in a DC Smart Grid [7, 8].

2. RESEARCH METHOD

2.1. DC House System

The DC house system gains its interest due to the concern to use electricity at low cost [9]. A DC house can be supplied by electricity resulted from various renewable energy resources available surrounding the house [2,7]. An example of the basic design of a DC-house is shown in Figure 1.

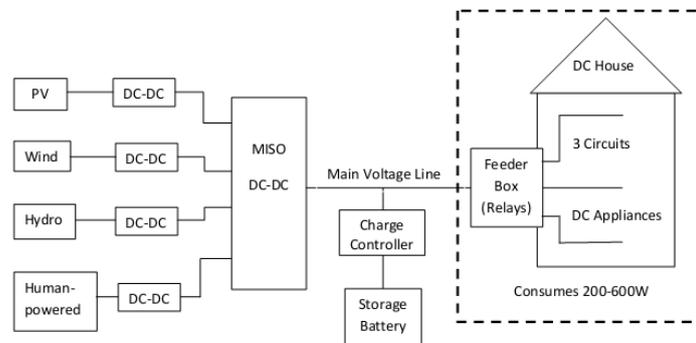


Figure 1. The basic design of a DC-house

As shown in Figure 1, there are four renewable energy resources as the source of electricity. The DC generated electricity is connected to each of the boosting DC-DC converters to raise the voltage level of generation, for example from 12V to 24V [9]. It then becomes the input of a Multiple-Input Single-Output (MISO) DC-DC converter which is then connected to the Main Voltage Line of a Feeder Box (Relays). The main voltage line is connected through a charge controller to a battery storage with a certain capacity. The feeder box comprises relays, including multiple circuit breakers and fuse to control the distribution of energy and to protect against the ground faults on the DC [9].

2.2. LED (Light-Emitting Diode)

Light-emitting diode, or known as LED is a two-lead semiconductor light source in the form of a p-n junction diode emitting light when activated. Commonly, it does not emit light in all directions, although omnidirectional lamps are becoming more popular. The LED design considered in this paper is based on the latest LED lighting technology, the high-power LED as shown in Figure 2, which is capable of producing high light intensity (up to 80-100W/lumen) with small power consumption. The LED requires a certain driver to turn on and generates considerable heat (high heat), which is not coming from the light but from the back part of the LED. Consequently, an appropriate heatsink is required.

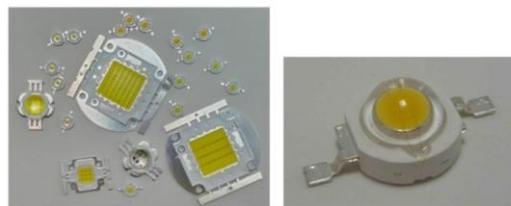


Figure 2. High-power LED

2.3. LED-Lamp Design

An overview of the general arrangement of an LED light bulb in producing light is given in Figure 3. As seen, the VIN and GND are supplied directly from the 48V DC-bus voltage of the DC house. They are connected directly to the LED driver which should be designed based on the desired LED-Lamp design. The positive output side of the LED driver is connected to the positive input side of the LED Array,

whereas the negative output of the LED Array is fed into the negative side of the LED driver LED_N. Based on this arrangement the LED will produce light.

The block diagram of the LED driver LT3590 is given in Figure 4. It is a high voltage current-mode buck-mode LED driver which is able to generate a constant current to the LED circuit with a voltage up to 40V. It has internal compensation feature, a 55V internal power switch and a 55V internal Schottky diode which allow the DC current up to 50mA with an efficiency up to 91% [10].

The LT3590 has a 3.3V linear regulator onboard with an ability to supply external device up to 1mA. The 3.3V regulator remains available even when at the shutdown state. This feature can be used to power-up external LT3590 controller which can control the LED current resulted by activating the CTRL pin. Alternatively, the output pin regulator (VREG) may be connected directly to the CTRL pin (Pin 5). When the CTRL pin is given the voltage over 150mV, the oscillator, PWM comparator, and the error amplifier will be active. The LT3590 using the buck-mode converter to regulate the output voltage to the LED voltage levels required to match the required current [10].

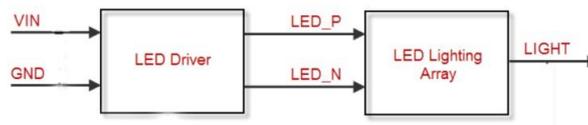


Figure 3. Block diagram of the Bulb Circuit

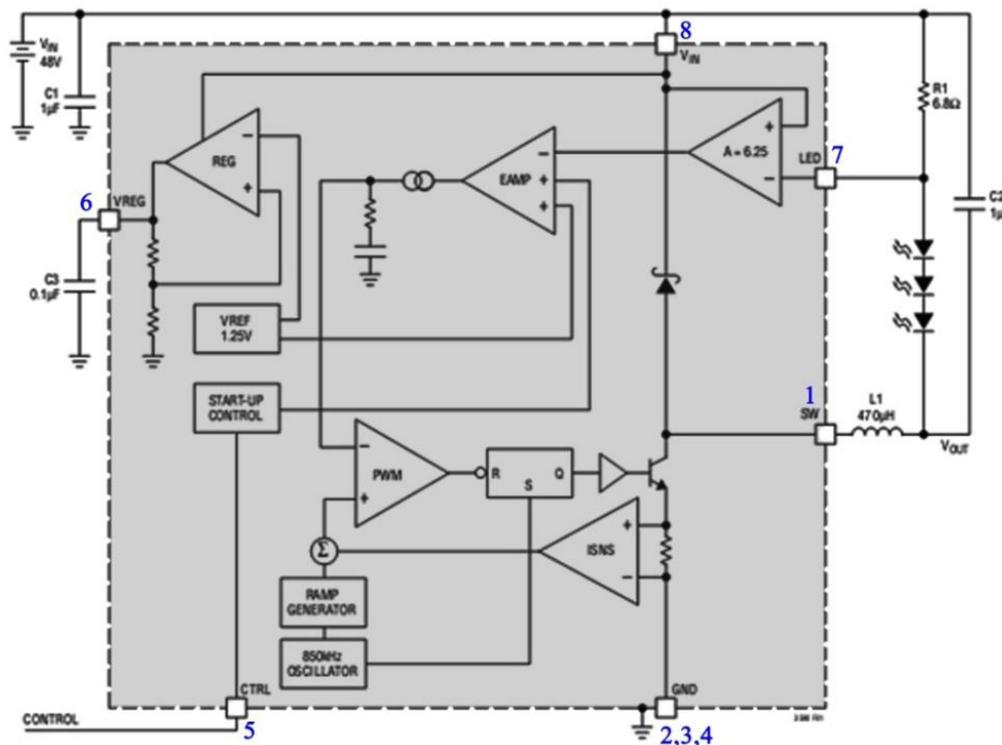


Figure 4. The block diagram of the LED driver LT3590

2.4. LED Array

The LED design should match with the standard of the lamp dimensions to be adopted. Thus, the design of the LED arrays must fit well with the dimensions of the lamp. In this paper, the LED bulb housing has been customized from that of the existing Royal 12VDC LED bulb lamp, as shown in Figure 5. The used LEDs are made by Epistar [11]. The Epistar LED lamp produces the luminous flux of about 400 lm, containing 5 LEDs, giving a luminous flux of 80 lm each. As the designed bulb lamp in this paper uses three LEDs, it should produce 240 lm and be arranged in a triangular form on the top of a Metal-Core PCB

(MCPCB) before being attached to an aluminum heatsink. The final design of this LEDs array is shown in Figure 6.

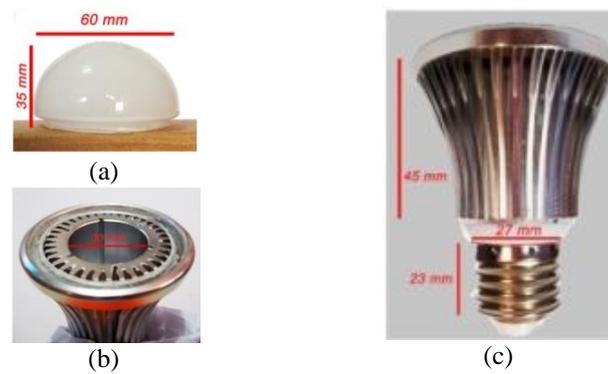


Figure 5. Bulb Mechanics, (a) Light Diffuser, (b) Aluminum Heatsink's dimension, (c) Aluminum Heatsink and E27 Screw Base

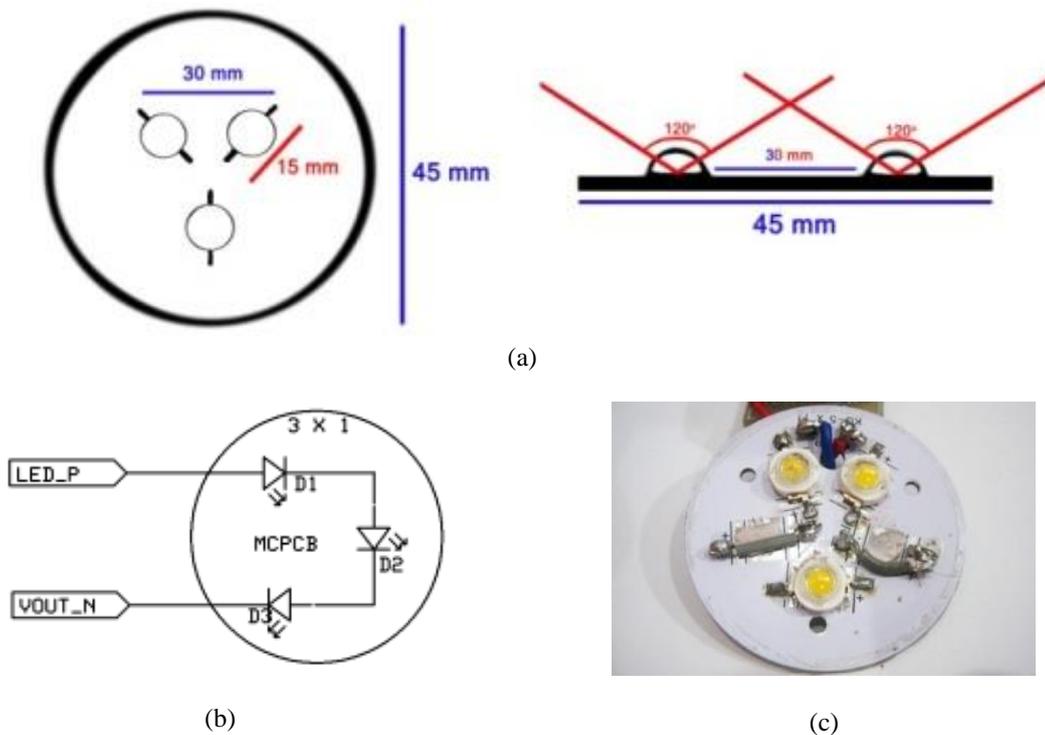


Figure 6. The placement of the LEDs on the MCPCB of a used Royal LED, (a) the LED distance design, (b) schematic design, (c) physical design

In order to form a triangular formation, the LEDs position and the distance between them need to be calculated. It is aimed to make the LED lamp be able to spread the light equally. The distance is determined based on the size of the LED, which is about 15 mm. The position has been made to form an equilateral triangle to produce a viewing angle of 120°, giving a distance of 30 mm between LEDs. This is the best distance with respect to the MCPCB dimension, in order for the light bulb to produce the maximum light intensity. However, in order not to cause the light out in one spot only, a light diffuser to spread the beam is required (Figure 5).

2.5. LED Driver

The LED driver design shown in Figure 7 comprises the following components [12]:

- a. 6,8Ω resistor providing the current ILED 30mA
- b. 470μH inductor to make the constant DC current
- c. 1μF 50V polar capacitor (C1) as the output capacitor to regulate the VIN=48V
- d. 1μF nonpolar capacitor (C2) as the regulator capacitor in the LED array circuit
- e. 0,1μF nonpolar capacitor (C3) as the regulator capacitor which is connected to pin VREG whose voltage is regulated.

3. RESULTS AND ANALYSIS

3.1. Simulation Results of the Current ILED as a function of time

The graph of the current ILED as a function of time t obtained using the LTSpice simulation program is given in Figure 8. It is the LED current flowing in D1, in Figure 7. As the three LEDs are connected in series, the current graphs of the D2 and D3 are the same. The input current is determined by the resistance of the installed resistor R1, as seen in Figure 7. The resulted input power PIN can be seen in Figure 9. The efficiency can be obtained using the data of VIN, IIN, and VOUT, IOUT in Figure 9. It gives an efficiency of the bulb higher than 80%, which is 97.51%. The overall simulation results of the DC LED light bulb are presented in Table 1.

3.2. The Resulted Layout of 2-Layer PCB Custom Design

The 2-Layer PCB custom design has been obtained using two steps in designing the PCB LED Driver. The first step is creating a circuit’s schematic, which has been done using ExpressSCH, as shown in Figure 10. The next step is creating a PCB prototype design using ExpressPCB - a PCB design application which can be used for creating 2-layer until 4-layer PCB prototype designs. The resulted 2-layer PCB design is shown in Figure 11, containing the schematic design as well as the physical design of each layer.

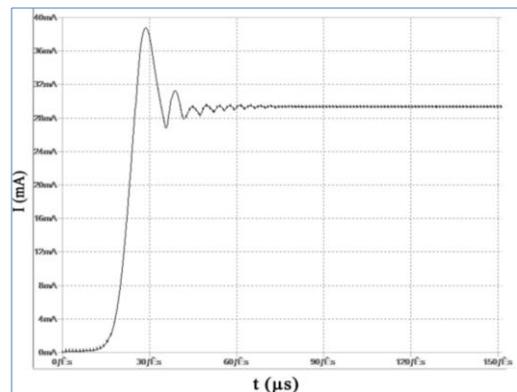
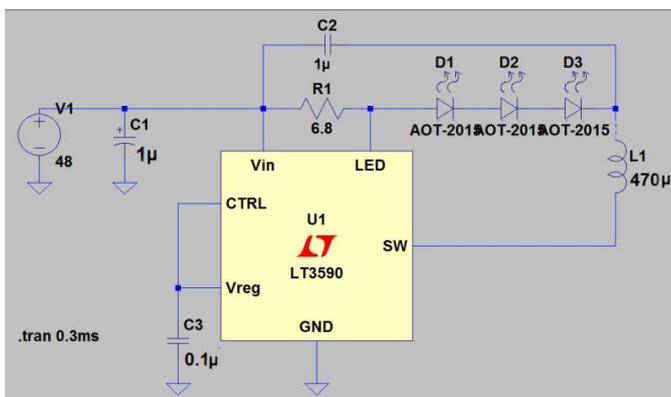
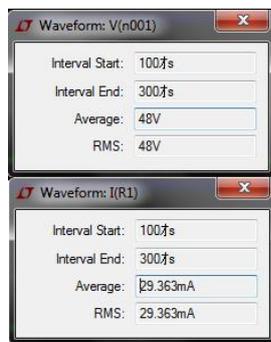
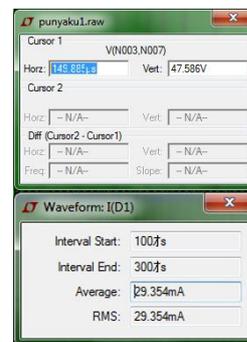


Figure 7. LED Driver Schematic at 48V Buck-Mode LED Driver

Figure 8. The ILED current graph as a function of time



(a)



(b)

Figure 9. The resulted values of (a) VIN and IIN (b) VOUT and IOUT in the LTSpice Simulation Software

Table 1. Simulation Results of the DC LED Light Bulb

Parameter	Specification
Bus Voltage (Simulation):VIN	48V
Output Voltage in Buck-Mode :VLED	0V – 12V
Efficiency at Full Load*	97.51%
Power Consumption*	4.189W
LEDs in Series	3
Color Temperature	Cool White
Maximum Temperature Junction	85oC
Luminous Flux	Up to 240lm
Maximum Forward Voltage	3.25V
Maximum LED's Forward Current	350mA
Constant Voltage Regulation	Yes
Constant Current Regulation	Yes

*Test Result using AOT-2005 (x3)

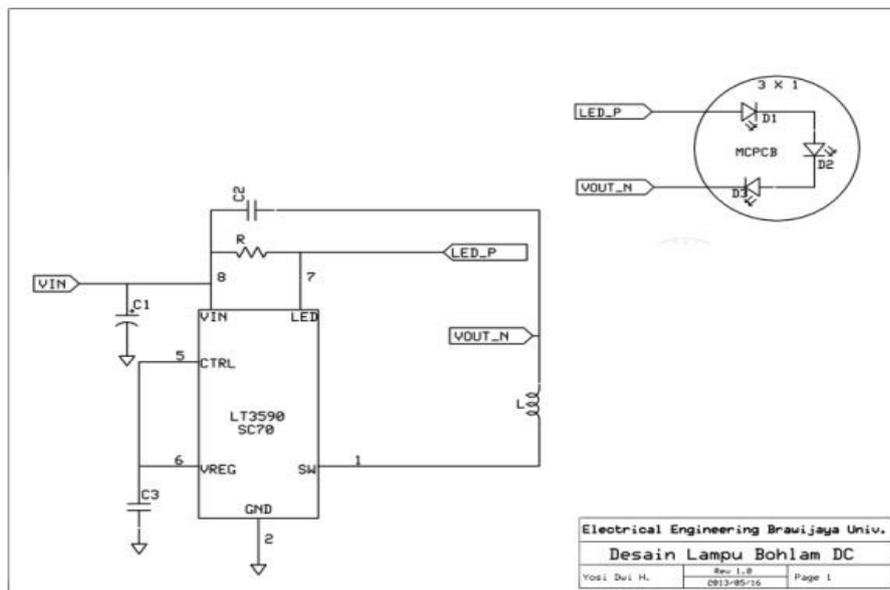


Figure 10. The schematic design of the DC Light Bulb using ExpressSCH

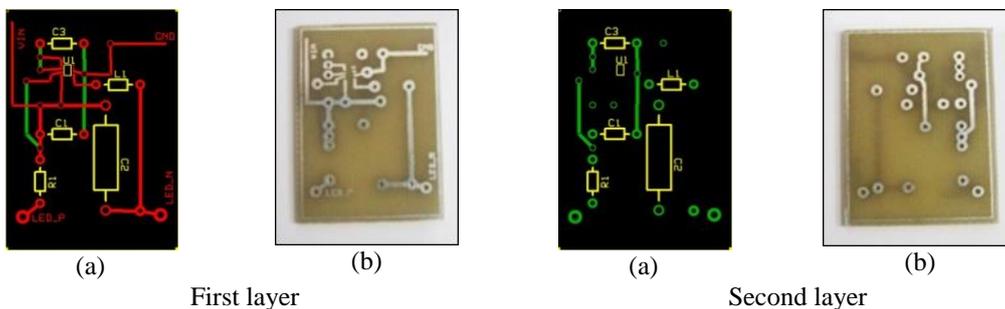


Figure 11. The 2-layer PCB design, (a) schematic design, (b) physical design

The obtained PCB with the dimension of 3.5x2.5 cm were then ready to be mounted with the required components as determined in the datasheet of LTSpice, as seen in Figure 13.

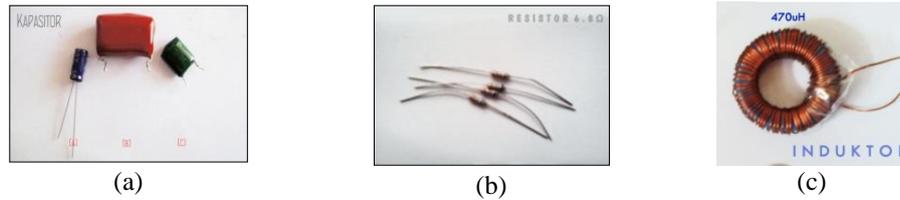


Figure 13. Components used for outer circuit design, (1) Capacitors (a) Polar 1 μ F (b) Nonpolar 1 μ F (c) Nonpolar 0.1 μ F; (2) Resistor; (3) Inductor

3.3. The Efficiency Test Results

The efficiency has been known from the results of measurements performed using a multimeter to get ILED, VLED, with the given input voltage VIN range of 0V - 48V, as seen in Table 3.

Table 3. Data of measurement results on the DC LED Bulb

V _{IN} (V)	I _{IN} (mA)	P _{IN} (W)	V _{LED} (V)	I _{LED} (mA)	V _{OUT} (V)	P _{OUT} (W)	Efficiency	LED State
0	0	0	0	0	0	0	-	Off
6	0.6	0.0108	1.3	0	4.3	0	0	Off
12	122	4.3920	8.5	29.9	3.9	0.3498	7.9652	On
18	70.8	3.8232	8.5	29.9	9.7	0.8701	22.7582	On
24	52.3	3.7656	8.5	30	17.7	1.5930	42.3040	On
30	40.6	3.6540	8.5	30	23.8	2.1420	58.6207	On
36	35.8	3.8664	8.5	30	29	2.6100	67.5047	On
42	30.9	3.8934	8.5	30	32.9	2.9610	76.0518	On
48	26.5	3.8160	8.5	30	39.6	3.5640	93.3962	On

As seen from Table 3, the LED driver LT3590 could operate optimally, being indicated by the value of LED voltage VLED dan current ILED which were of constant values although the input voltage VIN had been increased up to 48V. As the LT3590 is a Buck-Mode LED Driver, the input voltage can be decreased and regulated. When the voltage started to be constant, the input current IIN started to decrease. When the input current to the lamp is lower, higher will be the resulted efficiency. The calculated efficiency of the LED lamp was about 93.39% at 48V, which is higher than 80% and more approaching the result of simulation. Figure 14 indicates the comparison of VLED as a function of VIN and ILED as a function of VIN.

3.4. The Temperature Test Results

The temperature measurement of the DC light bulb has been undertaken using an infrared thermometer, which is a laser-based temperature measuring device, as seen in Figure 15. The considered maximum junction temperature of the LED was 85°C as suggested in [11]. In order for a LED to have a long life, the measured temperature should be less than the maximum junction temperature. The measurement results are displayed in Table 4.

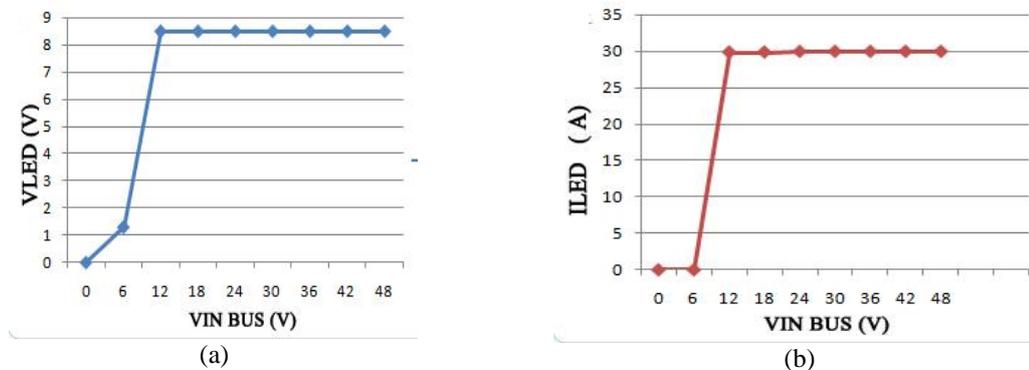


Figure 14. The curves (a) VLED–VIN, (b) ILED–VIN



Figure 15. Infrared Thermometer

Table 4. Measurement Results of Temperature on the PCB and LED Arrays using an Infrared Thermometer

t (minute)	Temperature (°C)					
	Day 1		Day 2		Day 3	
	PCB	LED Array	PCB	LED Array	PCB	LED Array
0	28	28.3	27	28	28	28.4
5	29	31.9	27.7	32.1	28.9	34.3
10	31	35.2	28.2	34.5	31	33.6
15	33	40.3	28.6	41.1	32	43.3
20	35	43	29	42.1	33.5	41.4
25	36.4	46.6	29.4	45	35	47.1
30	35.8	51	31	50.5	35.4	50.2
35	35.9	53.5	32.1	55.9	35.9	55.1
40	36	55.3	34.5	58.3	36	58.1
45	36	58.6	34.9	59.9	36.1	60
50	36	61.3	35.5	61.3	36.6	61.6
55	36	61.4	35.5	61.7	37	61.8
60	36	61.4	35.6	61.8	36.9	61.8

As seen in Table 4, all the measured temperatures are below 85°C. It means that the resulted design is ensured to be safe and long-lived. However, from the observation done it could be known that the placement of aluminum heatsink mounted on the MCPCB could have still been improved, which would bring about cooler temperatures than what had been measured.

3.5. Lumination Measurement Results

The results of calculation and measurement of the light intensity are given in Table 5. The lumination has been measured using a lux meter. The obtained data are then used to calculate the luminous efficacy by using some following formulas.

The area of a sphere:

$$A_{\text{SPHERE}} = 4\pi r^2 \quad (1)$$

$$1 \text{ lux} = \frac{\text{lumens}}{\text{m}^2} \quad (2)$$

$$\text{luminous efficacy} = \frac{\text{lumens}}{P_{\text{in}}} \quad (3)$$

$$\text{Luminous flux total on a working place (lumen):} \quad F_{\text{total}} = \frac{E \times A}{k_p \times k_d} \quad (4)$$

where E is the lumination (lux), A is the working area, k_p is the utility factor, k_d is the light loss coefficient.

Table 5. The Results of Calculation and Measurement of the Light Intensity

	Distance (m)	Lumination (lux)	V _{IN} (V)	I _{IN} (mA)	P _{IN} (W)	A _{SPHERE} (m ²)	Luminous Flux (lm)	Luminous Efficacy (lm/W)
1	1	25	0	0	0	12.56	314.00	0.00
2	1	25	6	0.6	0.0108	12.56	314.00	0.00
3	1	25	12	1.22	4.392	12.56	314.00	71.49
4	1	25	18	70.8	3.8232	12.56	314.00	82.13
5	1	25	24	52.3	3.7656	12.56	314.00	83.39
6	1	25	30	40.6	3.654	12.56	314.00	85.93
7	1	25	36	35.8	3.8664	12.56	314.00	81.21
8	1	25	42	30.9	3.8934	12.56	314.00	80.65
9	1	25	48	26.5	3.816	12.56	314.00	82.29

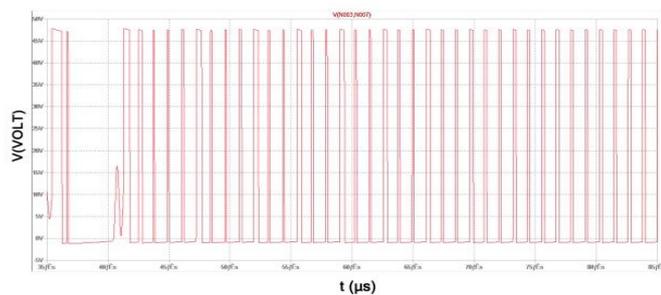
By determining the F_{total} as 240 lumens as the luminous flux specified during the beginning of the design for 3 LEDs, the lumination of about 100 lux with light losses coefficient of 0.8 [13], and utilization factor of 0.5 [14], the area of 0.96 m² has been obtained. By assuming a rectangular area, it has been approximated to have a side of 1 meter, giving a lumination of 25 lux as displayed in Table 6. The distance between the lamp and luxmeter has been obtained as 100 cm using Eq. 4. The obtained result of lumination measurement at the distance of 100 cm is 25 lux. Based on these data and using Eqs. 1-3, the luminous flux of 314 lumens and a luminous efficacy about 82.29 lumens/W at a voltage of 48V have been obtained. It indicates that the resulted LED light bulb meets the minimum criteria for indoor lighting needs at home.

3.6. Comparison of Simulation Results and Testing Results

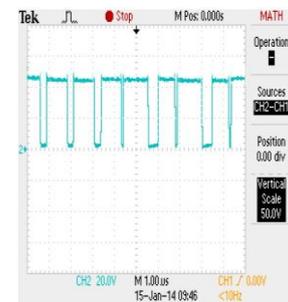
The comparison of complete simulation and measurement results is given in Table 6. In general it indicates the close concordance between the simulation and measurement results. The characteristic graphs of the buck-mode LED driver LT3590 obtained from simulation and measurement are shown in Figure 16. As indicated, both of them show the similar shape of graphs of the voltage through the LED bulb lamp with the maximum value of about 48V.

Table 6. Comparison of Simulation Result and Testing Result

Parameter	Simulation result	Testing result
Range Input Voltage	12V - 48V	12V - 48V
LED Voltage (VLED)	8.645V	8.5V
Efficiency at Full Load	97.51%	93.39%
Power Consumption	4.189W	3.86W
LED Manufacturer	AOT	EPISTAR
LED in Series	3	3
Luminous Efficacy	80 lm/W	82.29 lm/W
Luminous Flux	240 lm	314 lumen
Maximum Current	350mA	30mA
Maximum Temperature	85oC	61.8oC
Constant Current Regulation	Yes	Yes
Constant Voltage Regulation	Yes	Yes



(a)



(b)

Figure 16. The regulated voltage waveform of the LED-Lamp, (a) simulation result, (b) testing result

4. CONCLUSION

A LED lamp with low-power consumption and high efficiency has been designed and realized. It is potential to be used in a DC house being supplied using a renewable energy source or in a DC Smart Grid.

The experiment result of the designed LED bulb efficiency was relatively close to the results of simulation. The LED lamp could work properly on a DC-house bus voltage of 48VDC. The experiment results of luminous flux and luminous efficacy indicate that the obtained LED lamp design meet the criteria of lighting a room. The heat produced on the design could still be evacuated well through the aluminum heatsink used even though its mounting on the related MCPCB still was not perfect.

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