Design and Development of a DC Light-Bulb Using High-Power LEDs

Tri Nurwati  
Electrical Engineering Department  
Brawijaya University  
Malang, Indonesia  
trimurti@ub.ac.id

Aulia Adi Chandra  
Electrical Engineering Department  
Brawijaya University  
Malang, Indonesia  
adichandrajr11@gmail.com

Rini Nur Hasanah  
Electrical Engineering Department  
Brawijaya University  
Malang, Indonesia  
rina.hasanah@ub.ac.id

Nurusa’adah  
Electrical Engineering Department  
Brawijaya University  
Malang, Indonesia  
rossa@ub.ac.id

Taufik Tafzik  
Electrical Engineering Department  
Cal Poly State University  
San Luis Obispo, USA  
aviafit@gmail.com

Abstract—Electricity need is continuously increasing along with the increase in human population. The fulfillment of this need must consider the depletion of fossil energy sources as well as the environment protection. The development of renewable energy sources offers a promising solution. Concern on energy saving brings to an idea for reconsidering the use of alternating-current system of electricity. One technology being recently developed is a DC-home system by utilizing renewable energy sources. However, they may not generate enough energy for the house because the renewable resources are not always available at all times. Consequently, it is desirable to develop new home electrical devices that can work optimally using limited power. An important type of electrical load in a house being potential to adapt to the DC-home system is the light bulb. In this study, the use of High-Power LED (HPL) is explored to produce optimal illumination with low power consumption. An HPL requires a driver to activate and a heatsink to dissipate the generated heat. This study uses and LT3590 as the LED driver in conjunction with Arduino Nano as its microcontroller. The energy usage of the HPL is minimized by considering the amount of light entering the room with the help of a Light Dependent Resistor (LDR) sensor. The experiment results show that using a 3-watt light bulb the efficiency greater than 80% with luminous efficacy of 30 – 90 lm/W has been obtained. It has also been proven that operating the LED light by considering the amount of entering light into the room can provide the desired level of illumination with less power.

Keywords— DC House, Renewable Energy, DC - DC Buck Converter, HPL Lamp, LT3590, Arduino Nano, LDR Sensor

I. INTRODUCTION

The continuously increasing human population directly brings about the increase in electricity demand. As the fossil energy resources so far exploited are about to run out, people have been challenged to seek for other possibilities to fulfill the energy need. The undesirable impacts of fossil energy usage on environment have been raising awareness on the importance of renewable energy. Renewable energy resources help in fulfilling the need of environmentally friendly electricity while at the same time meeting the target of providing access to electricity for people living in remote areas. There are many areas in the world which are unreachable by the existing electricity grids but being endowed with potential sources of renewable energy.

The nowadays electrical systems are dominated by the Alternating Current (AC) systems. Recent development of renewable energy sources makes people reconsider the use of Direct-Current (DC) electrical systems. The electricity generated by some renewable energy sources like solar power and fuel-cell based electricity, for example, is in the form of DC voltage. Researches on DC House system development [1] have been inspired by this reality.

DC House is a house that can provide its own electricity needs by means of converting various forms of renewable energy around the house such as photovoltaic, hydropower, wind, and even human power [1]. It fulfills the electricity needs by utilizing residential DC electrical system. It is not necessary to convert the DC voltage form generated by renewable energy sources into AC voltage form to be used by home appliances. This kind of system is suitable for implementation in remote areas in developing countries where electricity is not readily available or not affordable [2]. An example of basic design of DC house system is shown in Fig. 1 [3].

As seen in Fig. 1, there are four renewable power sources connected to the DC-DC boost converter, each of which increases the voltage from approximately 12V to 24V. These voltages then feed into the Multiple-Input-Single-Output (MISO) DC-DC Converter which sums the total power generated at the generator side and provides the DC bus voltage for the house at 48V [4]. The DC bus is then connected to a charge controller and a storage battery for any excess of energy. The DC bus further connects to a feeder box which consists of relays, circuit breakers and fuses to control the distribution of energy into the house and protect against any power faults in the DC house.

Fig. 1. Design diagram of a DC House System [3].

Authorized licensed use limited to: Universitas Brawijaya. Downloaded on December 10,2020 at 06:48:19 UTC from IEEE Xplore. Restrictions apply.
One of the most important and must-have appliances in a house is lighting. A known form of energy efficient lamps is LED light. A study on the DC LED lamp design produces a bulb whose efficiency was 85.63% with a working voltage range of 24V-72V and 13.44 watts of power consumption [5].

High Power LED is one of the latest developments of LED lamp technology that is capable of producing high luminous efficacy between 30-90 lumens/W with a small power consumption. Despite many advantages of the high-power LED, it generates high enough heat, which originates from the back of the LED. The high-power LED lamp (Fig. 2) requires a cooling fin as heatsink [6].

![Figure 2: High Power LED.](image)

This paper presents the development and construction of a light-bulb using high power LEDs and investigates the working efficiency of the light-bulb when being operated by considering the light entering the room in a DC house.

II. SYSTEM DESIGN METHOD

A. Circuit Block Design

The block diagram of the HP-LED lamp system to be designed is given in Fig. 3.

![Figure 3: Circuit block diagram](image)

Fig. 3 represents the arrangement of the HP-LED light-bulb system in producing lighting. \( V_{IN} \) and GND are directly supplied from the 48V bus voltage coming from the DC bus voltage of the DC house. \( V_{IN} \) and GND are directly connected to the LED driver being designed according to the specified requirements. The ADJ signal is being used to vary the potentiometer of the dimmer circuit. \( P_{PWM} \) is the resulting pulse width modulation (PWM) signal in 5V that is issued from the dimmer circuit. The positive LED driver (\( L_p \)) is connected to the positive LED array input and the negative LED array output enters the negative LED driver (\( L_n \)).

B. LED Array

In this study, the LED used is of the EPISTAR brand [4]. The lamp can produce luminous flux of 240 lm, so each of the three LEDs has an 80 lm luminous flux. The LED array image used in the study is shown in Fig. 4. The three LEDs are arranged in a triangular series on an aluminum heatsink [9]. The purpose is to produce even LED lighting results. The distance between the LEDs is calculated by knowing the overall LED size. The length of each LED including its legs is 15 mm. The three LEDs are arranged to form an equilateral triangle position with viewing angle of 120°. Distance between LEDs (equilateral triangle) is determined based on their length and position in the triangular configuration, giving a value of 30 mm. It becomes the most appropriate distance adapting to the shape of the aluminum heatsink. This calculation is intended to produce maximum light levels. However, there is still a possibility that the coming out light is only focusing in one point. A light diffuser is required to spread the light beam.

![Figure 4: a). LED spacing design, b). schematic design, and c). physical design](image)

C. LED Driver

Fig. 5 shows the schematic design of the LED driver to be used for the DC light bulb.

![Figure 5: LED Driver Schematic on 48V Buck Mode LED Driver](image)

For the design of this PCB lamp bulb, we created a circuit schematic using EAGLE 8.5.1, as shown in Fig. 6 with the following component specifications:

- resistor 6.8 Ω to produce \( I_{LED} \) 30mA
- inductor 470 μH to keep DC current constant
- non-polar capacitors \( C_1 \) 1μF/50V are output capacitors to be passed by \( V_{IN} \) 48V
- non-polar capacitor \( C_2 \) 1μF as regulator capacitor in the LED series
• non-polar capacitor $C_3$ 0.1pF as regulator capacitor connected to the $V_{reg}$ legs which have a regulator voltage

• $C_4$ 1μF and $R_2$ 1KΩ for PWM filter circuits

Fig. 6. Schematic Design for DC Bulb Lights using EAGLE 8.5.1

Fig. 7 and 8 show the schematic and physical design in layer 1 and 2, respectively.

Fig. 7. Layer 1 a. Schematic Design, b. Physical design.

Fig. 8. Layer 2 a. Schematic Design, b. Physical design

D. Dimmer Circuit

There are two important components in the dimmer circuit design: Arduino Nano Module and LDR sensor Module. PWM signals in this study were generated using the Arduino Nano Module and how much PWM signals were generated was depending on the light entering the room and received by the LDR sensor module. This means the number of lumens produced by the LED light bulb depends on how much light is received by the LDR sensor Module.

E. Arduino Nano

Arduino Nano is a board that has an ATmega328P IC, as shown in Fig. 9. It has the similar function to the Arduino Duemilanove which operates with a DC voltage and works with a Mini-B USB cable [7]. As a main controller in this research, Arduino generates a synchronous PWM.

Fig. 9. An Arduino Nano board.

F. LDR Sensor Module

The LDR sensor module, as seen in Fig. 10, is used to detect light intensity. This is associated with analog output pins and digital output pins, each labeled AO and DO. Responding to light, the LDR resistance will be following the light intensity. The greater the intensity of the light, the lower the LDR resistance. This sensor has a potentiometer button that can be adjusted to change the sensitivity of the LDR to light [8].

Fig. 10. LDR sensor module

G. IC LT3590

LT3590 is a high-voltage current-buck mode LED driver that is capable of generating constant current into an LED circuit up to a total voltage of 40V. It has an internal compensation feature, a 55V internal power switch and a 55V internal Schottky diode that can carry DC current up to 50mA with an efficiency of up to 91% [5].

Fig. 11. IC LT3590 SMD

The LT3590 has a 3.3V onboard linear regulator which has the ability to supply up to 1mA for use by an external device. The 3.3V regulator remains available even in the shutdown state. LT3590 uses a buck mode converter to regulate the output voltage to the level of voltage needed by the LED to match the desired current [8]. If it is still less than 100mV, the switch (BJT in the circuit) is inactive and the current sense voltage and current LED are zero. In this study the CTRL pin (pin 1) is connected to Arduino to generate PWM so that it can adjust the desired light intensity.

H. Calculation of Performance Parameters

The efficiency can be calculated using the equation:

$$P = V.I$$

(1)
efficiency = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \quad (2)

For this test, the level of light was measured first using a lux meter. After getting data using this measuring instrument, which is in lm/m², we can then find luminous efficacy by using the following equations:

Ball area = 4. \pi r^2 \quad (3)

1 Lux = \frac{1 \text{ lumens}}{1 \text{ m}^2} \quad (4)

Luminous efficacy = \frac{\text{lumens}}{\text{watt}} \quad (5)

To calculate luminous efficacy, it is also necessary to know the light intensity using a lux meter. The distance between the lamp and the luxmeter are determined by the following formula:

F_{\text{total}} = \frac{E \cdot A}{K_p \cdot K_d} \quad (6)

where \( F_{\text{total}} \), \( E \), \( A \), \( K_p \), and \( K_d \) are the total luminous flux that illuminates the working area, the light intensity (lux), the working area, the usage factor, and the coefficient of light loss.

To determine how many lights are needed in a room we can use the utilization factor formula:

\[ N = \frac{1.25 \cdot E \cdot L \cdot W}{k \cdot \Phi \cdot \eta \cdot L \cdot \eta} \quad (7) \]

where \( N \), \( E \), \( W \), \( L \), \( \Phi \), \( \eta LB \), \( k \), and \( \eta R \) are the number of armatures, the lighting intensity (lux), the room width (m), the room length (m), the light flux (lm), the armature efficiency (%), the room factor, the room utilization factor (%), and 1.25 is the planning factor.

Light flux itself can be known through the following formula:

\[ \Phi = W \cdot \frac{L}{w} \quad (8) \]

where \( \Phi \), \( W \), and \( L/w \) are the light flux (lm), lamp power (watt), and Luminous Efficacy Lamp (lumen/watt).

Room Factor (k) can be calculated from the room dimension data using the following formula:

\[ k = \frac{A \cdot B}{h \cdot (A + B)} \quad (9) \]

where \( A \), \( B \), and \( H \) are the width (m), length (m), and height (m), then \( h \) is \( H - 0.85 \) (m).

III. EXPERIMENT RESULTS AND ANALYSIS

A. Efficiency Testing

Table 1 shows the results of experiment on the efficiency of the DC light-bulbs. The measurements have been done by using a multimeter to get the values of \( I_{\text{in}} \), \( V_{\text{LED}} \), \( I_{\text{LED}} \), \( V_{\text{out}} \), while fixing the DC input voltage at 48V and changing the PWM adapting to the required levels of lighting.

<table>
<thead>
<tr>
<th>PWM (%)</th>
<th>( V_{\text{in}} ) (V)</th>
<th>( I_{\text{in}} ) (mA)</th>
<th>( P_{\text{in}} ) (W)</th>
<th>( V_{\text{LED}} ) (V)</th>
<th>( I_{\text{LED}} ) (mA)</th>
<th>( V_{\text{out}} ) (V)</th>
<th>( P_{\text{out}} ) (mW)</th>
<th>Lux ( (\text{LUX}) )</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>48</td>
<td>2.08</td>
<td>0.09</td>
<td>7.89</td>
<td>7.83</td>
<td>8.02</td>
<td>62.79</td>
<td>9.17</td>
<td>62.9</td>
</tr>
<tr>
<td>20</td>
<td>48</td>
<td>3.09</td>
<td>0.15</td>
<td>8.23</td>
<td>11.78</td>
<td>8.34</td>
<td>98.29</td>
<td>10.94</td>
<td>66.3</td>
</tr>
<tr>
<td>30</td>
<td>48</td>
<td>3.91</td>
<td>0.19</td>
<td>8.46</td>
<td>14.98</td>
<td>8.66</td>
<td>129.73</td>
<td>12.71</td>
<td>69.1</td>
</tr>
<tr>
<td>40</td>
<td>48</td>
<td>4.68</td>
<td>0.22</td>
<td>8.58</td>
<td>18</td>
<td>8.78</td>
<td>158.04</td>
<td>14.48</td>
<td>70.3</td>
</tr>
<tr>
<td>50</td>
<td>48</td>
<td>5.43</td>
<td>0.26</td>
<td>8.86</td>
<td>20.95</td>
<td>8.98</td>
<td>188.13</td>
<td>16.25</td>
<td>72.2</td>
</tr>
<tr>
<td>60</td>
<td>48</td>
<td>6.2</td>
<td>0.29</td>
<td>9.03</td>
<td>23.92</td>
<td>9.33</td>
<td>223.14</td>
<td>18.02</td>
<td>75</td>
</tr>
<tr>
<td>70</td>
<td>48</td>
<td>6.82</td>
<td>0.33</td>
<td>9.19</td>
<td>26.51</td>
<td>9.5</td>
<td>251.85</td>
<td>19.79</td>
<td>77</td>
</tr>
<tr>
<td>80</td>
<td>48</td>
<td>7.32</td>
<td>0.35</td>
<td>9.23</td>
<td>28.56</td>
<td>9.65</td>
<td>275.60</td>
<td>21.56</td>
<td>78.4</td>
</tr>
<tr>
<td>90</td>
<td>48</td>
<td>7.49</td>
<td>0.36</td>
<td>9.26</td>
<td>29.20</td>
<td>9.72</td>
<td>283.82</td>
<td>23.33</td>
<td>79</td>
</tr>
<tr>
<td>100</td>
<td>48</td>
<td>7.49</td>
<td>0.36</td>
<td>9.6</td>
<td>29.30</td>
<td>9.8</td>
<td>287.14</td>
<td>25</td>
<td>80</td>
</tr>
</tbody>
</table>

As presented in Table 1, the smallest PWM of 10% produces an efficiency of 62.9%, while the largest PWM of 100% produces an efficiency of 80%. The PWM setting affects the required input current and power. The smallest PWM 10% produces \( I_{\text{LED}} \) of 7.83 mA, \( P_{\text{in}} \) of 0.9984 W and \( P_{\text{out}} \) of 0.062966 W, while the largest PWM of 100% produces \( I_{\text{LED}} \) of 29.30 mA, \( P_{\text{in}} \) of 0.35952 W and \( P_{\text{out}} \) of 0.28714 W. Based on Table 1, changes in PWM affect the LED current value. The greater the PWM value, the greater the LED current. Consequently, changes in PWM also affect the efficiency, where we can observe that the greater the value of PWM, the greater the efficiency.

B. Temperature testing

The DC light-bulb design has been tested by using an infrared thermometer. It was a temperature measuring device using a laser and weighing approximately of 1 kilogram. This temperature measuring tool has a measurement range of -32°C to 330°C or -26°F ~ 626°F and has an accuracy rate of ±2°C±2%. The maximum LED junction temperature was specified at 85°C, as it is important to operate the LED while maintaining its temperature below this value so that the IC LT3590 could last for a long time [3].

![Graphic of temperature as a function of time on the IC PCB](image-url)
The results of temperature measurement on IC PCBs and LED Array Board show that the temperature was below 85°C when the room temperature was at 23.6°C. Referring to Fig. 12 and 13, it is seen that the change in time as well as PWM setting did not bring about much change in temperature. The temperature values during the early minutes (0-10) have an average of 23.34°C and 26.99°C. During the final minute values (50-60) the average values are respectively 28.56°C and 28.57°C. The highest temperature reaches the values of 32.4°C and 30.9°C at the 60th minute with 100% PWM. The results of the IC LT3590 temperature measurement show that it is still within the safe limit because the maximum temperature did not reach 85°C. Temperature measurement activities are shown in Fig. 14.

C. Bright Level Testing

By determining the total luminous flux $F_{\text{total}}$ of 240 lumens of the three LEDs lamp, the illuminance of 100 lux was obtained with a light loss coefficient of 0.8 and the utilization factor of 0.5 over a field area of 0.96$m^2$. The distance calculation has been done by using the length of square-side, giving a value of 0.97m, or close to 1 meter. At this distance, a light intensity of 25 lux was obtained. Using this data then the luminous efficacy was calculated, as shown in Table 2. It can be concluded that the LED bulb lights meet the minimum lighting requirements of the house.

The total number and power of LED lamps required was calculated using (7) - (9). For a room area of 3$m^2$ and a height of 3m as well as a standard value of 100 lux, 13 lamps were needed with the required power of 4.67 watts.

IV. CONCLUSION

Based on the results of the analysis and testing of the hardware prototype, a 10% PWM in the designed light bulb could produce an efficiency of 62.9%, while a 20% and a 100% PWM could produce an efficiency of 66.3% and 80% respectively. The efficiency value increases linearly with the change in PWM setting from 62.9% to 80%. We could also conclude that greater the PWM provided, greater the power efficiency obtained. For the constructed LED light bulb, the 100% PWM has 80% power efficiency. The efficiency increases linearly, starting from 10% PWM with an efficiency score of 62.9% to 100% PWM with an efficiency value of 80%

REFERENCES


TABLE II. MEASUREMENT AND CALCULATION OF LIGHT INTENSITY

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>PWM (%)</th>
<th>$V_m$ (V)</th>
<th>$I_m$ (mA)</th>
<th>$P_m$ (W)</th>
<th>Luminous Flux (lm)</th>
<th>Luminous Efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>10</td>
<td>48</td>
<td>2.08</td>
<td>0.09984</td>
<td>8.45</td>
<td>84.64</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>48</td>
<td>3.09</td>
<td>0.14832</td>
<td>10.08</td>
<td>67.97</td>
</tr>
<tr>
<td>25</td>
<td>30</td>
<td>48</td>
<td>3.91</td>
<td>0.18768</td>
<td>11.71</td>
<td>62.41</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
<td>48</td>
<td>4.68</td>
<td>0.22464</td>
<td>13.34</td>
<td>51.2</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>48</td>
<td>5.43</td>
<td>0.26046</td>
<td>14.97</td>
<td>57.45</td>
</tr>
<tr>
<td>25</td>
<td>60</td>
<td>48</td>
<td>6.2</td>
<td>0.2976</td>
<td>16.60</td>
<td>55.80</td>
</tr>
<tr>
<td>25</td>
<td>70</td>
<td>48</td>
<td>6.82</td>
<td>0.32736</td>
<td>18.23</td>
<td>55.71</td>
</tr>
<tr>
<td>25</td>
<td>80</td>
<td>48</td>
<td>7.32</td>
<td>0.35136</td>
<td>19.86</td>
<td>56.55</td>
</tr>
<tr>
<td>25</td>
<td>90</td>
<td>48</td>
<td>7.49</td>
<td>0.35952</td>
<td>21.50</td>
<td>59.80</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>48</td>
<td>7.49</td>
<td>0.35952</td>
<td>23.04</td>
<td>64.08</td>
</tr>
</tbody>
</table>