# Energy Efficient Light Driver Controller

Abdul Muiz Dollah
Faculty of Electrical Engineering
Universiti Teknologi MARA
Shah Alam, 40450, Selangor, Malaysia
Email: mezz_89@yahoo.com

*Abstract* — **In pursue of energy efficient technology, lighting system has been among the major concern of the global warming effect due to the high power consumption. Therefore, this study is an attempt to investigate and design a new mechanism for reducing energy consumption by targeting to the indoor lighting system. Furthermore, the study has been carried out by divided in three stages; design, simulations and implementation. Complex Programmable Logic Device (CPLD) Altera Max EPM7128SLC84-15N has been used as target device for controlling luminance and power consumption of LED at design stage. On top of that, several range of duty cycle start from 6% until 93% has been designed, simulated and tested on CPLD to determine the suitable luminance range at the optimal power consumption for indoor lighting. Altera Quartus II version 11.1 has been used to construct, compile and simulate the proposed design. Meanwhile, Arduino Uno R3 has been used as an interface for the sensor at the implementation stage. The system has been successfully developed and tested using several range of inputs variables. Evidently, the optimal luminance is influenced by the range of duty cycle and numbers of LED bulb. Hence, the proposed system using 15 LEDs at 73% duty cycle produces 480 lux which approaching with the normal office illumination at 500 lux. Therefore, the proposed system is capable to reduce 27% power consumption to produce optimal standard indoor illumination.**

***Keywords: Complex Programmable Logic Device, Energy efficiency chip, Current driver***

## I. INTRODUCTION

The new infrastructure development due to the exponential growth rate of the world population has increased the demand for lighting system globally [1]. Therefore, the energy demand has also increased pertaining to this scenario which direct to the development of new power plant. Sustainable and renewable energy have been explored and commercialized to support the demand from different prominence area since the development and operational cost for power plant is very expensive.

On top of that, the new power plant required proper distribution channel or grid connected to distribute electricity. Thus, the additional cost is required instead of development and operational cost of the power plant. In the long run, maintenance cost is the must to be calculated for maintaining the electrical supply over the grid connected [1]. Therefore, this project is trying to reduce the power surplus on lighting system via efficient power management, while maintaining the standard level of luminance.

This project highlighted the new approach of reducing power consumption over lighting system using intelligent system on Very Large Scale Integrated Circuit (VLSI) controller. The new design of proposed intelligent lighting system controller is coded using Verilog Hardware Description Language (HDL) code and targeted to Altera Max EPM7128SLC84-15N.

Therefore, several topics have been added in this paper to complete the preliminary design until the completed prototype was constructed and tested. The review from the current practice is highlighted in section II. This is including the recent indoor lighting technology, system block diagram and luminance calculation. The operation of LED lighting system also discussed in specific subtopic.

The new proposed architecture and design are described in section III. Four subsections were added to complete the section outline: Theoretical calculation, overall system design in applied environment, the system block diagram and the final subsection is the flow of system operation.

In section IV, the complete system design from schematic level was outlined. Three subtopics have been added under this section: System schematic design, HDL code design and system simulation and testing. The construction of CPLD board design, LED driver, Pulse Width Modulation (PWM), sensor interface and computer interfacing are detailed discussed under system schematic design. Altera Quartus II version 11.1 has been used to construct the proposed system HDL code under HDL code design. In the simulation stage, the testbench was constructed to verify the proposed system HDL code using ModelSim Altera 10.0c. The testing was carried out using Arduino Uno microcontroller since it has been widely used for prototyping design and testing reported in [2] - [3]. A part from that, Microsoft Visual Basic 2010 has been used to interface testing circuit with energy efficient light driver prototype.

The system integration and testing were discussed in result and discussion section. Four subtopics have been added to complete the analysis and discussion of the proposed design. The Register Transfer Logic (RTL) of the proposed design is detailed discussed in the first subtopic. Meanwhile, the second subtopic highlights the simulation result for the proposed design. Every signal response over PWM and luminance is detailed discussed in the last subtopic. Several recorded data from oscilloscope and luxmeter were used to support the discussion. Finally, the conclusion section will conclude the findings for this project from the starting until the implementation and testing stage.

## II. CURRENT PRACTICE REVIEW

### *A. Recent Indoor Lighting Technology*

LED technology has been discovered by Dr Nick Honyak in early 1960's. Nowadays, LEDs are no longer used for simple indicator lights on electronic devices. Instead, advances in technology have given LEDs to be used as major practical light sources. The main benefits of using LEDs are durability, long life span and great efficiency. LEDs can save 50% and even more in energy costs compared to conventional light of incandescent and fluorescent [1], [5]. The replacement of fluorescent lamps, which contain highly toxic mercury, with LED proved to have good environmental value.

The commonly used method for controlling low power LED is by limiting variable resistor [6]. Using this method, a resistor is connected in series with an LED as shown in Figure 1. The voltage drop across the resistor will limit the voltage across the LED as its forward voltage. Equation 1 defines the voltage drop across resistor as $V_R$. While, $V_{F(LED)}$ as the forward voltage and $V_{DD}$ is the voltage source. The higher value of resistance will reduce the forward voltage across $V_{F(LED)}$. Therefore, the luminance of the LED started to dim depending on the changing value of the resistance. The amount of current is constant and not affected for any changes of the resistance value.

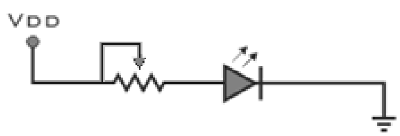


Figure 1: Limiting variable resistor voltage circuit

$$V_R = V_{DD} - V_{F(LED)} \quad (1)$$

Meanwhile, calculation on power dissipation is defined as

$$P_R = I_R^2 \times R \quad (2)$$

where $P_R$ is the power consumption across the variable current limiting resistor, $I_R$ is the total current across the variable current limiting resistor, and R is it's resistance value. Based on Equation 2, the brightness of the LED can be controlled by the variable current limiting resistor but the power consumption is not affected by the changes. Meanwhile, the variable current limiting resistor dissipates the power into heat. Figure 2 show the full circuit of the system.

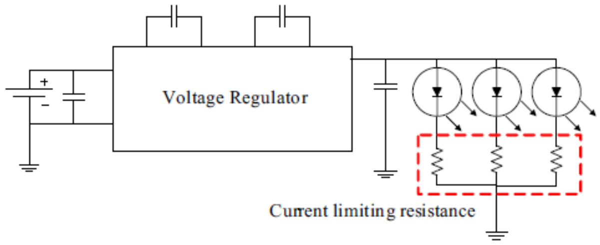


Figure 2: Limiting resistor voltage circuit [6]

The complete voltage regulator and current limiting resistor model highlighted in [6] and shown in Figure 2. The production cost for this model is slightly cheaper due to its simple circuitry and using basic components as the main part of the device. However, the low efficiency due to the high power dissipation across the resistor has reduced its potential in the real implementation of power LED application. The inconsistent supply voltage produced unstable luminance due to the significant difference on the LED current explained in [7].

Reviewing other common used lighting system on LED is the linear current-regulator method, as shown in Figure 3, has simple circuit configuration. It is widely used for dimming applications by modulating the current amplitude of the parallel-connected LED lamps [8]. However, linear dimming is not recommended at lower current because it may produce unpredictable results and varies its performance. Furthermore, the uncontrollable current amplitude will shorten the lifetime of the LED lamp [8] - [9].

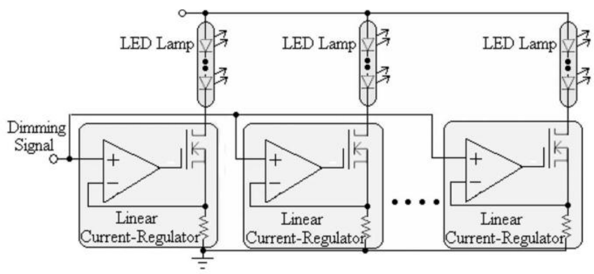


Figure 3: Linear current regulator

LED driver is an electrical device to drive current or voltage as to supply the LED. Drivers should be current-regulated where it delivers a consistent current over LED as the load. Both the power and the current control can be implemented into a device, without auxiliary current control circuit or ballast resistor as on fluorescent lamp. For different type of LED and arrays, different manufactured drivers may be used for more than one circuit in order to control multiple component specification.

The reason that LED bulb is not suitable to be installed with transformer is that it does not meet the load requirement. Common transformers often have its' own load requirement, which is high in power. Instead, LED driver does not. It has no minimum wattage, hence is fully compatible for LED bulb. Furthermore, the design which can maintain the efficient operating temperature will enhance the life span of LED.

LED driver offers two types which is constant current or constant voltage. A single bulb or a series connection of LED bulb would require constant current driver. This is to ensure that the current in the loop is the same with every bulb. As LEDs are connected in series, higher voltage would be required, thus the voltage may varies. However, multiple bulbs in parallel connection would require constant voltage driver. The driver keeps the voltage constant for each bulb so that it runs at the voltage reference.

Dimming function is to control and vary the brightness of LED which can be designed on LED driver. For PWM, efficiency does not affected by the dimming process. LEDs are still operating at the same voltage and current as preset level. It is just the switching of operating states to be on and off. Unlike on fluorescent lamp, the life span of LED can be lengthening as the dimming process reduces its operating temperature to a safer level. In the other hand, this project intends to overcome the disadvantage of the common device.

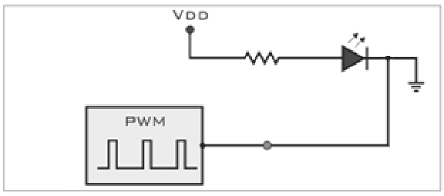


Figure 4: PWM generator

As in Figure 4, this project of PWM acts as a current sink. The PWM generator which is the CPLD board is connected to the cathode of the LED. By doing so, PWM pulses can pull down the current through anodes of the LED and thus turns it on. When the PWM in positive state, it blocks current through LED so it will turned off.

## B. System Block Diagram

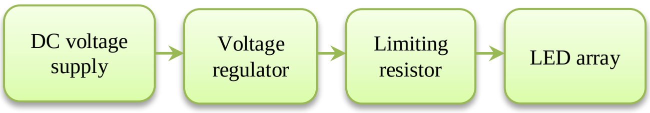


Figure 5: System block diagram for limiting resistor circuit

For the limiting resistor device, the system block diagram is shown in Figure 5. Normally, an adapter is used to convert and drop down the standard 240V AC into 12V DC. Voltage regulator is then used to regulate the 12V into suitable 5V voltage of electronic circuit. As the current may be still in high value, the calculation in Equation 1 is used to calculate the $V_R$ to be dropped so that the LED can achieved its desired $V_F$ and $I_F$. To dim the LED, different value of resistance should be applied across the limiting resistor. Thus, the potentiometer is used to vary the resistance and so does the LED luminance. The luminance decreases proportionally with the increases of resistance value.

## C. Luminance Calculation

Lux is a measurement defined as being equivalent to one lumen which spread over a particular area of one square meter. For example, 1000 lumens bulb applied on an area of ten square meters will lights up with 100 lux.

Hence, lighting up into a larger area of the same LED properties would require larger lumen. In addition, more fixtures can be attached to increase the lux of the particular area.

Wattage is the power required to operate a light fitting. It refers to the total electricity that is consumed which will including the heat generated by the light source, operational aspects depending on the type of lighting device, and the energy of the light emitted from the bulb.

So the rated wattage of a light source refers to the entire power consumed to drive the source and lumens only refer to the light output of that source.

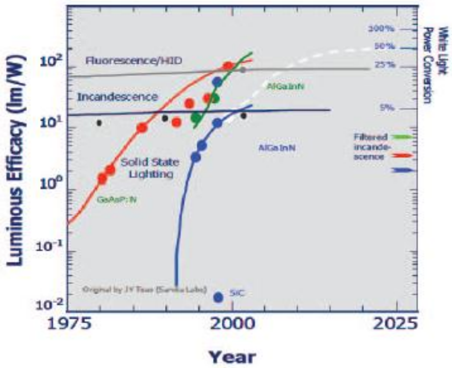


Figure 6: Luminous efficacy [10]

A light engineering term for the measurement of the rate where a lamp is able to convert electrical power to light is referred as luminous efficacy. Figure 6 show the luminous efficacy level for the incandescent, fluorescent and LED lighting from 1975 to 2025. The LED efficacy graph has rises even surpasses the fluorescent's [10].

# III. PROPOSED ARCHITECTURE & DESIGN

## A. Theoretical Calculation

PWM is a method for controlling analog circuits and systems, using the digital outputs. By altering its state and frequency, PWM can be controlled according to the required value. As a semiconductor-based component, LED can be turned on and off much quicker than other lighting appliances. Hence, this high speed switching makes LED suitable for use with PWM methods for dimming purpose [11] – [14].

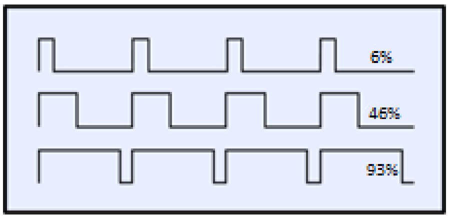


Figure 7: PWM Duty Cycle

The signals shown in Figure 7 are in square wave oscillations modulated as per their oscillation width, which is the duty cycle. As in Equation 3, they run the same frequency, but differ on the width of the positive state. The duty cycle is the percentage of the positive state compared to the period of the signal.

$$\text{Period (T)} = \frac{1}{\text{Frequency (F)}} \tag{3}$$

$$\text{DutyCycle} = \frac{\text{T x T}_{\text{On}}}{100} \tag{4}$$

One of the most popular usages of PWM is the control of voltage delivered to loads. Those loads could be for example an LED which would utilize as LED dimmer, or a motor that could be a simple DC motor or servo motor where it would be converted to a signal control [12]. In example is as used in the modern PC motherboard fans.

$$\text{Power (P)} = \text{Current (I) x Voltage (V)} \tag{5}$$

Equation 5 shows the relationship between power and the multiplication of the value of current with voltage. As the voltage is commonly fixed is most devices, we can vary the value of current to reduce the power consumption.

Varying the duty cycle of PWM will varies the brightness, thus reduce the current draw and the power consumption as well [13]. Theoretically, a PWM signal with 100% duty cycle would deliver 100% of the voltage. It would be like a DC power supply with constant magnitude. But by altering the duty cycle, the result is to reduce the area of the power delivered to the load.

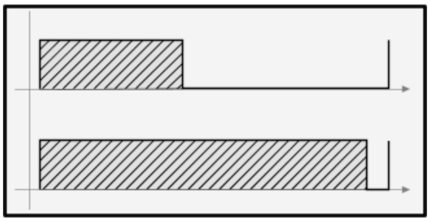

Figure 8: Power Delivered

As in Figure 8, the total power delivered to the connected load each time, is the area under the positive state of the PWM. It is clearly seen that by altering the duty cycle, we can alter the power delivered by the supply [11].

And because the wave form is a square wave, the power supplied each time is calculated by:

$$P_{Delivered} = P_{Supplied} \text{ x DutyCycle} \tag{6}$$

Equation 6 shows $P_{Delivered}$ is the power that supply to the load while $P_{Supplied}$ is the supplied source power. The lower value of $P_{Delivered}$ indicates that less power used so thus the brightness level.

### B. *Overall System Design*

For the overall system design in applied environment, each steps should be taken into consideration while keep the focus on achieving the objectives. Figure 9 shows the complete prototype system design for this project. As it is using 12V rated supply voltage, a constant supply should be connected for the system to function. As for this project, luxmeter is used to measure lux of a 12m^2 area of a room where 500 lux can be obtained using the conventional light system.

Integrated with light sensor system, LDR is used to react with the lux changes of the particular area. The higher lux will lower the resistance, thus giving lower LED luminance and vice versa. The sensor is a good idea to reduce human work and eases the user. This is suitable for standard low light indoor lighting system as low power LEDs are used for the system. The CPLD cannot withstand the high current draws.

The design uses fifteen pieces of LEDs, with series parallel connection. Three series connected of LEDs with five strings would be sufficient to give the comparable lux value with the standard conventional lighting system. More fixtures of the LED will produce higher lux. Users can switch to this prototype and benefits from it.

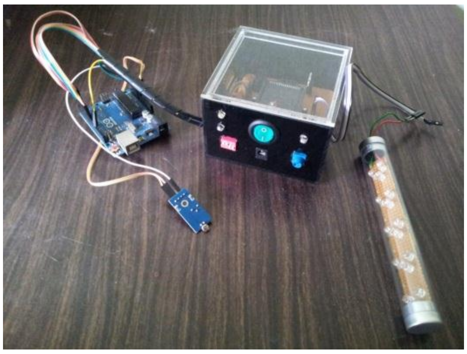

Figure 9: Prototype system design

## C. System Block Diagram

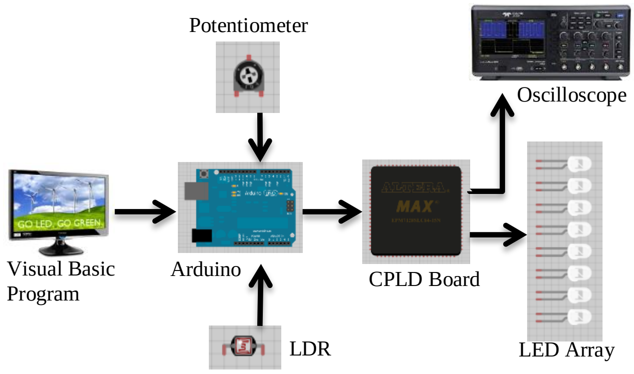


Figure 10: Hardware block diagram

The prototype uses the interfacing of Altera CPLD development board to Arduino microcontroller and Visual Basic. Arduino controls the input variables and send its output to CPLD for PWM technique. The signals have been monitored in oscilloscope to measure its behavior.

Hardware block diagram in Figure 10 shows the hardware block diagram of the prototype. There are three variables of input switches which is for the variable resistor, light depending resistor, and through serial interface using Visual Basic. Arduino microcontroller runs the command program and gives out output as input for CPLD board. As CPLD obtained inputs, it will start producing PWM signal for the output in LED array. As a result, different level of LED brightness can be produced. For testing purpose, the CPLD board can be connected to oscilloscope to display the measurement and observe the result.

## D. System Operation

As from flow chart in Figure 11, it shows the overall flow of the system prototype. At the starting, the user must check for the desired function swtich. There are three conditions should be met for the system to operate; Manual, Sensor or Serial. Otherwise, the system will off and nothing would trigger the system. The Manual switch allows user to manually control the LED luminance.

The sytem reads potentiometer analog value which then converted to digital signal through Arduino Uno for CPLD input. Meanwhile, the Serial system uses the serial communication to interface with Visual Basic. User can manually set the desired value by just a few simple setting. The serial input from Visual Studio is then transferred to be programmed by Arduino microcontroller before sending as CPLD input. The third switch is the Sensor where it reads the analog value of LDR (Light Depending Resistor) to automatically sense the lux condition of the particular area.

Through Arduino Uno, the data is interpreted and the output that corresspond with it will be as the input data for CPLD. After receiving the input, CPLD will then generate PWM to switch the LED on and off as its output function. The output can be measured by the value of current it draws.

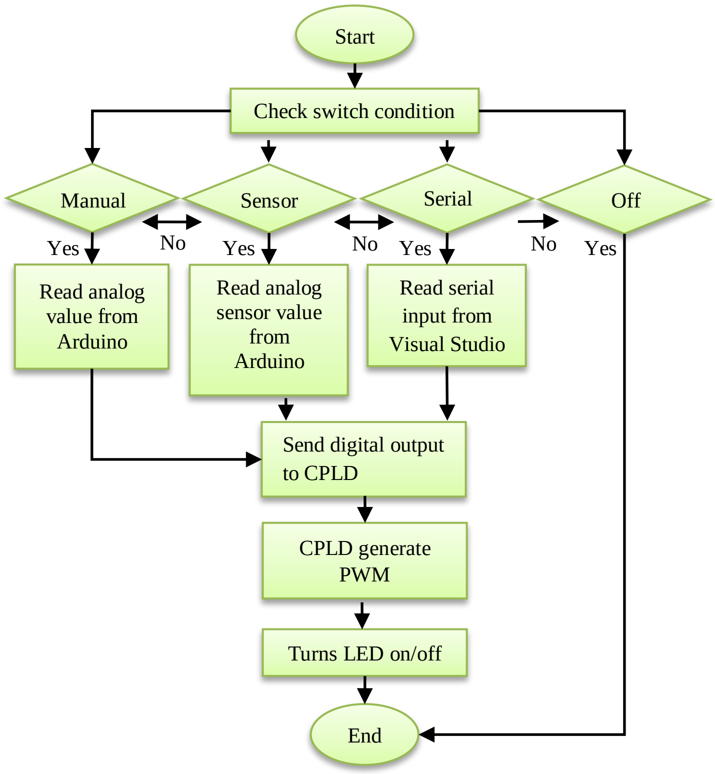


Figure 11: Flow chart of the system

# IV. COMPLETE SYSTEM DESIGN

## A. System Schematic Design

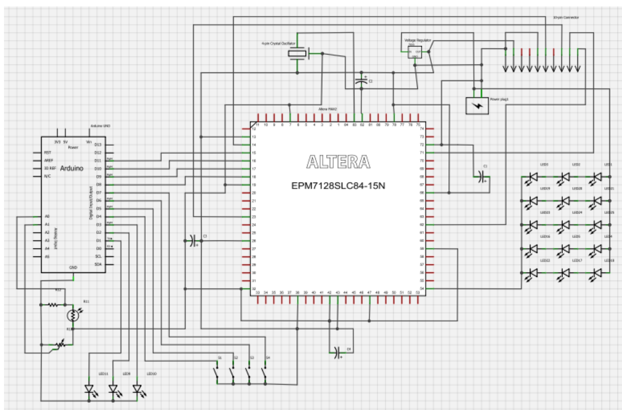


Figure 12: Circuit schematic

Figure 12 shows the whole circuit schematic for the prototype of the device. It includes from the supply source, inputs, oscillator, microcontroller, CPLD and through the end is the ouputs. As in the figure, four output pins digital of Arduino microcontroller are connected to Altera CPLD as inputs while fifteen LED arrays are set for its output. Direct current voltage of 12V with voltage regulator is used in the system as supply. The design was compact to reduce the size of the development board. LED array is connected in series parallel as common souce to acquire sufficient souce from the 12V DC supply.

### *B. HDL Code Design*

An HDL is a programming language used to describe electronic circuit essentially digital logic circuits. It can be used to describe the operation, design and organization of a digital circuit. It can also be used to verify the behaviour by means of simulations. The principle difference between HDL and other programming languages is that HDL is a concurrent language whereas the others are procedural i.e. single threaded. HDL has the ability to model multiple parallel processes like adders, flip-flops etc which execute automatically and independently of each other. It is like building many circuits that can operate independently of each other.

The two widely used HDLs are Verilog and Very High Speed Integrated Circuits (VHDL). For this project prototype, the code was instructed using Verilog HDL for implementation on CPLD. The designed code will generate PWM signal over clock triggered syncronization. Counter command program was instructed as to determine the delay period of each duty cycle.

Equation 7 refers to to the calculation of PWM counter.

$$p = t \text{ x } \mathrm{Clock}_{FPGA} \qquad (6)$$

Calculating step delay (sd):

$$sd = \frac{p}{x} \text{ where } x = 2^n \qquad (7)$$

$$\log_2(sd) = \text{Number of bits counter}$$

### *C. System Simulation & Testing*

Altera Quartus II 11.1 has the function to view the RTL for the code hardware design. By doing so, the hardware design of the chip can be verified into logic states. After done verifying the HDL code design, the next stage is on simulating it on ModelSim Altera 10.0c. The signal waveform is targeted on the input value and output result. The high speed hardware design chip can accurately be simulated ideally while synchronizing with the designed clock. During simulation, expected result can be compared to the tested result for better conclusion. For downloading the code onto the chip, Altera Programmer has been used to conduct the task.

The chip is then configured to Arduino Uno R3 along with the basic components of LED, resistor and switches. Several laboratory equipment such as multimeter, oscilloscope, luxmeter and power supply also been configured to get the experiment result. The equipment assists in all testing and troubleshooting stage while maintaining the safety and proper procedures to run the experiment. For testing LED luminance using luxmeter, a small room has been conducted with the proposed project. Observations and data obtained are further discussed in the next section of Results and Discussion.

## V. RESULTS AND DISCUSSION

After done some lab session, the data was observed and tabulate in accordingly. The connection of LED is connected with common source so that the supplied source is sufficient. The result includes all the required data and objectives of the project itself including the duty cycle and the current drawn.

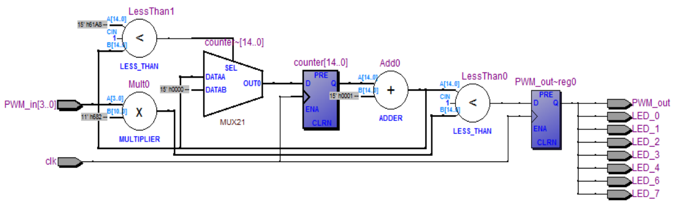


Figure 13: RTL Viewer

Figure 13 shows the RTL viewer of the CPLD from Quartus II. It shows the hardware architecture of the programmed CPLD from the input to the outputs where PWM are then generated. The PWM input which is the input of CPLD are from the output of Arduino Uno. The register for counter will determine the delay for each duty cycle. The generated PWM will then give the corresponding output for LED.

For simulation purpose, ModelSim ALTERA has been used to simulate the instructed verilog testbench. Figure 14 (a) shows the PWM technique simulated from the software. It shows how the top signal which is the clock edge, will trigger the output waves. The frequency used is 25Mhz oscillator. CPLD can generate the output fast enough as it is its advantage. The output remain the same as the counter holds the delay as to meet the instructed verilog command.

Meanwhile, Figure 14 (b) shows the signal after it is scaled out by thousand times of cycle. It shows the full result that obtained through PWM method. The input was set to get the simulation for 6%, 47%, 73% and 93% of duty cycle. As shown, the PWM waveform that are generated can be varied by different values of input. This shows how the counter can generate PWM waveform in respond to the clock edge

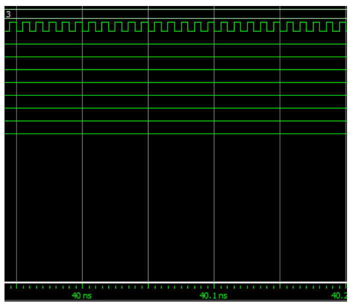

Figure 14 (a): PWM Simulation

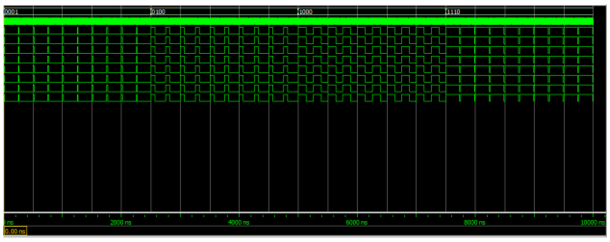

Figure 14 (b): PWM Input & Output

By using oscilloscope, measurement on a circuit can be executed. Signal waveforms of this project were obtained through connection with oscilloscope. As the connection of LED is connected as common source, hence the probe is set at the ground of LED. Observation was done for Figure 15 (a) – Figure 15 (d) where the PWM waveforms with different values of duty cycle are generated from CPLD. This simulates the altenating voltage that is triggered on and off through the LED.

The V_pp for this project prototype was obtained for 3.36V – 3.44V which indicates the operating voltage for the tested LED. As the prototype is tested, different values of inputs are set to get different expected output signals as in the simulation. The duty cycle varies for each output which gives different level of LED luminance.

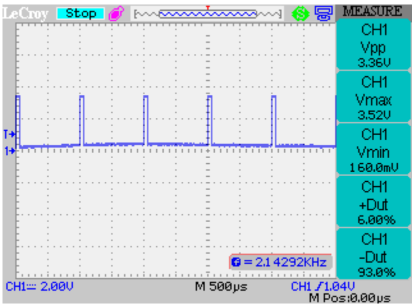


Figure 15 (a): 6% Duty Cycle

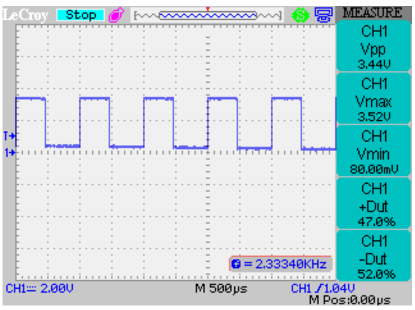


Figure 15 (b): 47% Duty Cycle

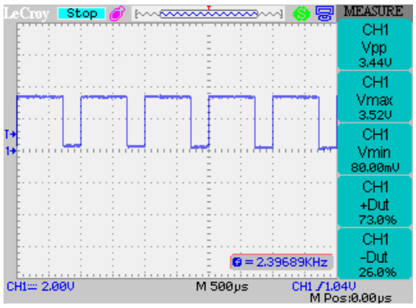


Figure 15 (c): 73% Duty Cycle

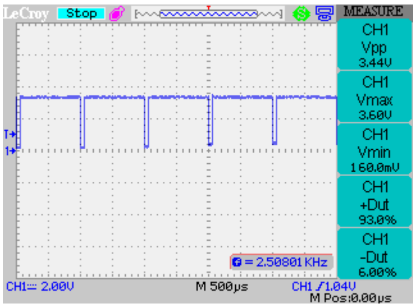


Figure 15 (d): 93% Duty Cycle

TABLE 1: OUTPUT DATA FOR DUTY CYCLE

| **Duty Cycle (%)** | **Input Bit** | | | | **Lux** | **Current (mA)** |
|---|---|---|---|---|---|---|
| | ***Bit 4*** | ***Bit 3*** | ***Bit 2*** | ***Bit 1*** | | |
| 6 | 0 | 0 | 0 | 1 | 40 | 1.3 |
| 47 | 0 | 1 | 0 | 0 | 300 | 5.4 |
| 73 | 1 | 0 | 0 | 0 | 480 | 10.0 |
| 93 | 1 | 1 | 1 | 0 | 650 | 16.4 |

The procedure of getting the result in TABLE 1 is by varying the input of CPLD. This is done by generating fixed value output of Arduino microcontroller. The outputs act as a switch counter for the program inside the CPLD. The LED array is connected in common ground where it shares the same voltage source with its ground connected to CPLD output. The higher current draw made higher intensity of the LED. The LED is alternated rapidly through CPLD so it seems differs for its intensity level. Multimeter is used for measuring current while luxmeter for lux of LED. LED's intensity is verified as proportional to its current value.

## VI. Conclusion

The design for the project was successful and achieved its objectives. In research and methodology, the project was thoroughly planned to make sure its functionality and overcoming the problem statement. Instead of using the variable resistor, which reduces the brightness by dropping excessive current as power loss, the PWM can utilize the current for least loss of power. The result on LED brightness is comparable with the device using potentiometer as its dimmer. PWM dimming technique has been proven as energy saving tool while it suits for a better solution of lighting system.

For future work recommendation, the concept should be studied and implemented for every type of LED lighting system. Some modification of the circuit should make the concept operates on high power LED also. For other application, servo motor could also be controlled using the proposed project concept.

To sum up, the PWM technique for LED lighting system is proven as a new way of energy saving. Electricity is not renewable and should be conserves properly. It has achieved the objectives and fulfills the requirements. In the race of a better product in this modern technology, this project surely has earned its own contribution.


## ACKNOWLEDGEMENT

The author would like to thank supervisor Mr. Syed Abdul Mutalib Al Junid, throughout the entire semester spans on completing the project. His patience and guidance with all the necessary tools and knowledge are greatly appreciated.

Acknowledgement is also towards all laboratory and workshop assistant that aided me in time of needs and their full cooperation in completing the project. Credits are also given to colleagues for their comments and thoughts in any matter throughout the entire project.


## REFERENCES


[1] L. K. Koh, Y. K. Tan, Z. Z. Wang & K. J. Tseng. “An Energy-Efficient Low Voltage DC Grid Powered Smart LED Lighting System”. Nanyang Technological University. 2011.

[2] Nik Arif Mat Tahir , Syed Abdul Mutalib Al Junid, Zulkifli Othman, Zulkifli Abd Majid, Sharifah Khalizah Syed Othman Thani. “Design Automatic Meter Reading (AMR) Data Logger With Xbee”, International Journal of Simulation, Systems, Science and Technology, Volume 13, Number 1, pp 67-73, 2013.

[3] Rohaida Husin, Syed Abdul Mutalib Al Junid, Zulkifli Othman, Sharifah Khalizah Syed Othman Thani, Mohd Faisal Saari,”Automatic Street Lighting System for Energy Efficiency Based on Low Cost Microcontroller”, International Journal of Simulation, Systems, Science and Technology, Volume 13, Number 1, pp 29-34, 2013.

[4] Sanghyun Cha, Deukhee Park, Yuenjoong Lee, Changseok Lee, Joongho Choi, Jaeshin Lee & Hyobum Lee. “AC/DC Converter Free LED Driver for Lightings”. IEEE International Conference on Consumer Electronics, 2012.

[5] Prathyusha Narra and Donald S. Zinger. “An Effective LED Dimming Approach”. Northern Illinois University. 2004.

[6] Chun-Yao Lee and Yun-Chih Chen. “Efficient Improvement of Driving Circuits for White Light LEDs”. Chung Yuan Christian University. 2012 Third International Conference on Digital Manufacturing & Automation. 2012.

[7] Wen-Ching Yang, Yu-Jen Chen, and Chin-Sien Moo. “An Efficient Driver for Dimmable LED Lighting”. National Sun Yat-Sen University. 2011.

[8] Huang-Jen Chiu, Yu-Kang Lo, Jun-Ting Chen, Shih-Jen Cheng, Chung-Yi Lin, and Shann-Chyi Mou. “A High-Efficiency Dimmable LED Driver for Low-Power Lighting Applications”. IEEE Transactions On Industrial Electronics, Vol. 57, No. 2, February 2010.

[9] Liu YU and Jinming Yang. “The Topologies of White LED Lamps' Power Drivers”. 3rd International Conference on Power Electronics Systems and Applications, 2009.

[10] Yang Zhao and Wai Tung Ng. “An Energy Conservation Based High-Efficiency Dimmable Multi-channel LED Driver”. April 2012.

[11] Huang-Jen Chiu, Yu-Kang Lo, Jun-Ting Chen, Shih-Jen Cheng, Chung-Yi Lin, and Shann-Chyi Mou. “A High-Efficiency Dimmable LED Driver for Low-Power Lighting Applications”. IEEE Transactions On Industrial Electronics, Vol. 57, No. 2, February 2010.

[12] Masahiro Nishikawa, Yoichi Ishizuka, Hirofumi Matsuo and Koichi Shigematsu. “An LED Drive Circuit with Constant-Output-Current Control and Constant-Luminance Control”. Nagasaki University, 2006.

[13] LU Jiaying, WU Xiaobo. “A Novel Multiple Modes PWM Controller for LEDs”. Zhejiang University. 2009.

[14] Chin-Sien Moo, Yu-Jen Chen, and Wen-Ching Yang. “An Efficient Driver for Dimmable LED Lighting”. IEEE Transactions On Power Electronics, Vol. 27, No. 11, November 2012.