# CHAPTER 1

# INTRODUCTION

## 1.1 General

LED or light emitting diode is a semiconductor device which, as the name suggests, emits light when current is passed through it. It works on electroluminescent principle and can emit light in visible spectrum as well as in infrared and ultraviolet. When the LED is forward biased, the holes and electrons recombine. As a result, photons are generated in the visible spectrum which reach the human eye and create the sensation of vision through light. In the last few years, LEDs have gained widespread popularity in a wide range of applications ranging from tiny little indicators to big video screens. LEDs are preferred over other sources of light because of availability in compact size, less consumption of energy and longer shelf life.

To utilize the LED in the most efficient manner, it becomes imperative to understand its voltage and current relationships. Fig. 1.1 shows a 2 pin variant of LED and the general LED symbol. As can be seen from Fig.1b, the longer leg always denotes the anode and the shorter one denotes cathode. This indifference in length is done for the sake of remembrance.

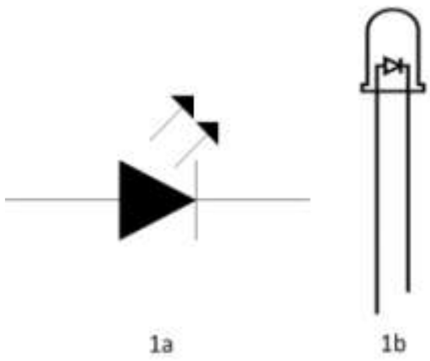



Figure 1.1 LED symbol and its 2 pin variant.

The LED lights have traversed a great range of applications, ranging from indicators to illuminators. During early times dating back to the 80s, LEDs were used as tiny indicators which would indicate the completion of a task been done. The LEDs then were used in digital display boards such as the seven segment displays and found applications in traffic lights as well. In the early 2000s, with the advent of RGB LEDs, they were started to be used as displays for television and smartphones. The LEDs are also used as sources of illumination these days with improvement in the white light LED technology. Figure 1.2 shows the various applications of LEDs.

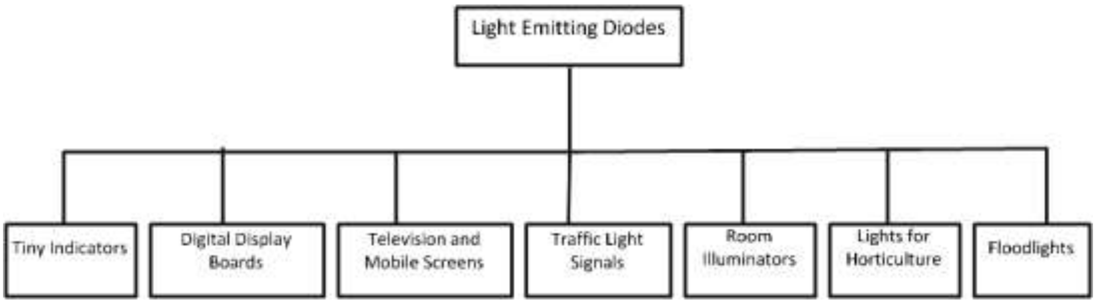



Figure 1.2 Various applications of LEDs

## 1.2 Motivation

Light emitting diodes have been fascinating ever since their inventions as indicators. LED lights have been chosen as the soul this work because they possess a variety of advantages over other lighting sources with each being described as follows:-

*Economy* – Although the LED lights are a bit costlier than their counterparts, the overall life costing of LEDs are lower.

*Efficiency* – LED lights have a higher efficiency and efficacy that is, the amount of light energy imparted in lumens per watt of electrical power consumed.

*Low power consumption* – The LED lights consume nearly half the power for the same amount of lumens of light than their counterparts such as CFL.

*Longer lives with low maintenance* – Led lights have a longer life span as compared to the CFL and incandescent lamp. A regular LED light can last upto thousands of working hours with ease.

Another major reason of choosing LED lights is the ability to be dimmed over a wide range without appreciable loss in lifespan of device. This dimming ability of LED lights has been the prime motivation of taking up the task of illumination control of given closed space.

The advent of Red Green Blue lights or better known as RGB lights has led to the creation of another application of LED lights, that is "Horticulture using LED". In horticulture, plant species are subjected to artificial lights under controlled environment or space. Earlier fluorescent lights were used as light for photosynthesis but these were not efficient. The RGB lights especially the hyper red and the deep blue lights have been found to increase the rate of growth of plants tremendously. Moreover, the near green spectrum lights are found to benefit the plants with micronutrients. To create these lights, the color mixing principle of RGB lights using variable dimming scheme has been found to be very effective.

### 1.3 Problem Formulation

To achieve the idea behind this work successfully, a sequence of objectives have been formulated. The objectives are:-

i) To model the IV characteristics of LNL-190UW-4H: SMD LED using two different techniques and to compare the advantages and disadvantages of both the techniques. The modeling has to be done in MATLAB coding IDE.

ii) To model, design and analyze an automated LED lighting system in Simulink and to realize the same work into hardware and compare various parameters such as THD to verify the results.

iii) To model an RGB LED lighting system for its application in Horticulture via the technique of color mixing using variable dimming scheme. A plant sample of Spirulina Platenesis has been taken to achieve the objective.

## 1.4 Dissection of Thesis

For the sake of clarity and better understanding of the reader, the complete work has been divided into chapters. There are a total of seven chapters in the thesis. Chapter 1 is a brief introduction to LEDs, their working, brief history and their evolution from indicators to illuminators. Chapter 2 is about the foundation of this work, that is, the literature reviews. A lot of in depth research has been conducted before compiling this work and due credits to all the researchers have been given in this chapter and references section too. Chapter 3 deals with the modeling of LEDs using two techniques namely Piecewise Linear Approximation (PLA) and Maclaurin series expansion based modeling. A comparison between the two techniques has also been made. Chapter 4 covers the heart of this work. An automated LED lighting system has been designed and simulated for the purpose of illumination control of a given closed space. Also, the work has been extended to the hardware stage and the target has been successfully achieved. Chapter 5 presents another application of LED lighting systems, that is, use of RGB lights in horticulture. Chapter 6 deals with the discussions of all the important results achieved throughout this work and inferences have also been drawn out of these results which help in validation of the work. Chapter 7 has been written to conclude the work on a good note and the scope of future work has also kindly been suggested.

## 1.5 Conclusion

In this chapter, a general introduction about the LEDs has been presented. The motivation behind this work has also been discussed. Furthermore, the objectives that are achieved in this work are also mentioned. The dissection of the thesis for a clear and better understanding has also been presented.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Light emitting diodes have become an area of widespread research in today's era of modernity. LEDs not only pose a great advantage in the technical field of energy efficiency but also have a great role in the field of luxurious decoration and designing.

Before starting this work, a lot of research had been done ranging from the basics of LEDs to the complex stuff like the driving schemes, the closed loop control of LED driver, etc. Although performing an exhaustive research in this area is next to impossible, an in-depth research has been made which eventually led to the development of the proposed work. The major areas of research include:-

1. The Modeling of IV characteristics of LED using MATLAB and Simulink.
2. Automated control of illumination level of a given closed space using LEDs.
3. Application of RGB LED lighting system in Horticulture.

## 2.2 The Modeling of IV characteristics of LED[1-9].

The basic modeling of the current-voltage characteristics (popularly known as the IV characteristics) of light emitting diode can be done by considering it as a resistor. The LED has two terminals, namely Cathode and Anode. It is similar to a diode except the fact that it emits light too. A.S. Sedra and K.C. Smith (2004) [1] in their book "Microelectronic Circuits" proposed the model of an ideal diode in series with a resistor and a battery which gives a shifted linear IV characteristic. The diode remains in off state until the applied voltage reaches the forward voltage of the diode. Since the diode is ideal, it offers zero resistance after forward voltage point and appears as short circuit. The forward voltage here is represented by a battery connected in series with internal resistance.

LNL-190UW-4H: SMD LED (2017) [2] is the datasheet provided by LIGHTOP Technologies of the LED sample taken up in this work for the purpose of modeling. It has provided the important data points like the knee voltage point, the maximum operating point, the rated operating point among others which help in the PLA and Maclaurin series expansion based modeling of the LEDs (taken up in detail in the next chapter).

R.L. Lin and Y.F. Chen (2013) [3] have presented the Taylor series expression based LED model for the analysis of the LED lighting system. To describe the nonlinear I-V characteristics of LEDs accurately, Taylor series expansion can be used to express the Shockley equation of LEDs that contains an exponential function. Based on the single unit LED models, the LED array with Q parallel strings of P LEDs in series can be built. Further, the equivalent resistances of the P x Q LED array can be derived. Finally, one LED array with eight paralleled strings of fifteen LEDs in series is built up to cross verify the small-signal resistance with the obtained results.

Tomasz Torzewicz et al [4-9] have discussed about the many properties and applications that the LEDs have to offer in the present time. Modern day lighting technology mainly revolves around LEDs. LED or light emitting diode is a semiconductor device which, as the name suggests, emits light when current is passed through it. When the LED is forward biased, the holes and electrons recombine. As a result, photons are generated in the visible spectrum which reach the human eye and create the sensation of vision through light. In the last few years, LEDs have gained widespread popularity in a wide range of applications ranging from tiny little indicators to big video screens and large illuminating lights. LEDs are preferred over other sources of light because of availability in compact size, less consumption of energy and longer shelf life.

## 2.3 Automated control of illumination level of a given closed space using LEDs. [10-25]

The illumination control, as the name suggests, requires the control of the dimming level of the controlled light source. Bautista August [10] in his article “what are the different methods of dimming” has suggested that light emitting diodes are the best device for light control and offer a very smooth control of brightness and illumination throughout the dimming range.

Present day electrical systems cannot be imagined without the inclusion of power semiconductor devices. Muhammad H Rashid [11] in his book "Power Electronics – Circuits, devices and Applications" has elaborately presented the working of a single phase full bridge diode rectifier. A rectifier is a semiconductor based device which converts alternating current (AC) to pulsating direct current (DC). This current/voltage can be stabilized using a capacitor connected in parallel to the output load.

Realizing any circuit into hardware or even a simulation requires the designing of the various components, their ratings and calculation of values. Ned Mohan et al [12] in their book have suggested about the calculation of the values of various components that are required in the building of a buck converter. Buck converter is a power semiconductor device that helps in stepping down of the dc input voltage to a lower value output voltage. It is also known as a dc-dc converter.

The closed loop control scheme becomes mandatory when the real time control of illumination is required. To achieve this, a lux sensor is required that constantly monitors the current illumination of the given closed space and sends its data to the controller. Steve Carter et al [13-14] in their articles have suggested a sensor namely, BH1750, which has been used in the hardware implementation of this work. The articles also provide with the valuable information such as datasheet and application notes that help in setting up and synchronizing the sensor with the complete hardware setup.

Lena Haber et al [15-18] in their articles have suggested that although LEDs are way much better than their counterparts like CFL and other fluorescent lights, but there are certain issues that arise due to the dimming of LEDs as suggested by Blanco A.M. et al [19]. S. Uddin et al [20-21] have suggested that one of the major issues that dimming creates is the effect on power quality and other issues which arise due to the fast switching of the semiconductor switches include 'flickering' which greatly affects the human eyesight. Abdel Rahman Ahmed et al [22-23] have suggested that LEDs are non linear devices and as such become a source of higher order harmonics in the electrical system. The presence of harmonics increases a parameter known as Total Harmonic Distortion or better abbreviated as THD. The

THD should be kept as low as possible and some measures are taken up to reduce it in the upcoming chapters.

The IEEE standard 519-2014 [24] has suggested that the harmonics production is due to the presence of power electronic switches and has also shown some standard waveforms with different setups. For $THD_v$ calculation, terms upto $50^{th}$ harmonic have to be considered. IEC standard 61000-3-2 [25] has suggested about the limit for harmonic current emissions into the supply due to lighting loads. For currents less than 16A and loads less than 25W, the permissible $THD_i$ should be less than 105%.

### 2.4 Application of RGB LED lighting system in Horticulture. [26-38]

One of the non-conventional uses of light emitting diodes is their application in horticulture. Horticulture is the branch of science which deals with the growth of crops and plants under controlled environmental conditions where these plants are kept and observed under a closed space with artificial light used for photosynthesis.

Feng Tian [26] has suggested the Study and optimization of lighting systems for plant growth in a controlled environment. H. M. Cathey and L. E. Campbell [27] have shown how lights of different colors affect the rate of growth of plants and also depicted the use of various sources of lights such as fluorescent lights to name a few. D. J. Tennessen et al [28] have carried out a work on light-emitting diodes as a light source for photosynthesis research and the efficiency and cost related advantages they posses over other lighting sources. Leora C. Radetsky [29] has shared a report on LED and HID Horticultural Luminaire Testing. T. D. Sharkey et al [30] have suggested that pulsed lighting through LEDs have better efficiency of photosynthesis than continuous LED lighting.

P. Eilers et al [31] have suggested a model for the relationship between light intensity and the rate of photosynthesis in phytoplanktons. P. H. Ravelonandro et al [32-33] have found out the importance of influence of light quality and intensity in the cultivation of Spirulina platensis from Toliara in a closed system. A study on effect of light emitting diodes on the cultivation of Spirulina platensis using NPK-10:26:26 complex fertilizer has also been carried out.

The RGB LEDs pose a greater advantage over the use of only hyper red or deep blue LEDs in the fact that the RGB LEDs not only take care of macronutrient requirement but also the micronutrient requirement due to the inclusion of near green spectrum of light. The datasheets [34-36] for the IV characteristics of the red green and blue LEDs individually have been taken up for the design of the circuit and calculation of parameters for the same purpose.

## 2.5 Conclusion

This chapter presents the literature review of all the valuable information that has been utilized in this work.

# CHAPTER 3

# MODELING OF IV CHARACTERISTIC OF LED

## 3.1 Introduction

Modern day lighting technology mainly revolves around LEDs. LED or light emitting diode is a semiconductor device which, as the name suggests, emits light when current is passed through it. When the LED is forward biased, the holes and electrons recombine. As a result, photons are generated in the visible spectrum which reach the human eye and create the sensation of vision through light. In the last few years, LEDs have gained widespread popularity in a wide range of applications ranging from tiny little indicators to big video screens. LEDs are preferred over other sources of light because of availability in compact size, less consumption of energy and longer shelf life. To utilize the LED in the most efficient manner, it becomes imperative to understand its voltage and current relationships. Fig. 3.1 shows a 2 pin variant of LED and the general LED symbol. As can be seen from Fig. 3.1b, the longer leg always denotes the anode and the shorter one denotes cathode. This indifference in length is done for the sake of remembrance. In this work, an LED sample LNL-190UW-4H has been taken up for study. The focus here is mainly on the I-V characteristics of the sample and not on its optical properties. An LED is basically a diode which has a non linear IV characteristic. Thus, it is not a good idea to model it using just a resistor which has a linear I-V characteristic. To tackle this problem, an approximate linear model was developed as can be seen in Fig. 3.2. In this model, the diode remains in OFF state until the applied voltage reaches a particular voltage known as knee voltage. The diode remaining in OFF state simply means that no current flows through it during this state.

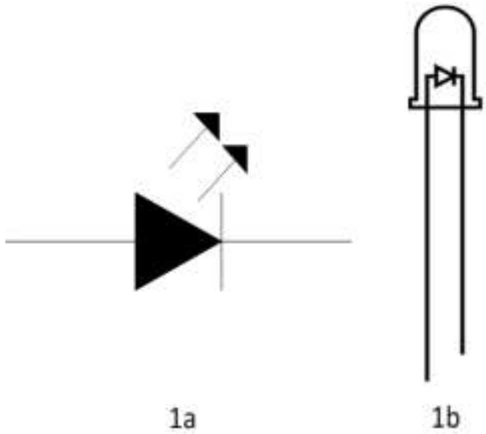



Figure 3.1 LED symbol and its 2 pin variant.

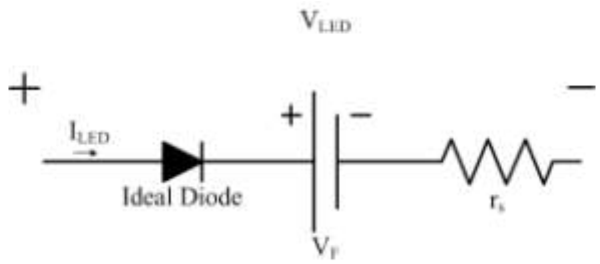



Figure 3.2 Approximate linear model.

Taking the above model as the basis, a new modeling technique has been presented in this work, namely Piecewise Linear Approximation (PLA) technique. In this technique, several diodes are connected in parallel. Each branch has different knee voltages and gets turned ON at different values of forward voltage applied. Thus, as the applied voltage increases, the branches turn on one by one, making the resistance change each time a new branch conducts. The slope of the characteristics changes for different pieces of curve and hence the technique gets its name Piecewise Linear Approximation (PLA).

The PLA technique becomes more efficient as the number of branches increases. At the same time, it becomes very complicated too. So, to handle this issue, a better technique has been introduced in this work viz Maclaurin series expansion based modeling as the measured I-V curve on inspection reveals that its non linear nature is quite similar to that of an exponential function. The Taylor series expression based modeling of LED as presented in had been done using SIMPLIS and convergence to the measured sample curve was achieved after taking 23 terms of the series. The Maclaurin series model is a simplified version of Taylor series model and has been modeled using MATLAB with results converging by taking lesser number of terms.

### 3.2 Modeling of LED

The measured I–V curve of the LED sample is shown in Fig. 3.3. As can be seen from Fig. 3.3, the nature of the curve is non linear.

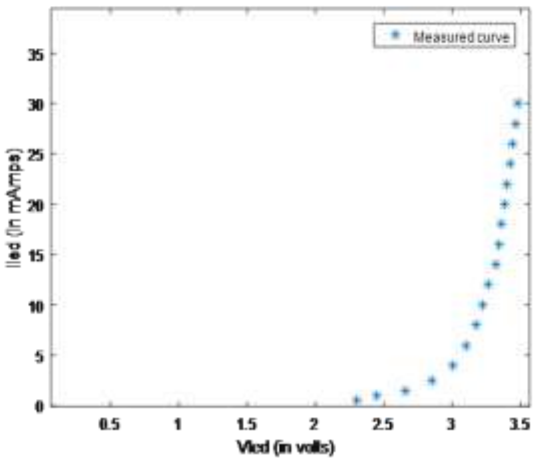



Figure 3.3 Measured I-V curve of LED sample, LNL-190UW-4H

In this work, the I-V characteristic of the given LED sample has been proposed and modeled using two different modeling techniques, namely:

1 Piecewise linear approximation

2 Maclaurin series expansion based modeling.

#### 3.2.1 Modeling using Piecewise Linear Approximation

The modeling of LED I-V characteristics using PLA technique involves multiple branches of series connected diode connected in parallel. More is the number of branches more is the accuracy of the plotted curve. Fig. 3.4 shows the generalized circuit of PLA technique. In this work, five series connected diode branched circuit has been used as can be seen from Fig. 3.5. The first branch has only one diode, second branch has two diodes, branch three has three diodes connected in series and so on. It is clear from Fig 3.5 that as the applied voltage increases branches get switched ON in serial fashion with branch one getting switched ON first, then second and so on. Since in parallel connection, the equivalent resistance is smaller than the smallest branch resistance, therefore, the equivalent resistance of the circuit decreases as the number of branches getting switched ON increases. Further, the slope of the I-V curve increases with decrease in equivalent resistance. In this technique, 5 points from the datasheet have been taken to achieve the resulting curve. The choice of selection has been made such that the modeled curve best traces the plot of discrete datasheet points.

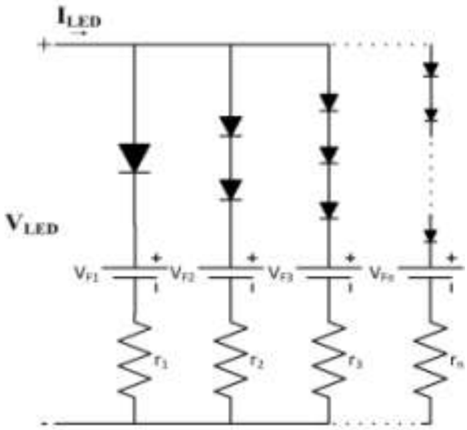



Figure 3.4 Generalized PLA model

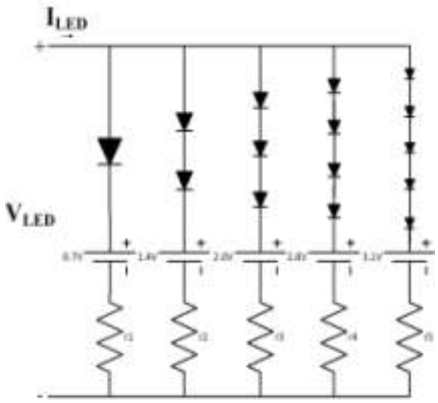



Figure 3.5 Five branched PLA model.

### 3.2.2 Modeling using Maclaurin Series Expansion

The modeling of LED I-V characteristics using Maclaurin series expansion technique involves the use of the famous Shockley equation as given below:

$$I_{LED} = I_{SAT}(e^{(qV_F)/(\eta kT)} - 1) \quad (3.1)$$

Where,

TABLE I VARIOUS PARAMETERS OF SHOCKLEY'S EQUATION

| | |
|---|---|
| $V_F$ | Voltage Drop across the LED |
| $I_{LED}$ | Current passing through the LED |
| $I_{SAT}$ | Saturation current of LED |
| ɳ | Ideality factor |
| q | Magnitude of the Electronic Charge (1.602 x $10^{-19}$ C) |
| k | Boltzmann's constant (1.38 x $10^{-23}$ J/K) |
| T | Absolute temperature (273 + $T_a$) in Kelvin |
| $T_a$ | Ambient temperature (in ˚C) |

In the forward biased region, beyond the knee voltage, the exponential term predominates and the equation of LED *I-V* characteristics can be modified and rewritten as follows:

$$I_{LED} = I_{SAT}(e^{(V_F)/(\eta VT)}) \quad (3.2)$$

$$V_T = kT/q \quad (3.3)$$

Where, $V_T$ is thermal voltage.

The Maclaurin series expansion of a function is given by the following equation:

$$f(x) = f(0) + \frac{f'(0).x}{1!} + \frac{f''(0).x^2}{2!} + \cdots \quad (3.4)$$

The use of Maclaurin series expansion is preferred over the conventional exponential function because it saves a valuable amount of computational time. As can be seen from equation (3.1), the LED current is a function of internal temperature also. Thus for the sake of simplicity, ambient temperature of LED sample is taken to be 25 ˚C. Fig. 3.6 shows the equivalent circuit of LED used during the I-V characteristics analysis using the Maclaurin series expansion of the Shockley equation. The equation of the LED forward voltage $V_F$ can be expressed in equation (3.5)

$$V_F = V_{LED} - r_s.I_{LED} \quad (3.5)$$

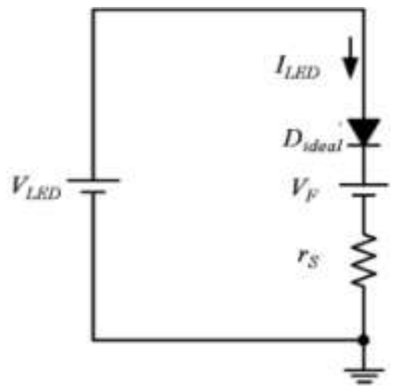



Figure 3.6 Equivalent circuit for Maclaurin series based model.

By using equation (3.2) (3.3) and (3.5), the expression for LED forward voltage can be written as follows:

$$V_{LED} = \eta . V_T \ln\left(\frac{I_{LED}}{I_{SAT}}\right) + r_s . I_{LED} \qquad (3.6)$$

## 3.3 Implementation

In this work, the I-V characteristics of the given LED sample have been modeled and implemented using two different modeling techniques, namely:

1 Piecewise linear approximation (PLA).

2 Maclaurin series expansion based modeling.

To implement the modeling techniques, certain parameters need to be calculated. The calculation method and the implementation of the techniques for both the methods are discussed below.

### 3.3.1 Calculation of parameters for PLA model

The voltage drop for each diode (considering it to be silicon based) in the branch has been taken to be the standard 0.7 V, when forward biased. Then, a few key points have been taken from the datasheet such that the voltage co-ordinate matches with the knee voltage drop of the branches. The internal equivalent resistance for each voltage range is then calculated using the ohm's law equation given as follows:

$$R_{eq} = V_{LED}/I_{LED} \qquad (3.7)$$

TABLE II
PARAMETERS FOR PIECEWISE MODEL

| **S no.** | **Voltage Range (volts)** | **$V_f$(volts)** | **$r_s$(kΩ)** | **Equivalent resistance $R_{eq}$(kΩ)** |
|---|---|---|---|---|
| - | 0-0.7 | - | - | Infinity |
| 1 | 0.7-1.4 | 0.7 | 3.5 | 3.5 |
| 2 | 1.4-2.0 | 1.4 | 1.4 | 1 |
| 3 | 2.0-2.8 | 2.0 | 4 | 0.8 |
| 4 | 2.8-3.1 | 2.8 | 0.0784 | 0.0714 |
| 5 | Above 3.1 | 3.1 | 0.0216 | 0.0166 |

Using parameters listed in Table II, the I-V characteristics using PLA technique have been plotted as can be seen from Fig.3.7.

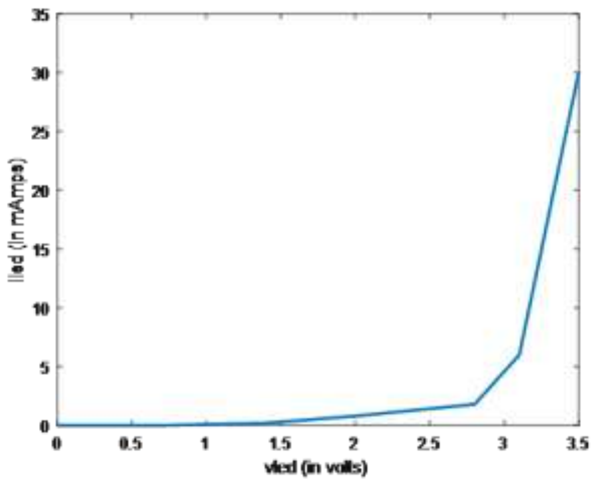


Figure 3.7 I-V characteristics using PLA technique.

### 3.3.2 Calculation of parameters for Maclaurin series expansion based model

In the datasheet of LED LNL-190UW-4H, the parameters $\eta$, $I_{Sat}$, and $r_s$ are not mentioned explicitly. However, in order to accurately determine the *I-V* characteristic curve of LEDs, the values of the unknown parameters $\eta$, $I_{Sat}$, and $r_s$ are required as can be seen in equation 3.6. These can be obtained by following the steps mentioned below.

STEPS TO CALCULATE $r_S$, $\eta$ AND $I_{SAT}$

*1.) Locating The Maximum Operating Point* ($V_M$, $I_M$)*:* Fig. 3.8 shows the section of the curve plotted using the datasheet where the maximum operating point can be easily located. Above this point, the loading of LED should not be done so as to avoid overheating problems.

*2.) Locating The Knee Point* ($V_K$, $I_K$)*:* Fig. 3.8 also mentions the information about the knee point. This is the point on the characteristics where the diode starts to conduct and after this point the curve almost becomes linear.

*3.) Calculating The Unknown parameters:* In Fig. 3.8, the slope of the curve between the rated operating point ($V_R$, $I_R$) and the maximum operating point ($V_M$, $I_M$) can be easily calculated due to the linear nature of the curve in this region. Since the value of internal resistance here will be the inverse of the magnitude of the slope of the curve, therefore, the equation to calculate $r_s$ can be obtained as shown in equation 3.8.

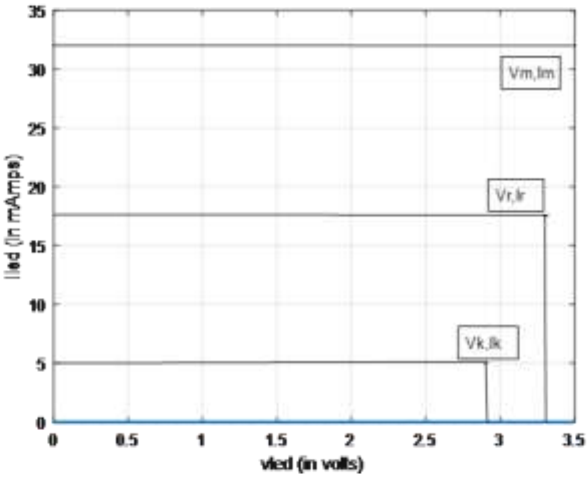


Figure 3.8. Section of LED *I-V* curve from datasheet locating key points.

$$r_s = \frac{V_M - V_K}{I_M - I_K} \qquad (3.8)$$

Following the above mentioned steps and applying equation (3.8) to equation (3.6), ɳ and $I_{Sat}$ can be calculated as per the following derived equations

$$ɳ = \frac{V_R - V_M - r_S.(I_R - I_M)}{V_T.\ln(\frac{I_R}{I_M})} \qquad (3.9)$$

$$I_{SAT} = \frac{I_K}{e^{(\frac{V_K - r_S.I_K}{ɳV_T})}} \qquad (3.10)$$

TABLE III
PARAMETERS FOR MACLAURIN MODEL

| Key point | Co ordinate value |
|---|---|
| $(V_M,I_M)$ | (3.5,32.5) |
| $(V_R,I_R)$ | (3.3,17.5) |
| $(V_K,I_K)$ | (2.9,5) |

Now, having calculated the essential parameters required the Maclaurin series expansion method can be applied to the Shockley equation as per the following expression:

$$I_{LED} = I_{SAT}\sum_{j=0}^{\infty} \frac{(\frac{V_{LED} - r_S \cdot I_{LED}}{\eta V_T})^{\wedge}j}{j!} \qquad (3.11)$$

Using the calculated parameters, the I-V characteristics using Maclaurin series expansion based modeling technique have been plotted as can be seen from Fig. 3.9.

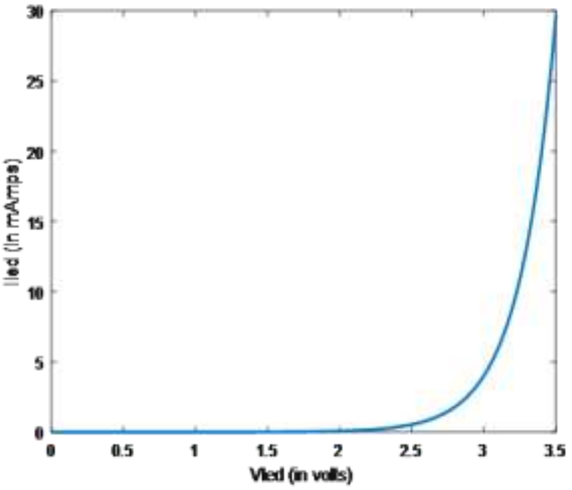



Figure 3.9 I-V characteristics using Maclaurin series expansion based modeling technique.

## 3.4 Conclusion

In this chapter, two methods have been employed to model the I-V characteristics of a LED sample. The PLA technique is the reprise version of the Piecewise linear approximation technique that has been proposed in [9]. It has been observed that the proposed PLA technique is more simplified as compared to Piecewise linear approximation technique. The second method namely, Maclaurin series expansion also has the advantage of saving processor time. The characteristics shown above have been plotted by rigorous coding done in MATLAB software. The results started to converge with the original datasheet plot after merely eight iterations. Moreover, the PLA technique has the disadvantage that to achieve a better accuracy, it has to rely more on the datasheet which is not desirable. The Maclaurin series method, on the other hand, relies only on three datasheet points to get the whole characteristics plotted. The Maclaurin series expansion based model can be used to predict the current flowing through the LED at a particular voltage without actually applying voltage to it. The above work can be extended to model the larger arrays of LED connected in series and parallel and design its power ratings. It can further be used to develop the small signal model of LED which helps in determining the dynamic internal resistance of the LED. It can be of immense help in designing the wireless LED lighting system or designing the LED panels for artificial horticulture which are the two main future prospects of the above carried out work.

# CHAPTER 4

# ILLUMINATION CONTROL USING LED LIGHTING SYSTEM

## 4.1 Introduction

One of the most important properties of LED is that the intensity of light emitted by it can be controlled. This control method is generally known as dimming of LED. There are various methods of dimming [1]-[3]. The LED lighting sources require a DC power supply to operate. Since at household levels AC supply is generally available as compared to the DC supply, therefore to facilitate the normal operation of LED, an AC-DC converter (a rectifier) is needed. As the rectified output has ripples, dc filters are required. Further, a DC-DC converter is required for further conditioning of the voltage. A DC-DC Converter is a switching device that is used to step-up or step-down the input in DC source voltage depends on its type. The DC-DC converter can change the voltage level by temporarily storing the input energy and then releasing the energy to the output at a different voltage. A buck converter is chosen for this type converter because it can step down voltage due to small voltage demand of Light Emitting diode (LED) load. The analysis is conducted in Continues-Current Mode (CCM). However, the LED needs a constant voltage due to temperature and variation of input because the small changes of voltage will cause large changes of current. Hence, the buck converter needs to operate in closed-loop condition to stabilize the power stage system when load disturbance occurs. This feedback system is important to improve the LED's intensity without inflicting any damage to them that can be caused due to over-current. This closed loop operation of the buck converter will lead to the efficient and reliable operation of the LED lights.

During the early 90s, the direct current to direct current power electronic converters were used to be controlled efficiently using analog integrated circuit (IC) technology and linear system design technologies. But these analog integrated circuit or IC technologies have a few drawbacks such as monitoring of a lesser number of signals for the sake of cost cutting. This leads to erroneous results sometimes. These at times also require auxiliary active and passive power electronic devices such as a power amplifier as an interface for the power electronics switches. For the last decade, digital control of power electronics switches has become prominent and has been actively replacing the analog control to a great extent. The digital controllers promote the benefits such as improved performances, a reduction in hardware price, etc to name a few. One of the major difficulties that one faces in power electronic circuit design is the construction of main controllers for the switch mode converters. The voltage regulation is generally obtained by the use of pulse width modulation (PWM) signalfor the gating of the power electronic switches. The PWM signal used here is generally produced at a fixed frequency. Regulation using variable frequency and variable duty cycle ratios are also being used these days.

LED lighting driver technology is one of the major examples of its application and development. Generally, the voltage ratings of the LED lights are much lower than the supply voltage, which is 220 volts. Moreover, the LED lights require a dc voltage and the supply voltage is ac in nature. Therefore, to encounter these two major issues, LED driver come to the rescue. The ac voltage supplied by the mains is lowered down by a step down transformer and then converted into a compatible dc voltage using an LED driver. The LED driver not only converts the ac voltage to dc using a rectifier stage but also performs a dc to dc conversion which helps in conditioning of the dc voltage as per the requirement of the LED lights.

The main objective of this work is to design an intelligent LED lighting system. Since the simulation is done using SIMULINK which lacks the LED block, the LED is modeled as a diode and complete modeling is also described.

This objective is further accomplished by:-

- Modeling of LED IV characteristics using piecewise linear approximation technique.
- Designing an LED driver circuit to convert the input AC voltage to a low valued DC voltage at output level to solve the problem of constant voltage regulation and overpower loss of the linear voltage regulator.
- Designing a control circuit which produces PWM generated by PI controller.

• Achieving the closed loop control over the switching of the MOSFET of buck converter by involving LED current sensing and intensity conversion technique.

### 4.2 Modeling and Design of Automated Controlled LED Lighting System

This section includes the complete modeling of LED lighting system:- modeling of LED using piecewise linear approximation technique, designing of the LED driver circuit using buck converter in closed loop scheme, formula for conversion of LED current into illumination levels.

#### 4.2.1 Block diagram of the model

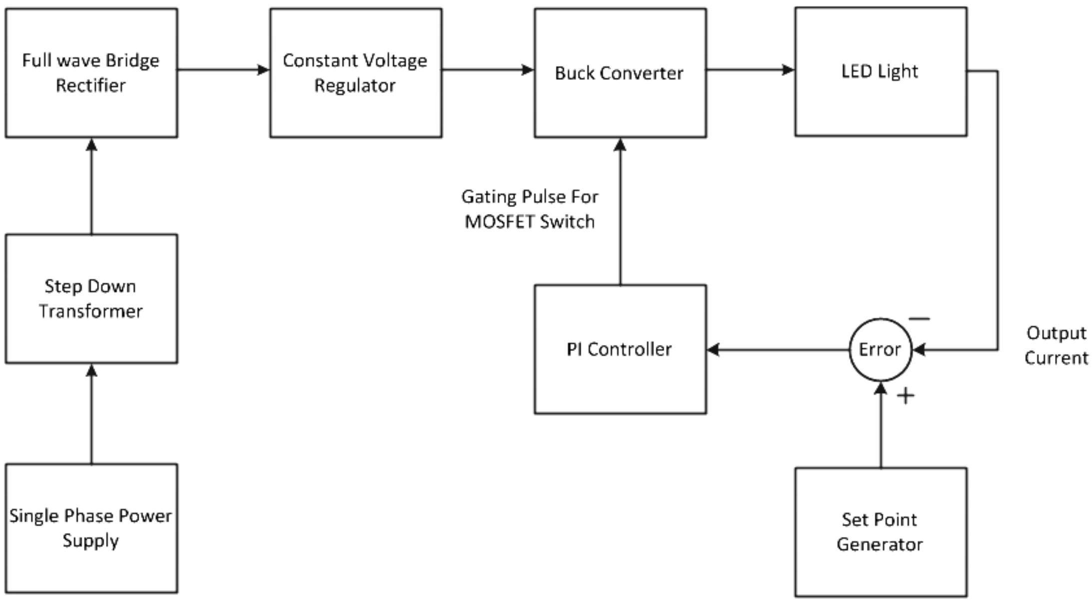



Figure 4.1 Block Diagram of the model

Figure 4.1 depicts the complete block diagram of the model that has been developed as a part of this work. The 230V ac supply has been stepped down to 18 volts rms and rectified using full bridge diode rectifier with further being stabilized using the parallel capacitor. This stabilized voltage acts as source for the buck converter feeding the LED load. The light through the LED (which is modeled using PLA approximation as discussed in previous chapter)is sensed by a sensor which is modeled here as a function of current through LED. This sensed value is fed to the PI controller which generates the gating signal for the buck converter MOSFET. This process controls the intensity of light to the reference value. Appendix A4 presents the simulink diagram of the LED lighting system.

### 4.2.2 LED driver design

LED driver is a power electronic device that helps in the smooth operation of the LED lights. The basic operation of a driver can range from providing a constant voltage to providing a constant current to the LED lights as per the demand of the situation. LEDs require a dc voltage to operate and the supply voltage available is generally alternating in nature. Therefore, the task of conversion of ac to dc is also at times accomplished by the LED driver. This stage is also known as the rectification stage. The design of the LED driver is a very intriguing task. This process involves knowing of the ratings of the LED lights that are to be driven. Once the ratings are known, it is to be decided whether the application requires constant voltage or constant current.

Constant voltage driving scheme is preferred when the variation in current is permissible. For example, the applications of LED lights where dimming is to be used. Constant current scheme is preferred when the variation of voltage is permissible. This scheme is generally implemented when long strings of LEDs are to be lit up connected in series and parallel combination.

- Simple Linear LED Driver Circuit
- Linear Regulator as LED Driver
- Switch Mode LED Driver Circuit

In simple linear LED driver circuit, the LEDs are driven directly at ac supply level. Here, the voltage is just brought down to a low level ac voltage with no due care taken to convert the ac voltage into the desired dc voltage levels. The reverse bias voltage of the LEDs used here is a bit higher than the negative cycle of the supply voltage and as such, the LEDs do not get damaged and a smooth operation 9s carried out. In linear regulator based LED driver system, the ac supply voltage is not only brought down to a low ac level voltage but also converted from ac to dc level. This dc voltage is linearly transferred to the LED lighting load. The only disadvantage of this driver circuit is its power loss as heat dissipation. As the LED light load increases the power loss as heat through the driver circuit increases. Moreover, the linear nature of this driver also tend to become non linear at higher loads. Switch mode LED drivers are power semiconductor electronic devices based drivers where these semiconductor devices are used as switches in the power electronic circuits. These are also known as dc to dc converters. These drivers can bring the input side dc level voltage to a lower dc level voltage, also known as buck converter based switch mode drivers, or these can bring the input voltage level to a higher output voltage level, also known as boost converter based switch mode drivers. There are other variants available as well like the buck-boost, cuk, SEPIC driver, etc to name a few. Switch mode drivers have an advantage over the linear regulator based driver that they do not dissipate much heat neither during operation nor during the off operation. But these switch mode drivers are costlier than the linear regulator based LED drivers. In this work, buck converter has been used as led driver due to its several advantages over linear driving circuit.

A buck converter is a power electronic device that converts the input side dc voltage to a lower valued output dc voltage by utilizing the principle of pulse width modulation (PWM). The output voltage is always lower than the input dc voltage. The relation between the input and output voltage shall be derived in the work done below. From the figure 4.2 as shown below, it can be seen that a MOSFET is connected in series with the supply and there is an inductor, a capacitor, a freewheeling diode and the load which altogether comprise of the buck converter. The inductor stores the energy in the form of magnetic field during the ON cycle of the buck converter and the capacitor is connected to store the energy in the form electric field and maintain a constant voltage at the output stage. During the OFF cycle when the MOSFET is in cutoff region of operation, the inductor discharges and the current continuity is maintained due to the presence of freewheeling diode. The duty cycle of the buck converter is defined as the ratio of the on time to the total time period of one complete ON-OFF cycle. The relation between input and output voltage is determined duty cycle. The duty cycle of an ideal buck converter is given by equation (4.1):

$$\text{Duty Cycle} = Vout / Vin \qquad (4.1)$$

Where,

$V_{in}$ is the voltage at the input of the buck converter

$V_{out}$ is the voltage at the load side of the buck converter.

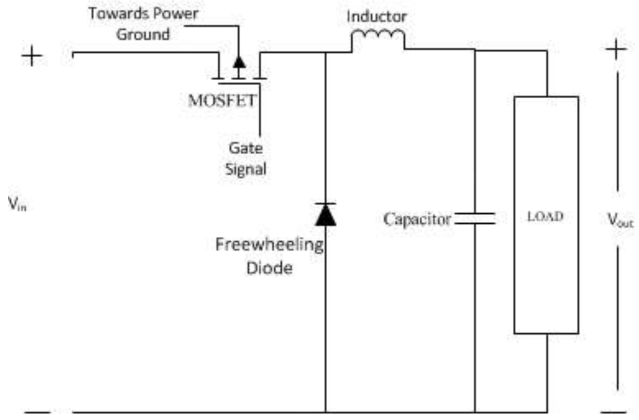



Figure 4.2 Basic Buck converter scheme

The minimum values of inductor and capacitor which allow the buck converter to operate successfully in the continuous conduction mode are known as critical values. These are given by equation (4.2) and (4.3):

$$Lc=\frac{(Vout\ x\ (Vin - Vout\ ))}{((\Delta Il\ x\ fs\ x\ Vin\ ))} \tag{4.2}$$

$$Cc=\frac{(1-\alpha)}{((16f*f\ Lc))} \tag{4.3}$$

TABLE IV SOME IMPORTANT PARAMETERS

| | |
|---|---|
| Input Voltage ($V_{in)}$) | 12 volts |
| Output Voltage ($V_{out)}$) | 2.4-12 volts |
| Switching frequency of the converter ($f_s$) | 15 kHz |
| Estimated inductor ripple current ($\Delta I_L$) | 0.2 amp |
| Critical value of Inductance ($L_c$) | 500 µH |
| Criticalvalue of Capacitance ($C_c$) | 55 µC |
| Duty Cycle (α) | 25-95 % |

### 4.2.3 Control circuit design

The control scheme used in this simulation has a PI controller used with saturation limits. The current passing through the LED is sensed and passed as a feedback signal to the controller. The set point or the reference point is the desired illumination level that is to be achieved as shown in the figure 4.3 below.

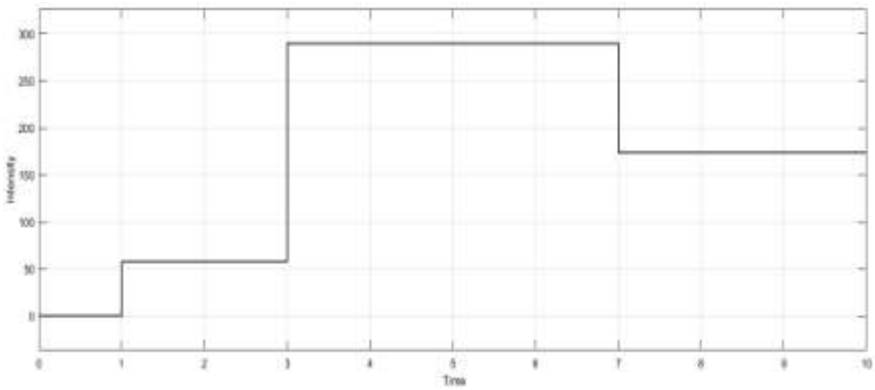



Figure 4.3 Desired Illumination level to be achieved

There is an illumination due to external sources as well as can be seen from figure 4.4. This signal is subtracted from the set point to tell the controller about the illumination that the LED has to achieve. The illumination level is brought down to current level by suitable conversion so that easy processing of signals can be achieved. The error signal is generated by finding the difference between the new set point signal and the LED current. This error signal is then given to the PI controller with a saturator for the generation of variable frequency-variable duty cycle PWM signal. This signal is then fed back to the MOSFET switch of the buck converter which eventually controls the LED current to desired value. The process continues till the error becomes zero.

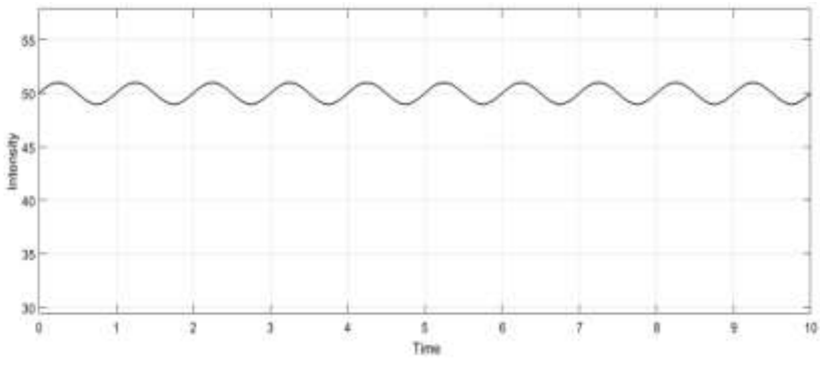



Figure 4.4 Illumination level of room

Relation between LED current and LED intensity

The LED flux is proportional to the square of the current passing through the LED at any instant of time. The luminous flux passing through a unit area is called the luminous intensity. Thus, if the area upon which illumination has to be calculated is fixed, then the intensity also follows a square relationship with the current passing through the LED as can be seen in figure 4.5. Through calculations, it has been found that the LED model used has the following intensity-current relationship as given by equation (4).

$$\text{LED intensity} = 411.764 \times \text{ILED} - 147.05 \times (\text{ILED})^2 \qquad (4.4)$$

Where,

LED intensity is in lux

ILED is the current passing through the LED in amperes.

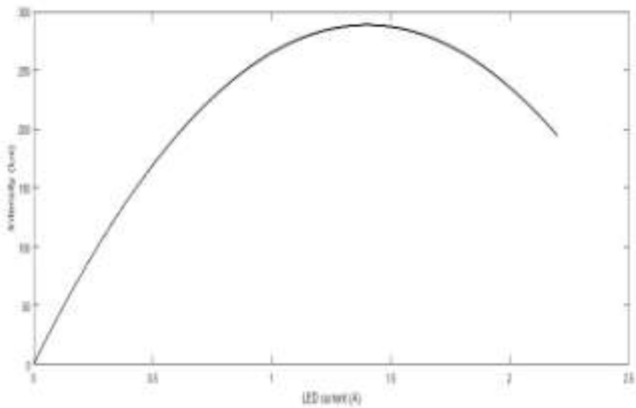


Figure 4.5 LED intensity vs LED current

### 4.3 Hardware Implementation

The designing of the circuit has always remained at the core of the making of any project. The approach to designing is from output level to the input level. Therefore, the output ratings, which are for LED light in this case, are first chosen and then the ratings of each and every component of the circuit are determined.

From figure 4.6, it can be seen that the input ac supply is stepped down from 230 volts to 18 volts (rms) and rectified and filtered to constant dc voltage of 12 volts. This dc voltage acts as input to the buck converter (used as led driver here) whose output is fed to the LED light load. The light from the LED and other external sources are sensed by a lux sensor (BH1750) which further sends this data to the microcontroller (arduino uno) for processing.

Using appropriate coding, a controlled pwm is generated which is fed to the gate driving IC. The signal from this IC is then fed back to the gate of the MOSFET switch of the buck converter. In the further section, the component selection procedure has been described.

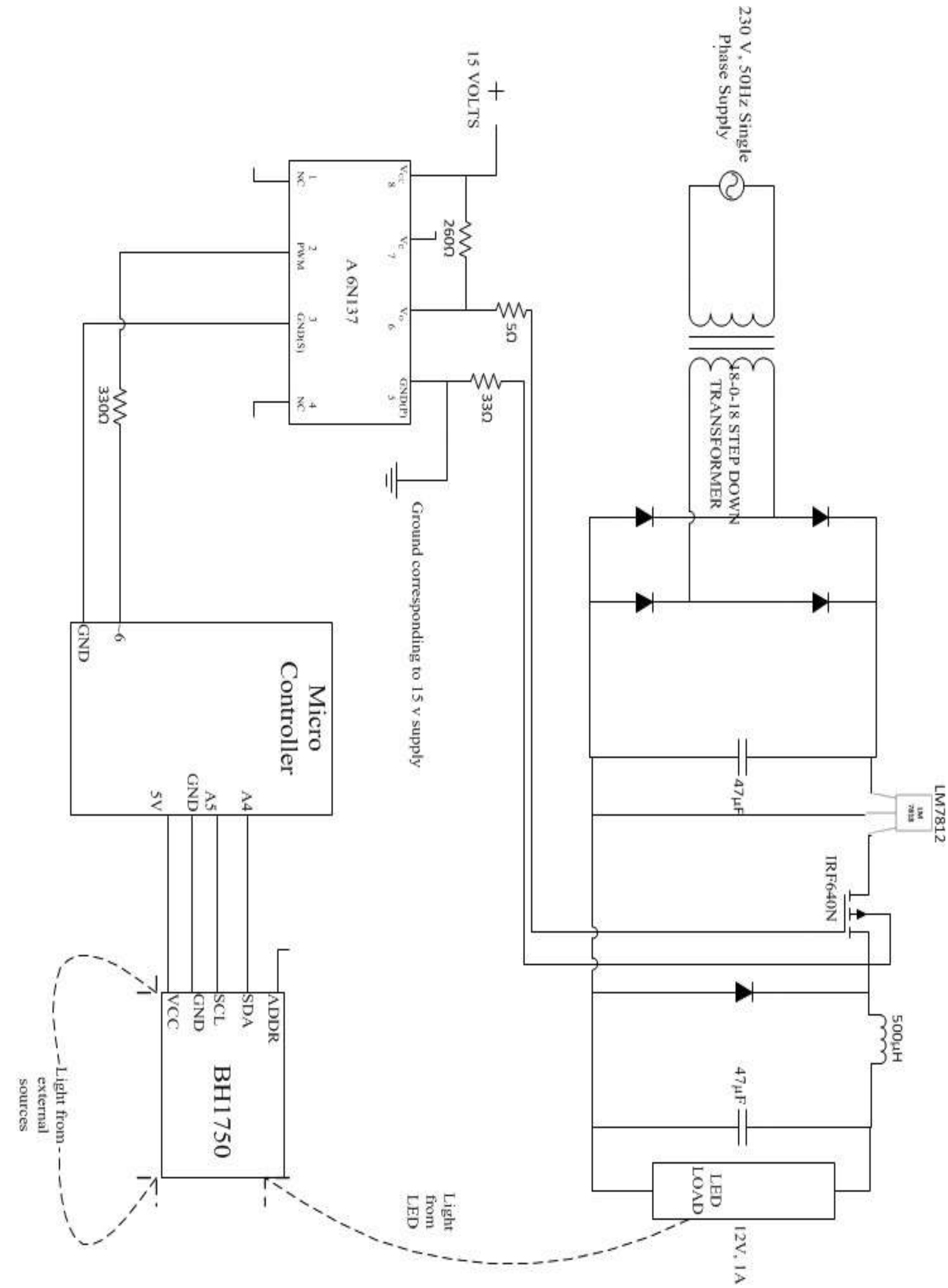



Figure 4.6 Complete circuit diagram of the proposed work

Using appropriate coding, a controlled pwm is generated which is fed to the gate driving IC. The signal from this IC is then fed back to the gate of the MOSFET switch of the buck converter. In the further section, the component selection procedure has been described.

### 4.3.1 AC to DC conversion circuit

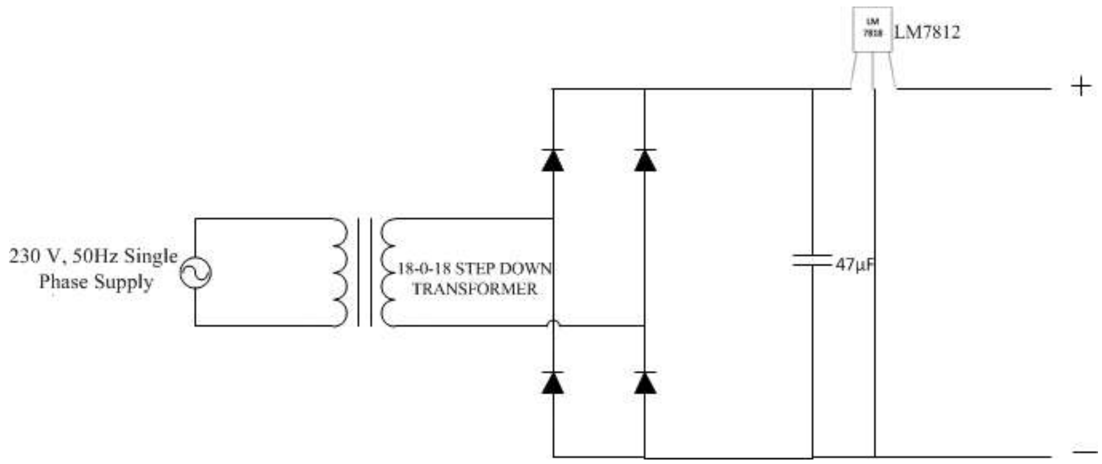



Figure 4.7 Rectifier circuit with dc voltage regulation

The transformers are used for converting the ac primary side voltage into lower or higher ac secondary side voltage depending upon their construction. The transformer with secondary side voltage less than the primary side voltage is called as a step-down transformer, and the transformer with secondary side voltage greater than the primary side voltage is called as step-up transformer. Here, a 230V AC is converted into 18V AC using a step-down transformer. The 18V output of the step-down transformer is an RMS value and its peak value is given by the product of square root of two with RMS value, which is approximately 25.455.

25.45 DC voltage can be stepped down to 18V DC voltage using a DC step-down converter called as voltage regulator IC LM7818. The first two digits '78' of IC LM7818 voltage regulator represent positive series voltage regulators and the last two digits '18' represents the output voltage of the voltage regulator.

### 4.3.2 LED driver circuit design

The LED driver scheme used here is based on power electronic step down semiconductor. The main challenge while designing of the hardware of the LED driver is the inductor design. The inductor design is a complicated process that involves the determination of the core type, size, material used, etc. There are a variety of core types available in the market such as the rectangular type or toroidal type. Each type has its own merits and demerits. An EI type core has been chosen for the purpose of this work. Once the core is chosen, then the selection of the gauge of the wire has to be made. The wire used in this work is a copper wire of standard wire gauge 24 (SWG 24). To determine the value of required inductance, the number of turns around the core is very important. The following equation (4.5), gives a very good measure of the value of the inductance required for the work:-

$$L=(Vout \times (Vin-Vout))/(\Delta Il \times fs \times Vin) \quad (4.5)$$

Vin = Input voltage

Vout = Output voltage

fs = Switching frequency of the converter

ΔIL = estimated inductor ripple current, see the following:

ΔIL = (0.2 to 0.4) x Iout (max)

The inductor ripple current cannot be calculated with above Equation because the value of inductance is not known. A good estimation for the inductor ripple current is 20% to 40% of the output current.

By using above formula we get inductor value as 500 micro henry.

Calculate Area Product

$$E = ½ LFm \quad (4.6)$$

$$Ap = Aw\ AC = 2E/KwkcJBm \quad (4.7)$$

where Bm = 0.2 T for ferrite, Bm = IT for CRGO, J = 3 A/mm2

and Kw = 0.6

By referring the datasheet, we get EE/25/13/7 CORE.

TABLE V DATA FOR INDUCTOR DESIGN

| Material | G (mm) | $A_L$ value approx. (nH) | $\mu_e$ | Ordering code **=27 (N27) -- =87 (N87) |
|---|---|---|---|---|
| N27 | 0.10 ± 0.02 | 489 | 425 | B66317G0100X1** |
| N87 | 0.16 ± 0.02 | 347 | 302 | B66317G0160X1** |
| - | 0.25 ± 0.02 | 250 | 218 | B66317G0250X1** |
| - | 0.50 ± 0.05 | 151 | 131 | B66317G500X1** |
| - | 1.00 ± 0.05 | 91 | 79 | B66317G1000X1** |

So we get 47 turns with an air gap of .25mm. and the gauge suitable for the wire is SWG 24.

Once the inductor is fully designed, the value of capacitor has to be determined. The best practice is to use low-ESR capacitors to minimize the ripple on the output voltage. Ceramic capacitors are a good choice if the dielectric material is X5R or better. If the converter has external compensation, any capacitor value above the recommended minimum in the data sheet can be used, but the compensation has to be adjusted for the used output capacitance.

With internally compensated converters, the recommended inductor and capacitor values must be used, or the recommendations in the data sheet for adjusting the output capacitors to the application in the data sheet must be followed for the ratio of L × C.

With external compensation, the following equations can be used to adjust the output capacitor values for a desired output voltage ripple:

$$C_{out}(min)=(\Delta Il)/(8 \times fs \times \Delta Vout) \quad (4.8)$$

$C_{out}(min)$ = minimum output capacitance

ΔIL = estimated inductor ripple current

fs = Switching frequency of the converter

$\Delta V_{out}$= Output voltage ripple

By putting all the values $C_{out}$ came out as 55 µF but the nearest value that is commercially available is 47 µF. So, capacitor of 47 µF value has been used in this work.

### 4.3.3 Gate driver (control circuit)

Gate driver or control circuit lies at the centre of the working of the switch mode LED driver. Gate driving, as the name suggests, helps in the control of the gate of the MOSFET or BJT switch that is used in the switch mode regulator or driver. When the gate of the switch is given a high voltage signal the switch turns on and when the gate of the switch is given a low voltage signal then the switch turns off. The ON-OFF cycles should be changed at a very fast rate and this is achieved using the pulse width modulated signal. The gate driver circuit forms the feedback part of the closed control loop. The chief functions of the gate driver are to receive the sensed input signal, compare the received signal with the preset signal, process the signal to produce a desired pwm voltage signal for the switching of the

MOSFET. For the comparison of sensed signal with the preset signal and the processing of the error signal a microcontroller of high processing capability is required. Hence an Atmega 328 processor on the arduino uno board has been taken to serve the purpose. The pwm signal generated by the uno microcontroller has a frequency of 15 kHz and the amplitude of this pwm signal is 5 volts. The MOSFET switch selected for this work (IRFZ644N) has a rating for its gate signal to be 15 volts. This creates a little problem as the pwm signal generated by arduino has the voltage level of 5 volts which is insufficient to drive this switch. To facilitate this and overcome the problem, a device called optocoupler has to be employed.

An optocoupler is a power electronic device that helps in solving two purposes. Firstly, it helps in isolating the low power signal circuit from the high power gating circuit. Secondly, it helps in stepping up the low voltage pwm signal from the microcontroller to a high voltage gate signal which facilitates the proper switching of the MOSFET switch. As the name of the optocoupler suggests, it couples the two different power level with the isolation being handled by a pair of photo diode and photosensitive BJT. This opto-isolation also helps in protecting the microcontroller from a burnout in the cases of overloading at output side.

As can be seen from figure 4.8 which is the depiction of the internal circuit of IC A6N137, the input from the microcontroller is given to pin number two. Pin number three is connected to the ground reference of the microcontroller low power level. Pin number one and four are not connected. An LED is connected between the terminals 2 (anode) and 3 (cathode). Pin number 8 is connected to the $V_{cc}$ terminal, pin number 6 is connected to the emitter of the photo BJT and pin number 5 is connected to the power ground level. When the pwm signal from microcontroller is high the LED lights up and emits infra red light onto the base of the photo BJT. The BJT switches on and is directly connected to the ground and hence a low level signal is passed on to the MOSFET gate terminal. When the pwm signal from microcontroller is low the LED turns off and the photo BJT is also turned off. The MOSFET gate is then directly connected to the Vcc through a resistor. This shows that there is an inverse relation between the pwm signal from microcontroller and the pwm signal output from the IC A6N137.

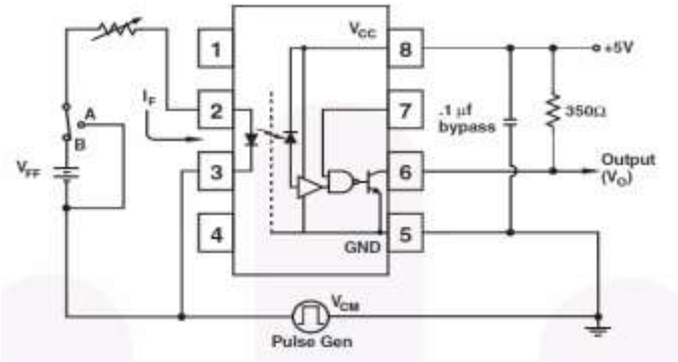



Figure 4.8 Internal circuit of IC A 6N137

A PWM signal is a periodic signal whose average value over the time period gives the output values of the signal. The duty cycle of the pwm signal is defined as the ratio of the on time to the total time period of the pwm wave. The following figure 4.9 shows a comparison of different duty cycles and their corresponding voltage levels.

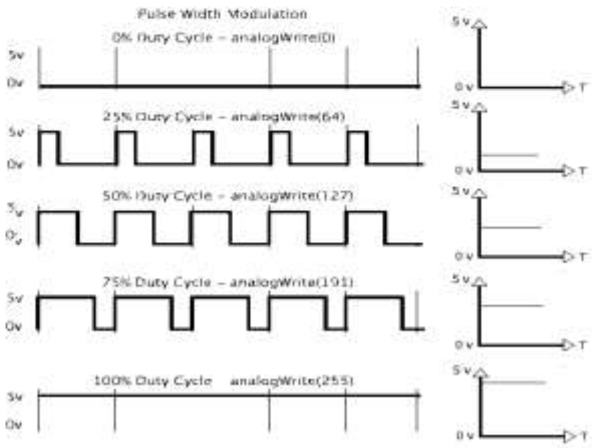



Figure 4.9 Generation of PWM using Arduino UNO

From the above figure, it is clear that when the duty cycle is increased, the output voltage (or power delivered) is also increased. For a duty cycle of 100%, the voltage available from the microcontroller is 5V and for a duty cycle of 50 %, the voltage available is 2.5V.

### 4.3.4 Sensing Circuit

The BH1750 Ambient Light Sensor Module is based on the digital Ambient Light Sensor IC BH1750FVI developed by ROHM Semiconductor. It is a digital IC with built-in 16-bit illuminance to digital converter. For communication with external devices like Microcontrollers, the BH1750 Ambient Light Sensor IC uses I2C Bus Interface.

Some features of this BH1750 Ambient Light Sensor are mentioned below.

- I2C Interface
- Wide range – 1 – 65535 lx
- Built-in A to D Converter where Illuminance is the Analog Input
- Small influence of IR Radiation
- Very minimum external components
- Two devices can be connected on the I2C bus

The BH1750 Ambient Light Sensor Module has 5 pins on it. The following figure 4.10 shows the pins of this sensor.

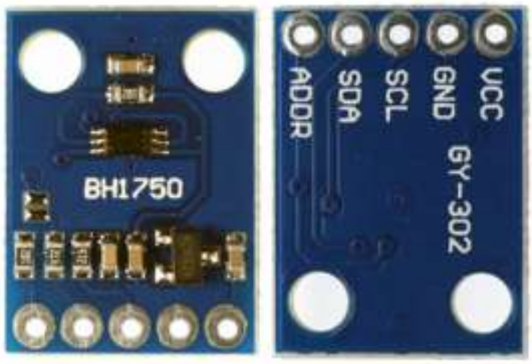



Figure 4.10 Pin configuration of BH1750

By interfacing BH1750 Ambient Light Sensor with Arduino, the ambient light data can be measured and used in any application like turning on a street light or night lamp. Since the BH1750 Ambient Light Sensor interfaces over I2C bus, the I2C pins of the Arduino have to be used. In case of Arduino UNO, Analog Pins A4 and A5 are the I2C Bus pins where A4 is SDA and A5 is SCL.

### 4.3.5 Software (Arduino IDE)

Connecting hardware according to the circuit diagram doesn't work really. Programming of the components has to be done so as to work according to the algorithm designed in order to make the project work properly. Following is the description of software used. The Arduino IDE is a cross-platform application written in Java, and is derived from the IDE for the Processing programming language and the Wiring project. It is designed to introduce programming to artists and other newcomers unfamiliar with software development. The code written for the implementation of the control algorithm for this project has been included in the appendix A3a. The complete list of components used in the construction of the hardware with their ratings has been listed in appendix A3b.

## 4.4 Conclusion

In this Chapter, the core application of LED lighting systems has been discussed. The various stages of building up the simulation of the circuit have also been discussed. After performing the simulation successfully, the hardware development and the various important ICs required have been discussed in detail. The results and discussions have been taken up in chapter 6 of this work.

# CHAPTER 5

# HORTICULTURE USING RGB LEDs

## 5.1 Introduction

One of the non-conventional uses of light emitting diodes is their application in horticulture. Horticulture is the branch of science which deals with the growth of crops and plants under controlled environmental conditions where these plants are kept and observed under a closed space with artificial light used for photosynthesis.

During the late 90s, the major sources of lights for horticulture were the incandescent lights. These lights provided for a wide range on the absorption spectrum of the photosynthetic pigments such as chlorophyll and carotenoids but these incandescent lights had two disadvantages. Firstly, they emitted a lot of heat and secondly the light emitted was scattered all over the absorption spectrum which resulted in loss of efficiency.

During the early 2000s, the incandescent lights were replaced by compact fluorescent lights. The only advantage it provided over the incandescent light had been that it produced less heat. The problem of scattered energy was still a problem until in 2013 when the deep blue LED was invented.

It has been found that the chlorophyll and carotenoids respond quite well to the lights of wavelength around 445nm and 660 nm. These two wavelengths correspond to the deep blue color and the hyper red color respectively. These two colors can be easily produced by LEDs that are fabricated using Indium Gallium Nitride (InGaN) and aluminium Indium Gallium Phosphide (AlInGaP) respectively. The advantages that deep Blue and hyper red LEDs have is that they don’t produce much heat and they emit light over a very narrow bandwidth of the absorption spectrum thereby optimizing the growth of the crop.

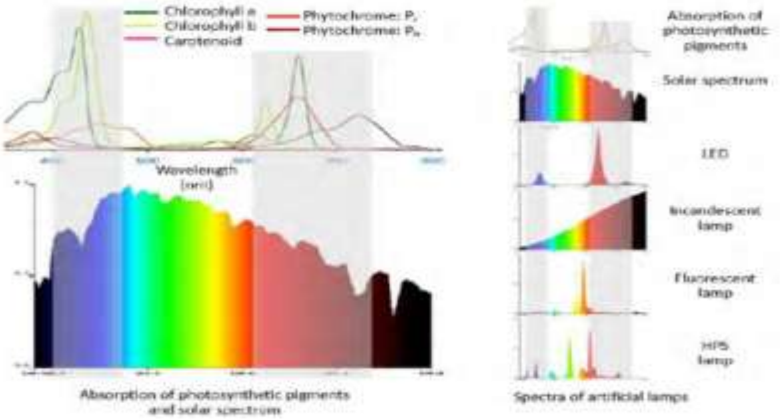



Figure 5.1 Absorption Spectrum of various photosynthetic pigments

Figure 5.1 shows the absorption spectrum of various photosynthetic pigments such as chlorophyll a, chlorophyll b and carotenoids. Alongside have been given the spectrums of light emitted by various sources such as sun, LED, incandescent lamp, fluorescent lamp, HPS lamp, etc. It can be easily seen that deep blue and hyper red LED lights provide the sharpest and the most tuned spectrums for the optimum crop growth.

## 5.2 Development of Simulink Model

As seen in the previous section, LED lights provide the best results for the optimum growth of plants and crops. In this work, a plant sample of Spirulina Platenesis has been taken up and an RGB LED based lighting system shall be designed in the upcoming sections. The RGB lights have been chosen over deep blue and hyper red due to the advantage of trace lights that RGB lights offer which help in fulfilling the micronutrient requirement of S. Platenesis. In the subsections to follow, a simulink model of the RGB LED lighting system shall be developed.

### 5.2.1 Calculation of parameters

S. Platenesis is the plant sample for which the RGB LED lighting system has to be designed. Firstly, it should be known that what the effective area of the crop that is to be monitored for growth is. In this work, around twelve square foot of plant area has been considered. As a thumb rule, 50 watts of light is required per square foot of plant area. Therefore, an LED lighting system of rating nearly 600 watts has to be designed.

The red green and blue LEDs are clustered together to form an RGB LED unit. These units are arranged in the form of an array to form the RGB LED lighting system. The datasheets for the hyper red, green and deep blue LEDs have provided the values of forward voltage, rated current drawn and the wavelength of light emitted. Using this data, the power rating of an RGB LED unit can be determined.

TABLE VI I-V DATA FOR RGB LIGHTS

| COLOR | FORWARD VOLTAGE (IN VOLTS) | WAVELENGTH (IN nm) |
|---|---|---|
| Hyper Red | 1.9-2.6 | 660 |
| Deep Blue | 3.1 | 445 |
| Green | 2.6-2.9 | 550 |

From the data given in Table VI and considering the forward current to be 700mA, it is easily found that the power rating of 1 RGB unit is about 6.02 watts.

Power rating for 1 Hyper red LED = 2.6 volts x 0.7 amps = 1.82 watts (5.1)

Power rating for 1 green LED = 2.9 volts x 0.7 amps = 2.03 watts (5.2)

Power rating for 1 Deep blue LED = 3.1 volts x 0.7 amps = 2.17 watts (5.3)

Therefore, Total power rating of 1 RGB LED unit can be given by adding the powers calculated in equations (1)-(3). That is,

Power rating for 1 RGB LED = (1.82 + 2.03 + 2.17) watts = **6.02 watts** (5.4)

As calculated earlier, the rating for the RGB LED lighting systems should be around 600 watts using the thumb rule [30]. Therefore, a hundred units of RGB LED units can just suffice the requirement. The RGB LED lighting system thus formed has a power rating of 602 watts.

The next problem that arises is the arrangement of the RGB units in the form of an array such that a majority of area is covered with not much complexity in the driving scheme. It has been found out that arranging the RGB units in a pattern of 50x2 that is, 50 rows and 2 columns, covers the crop area of 12 square feet very effectively.

The 50 Units in the row are connected in series and the two rows form the columns. These two rows are connected in parallel such that the total current drawn is 1.4 amperes.

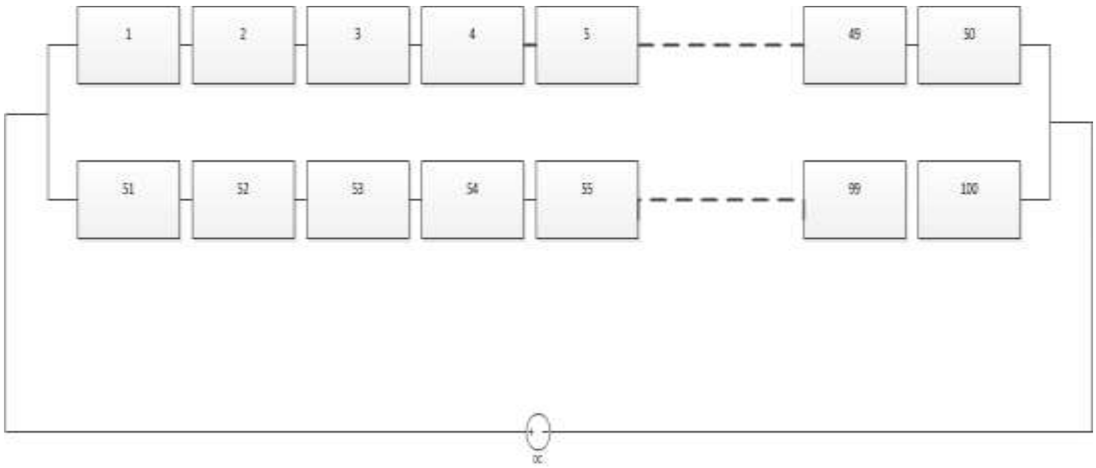



Figure 5.2 The connection scheme for each of the RGB LED array

From figure 5.2 it is clear that no two red green or blue LEDs are connected directly to one another. They are just clustered together physically with no electrical connection whatsoever. The voltage requirement for all three circuits can be calculated as below:-

Voltage required for red LED circuit = 2.6 volts x 50 units (in series) = 130 volts

Voltage required for green LED circuit = 2.9 volts x 50 units (in series) = 145 volts

Voltage required for blue LED circuit = 3.1 volts x 50 units (in series) = 155 volts

### 5.2.2 The RGB LED driver

LED driver is a power electronic device that helps in the smooth operation of the LED lights. The basic operation of a driver can range from providing a constant voltage to providing a constant current to the LED lights as per the demand of the situation. LEDs require a dc voltage to operate and the supply voltage available is generally alternating in nature. Therefore, the task of conversion of ac to dc is also at times accomplished by the LED driver. This stage is also known as the rectification stage. The design of the LED driver is a very intriguing task. This process involves knowing of the ratings of the LED lights that are to be driven. Once the ratings are known, it is to be decided whether the application requires constant voltage or constant current.

Constant voltage driving scheme is preferred when the variation in current is permissible. For example, the applications of LED lights where dimming is to be used. Constant current scheme is preferred when the variation of voltage is permissible. These scheme is generally implemented when long strings of LEDs are to be lit up connected in series and parallel combination.

There are driving scheme such as the DMX 512 control for RGB LEDs, but these are for driving these LEDs when used in a display with high resolution. In this work, such resolution is not required and the ratings of these lights as a unit is quite high(6.02 watts) which is humungous as compared to the consumption of one RGB LED dot in the display. Moreover, there is no need of controlling each and every dot individually here as all the lights in an array will light up with same intensity and will dim and brighten up together. The key to color change here shall be the control over individual color arrays as discussed in the scheme as shown below.

From figure 5.3 it is seen that the main source of power is a three phase ac supply. Since the RGB LED driver are based on buck converter scheme, therefore a stable dc supply would be required that can handle all the three drivers drawing current simultaneously. The connecting link here shall definitely be an AC to DC converter which is fulfilled by a three phase rectifier. To stabilize the output voltage of the rectifier, a capacitor bank is connected in parallel to the output. This stabilized output acts as the input to the three parallel RGB LED drivers as can be seen in figure 5.4

The red green and blue LEDs are clustered together to form an RGB LED unit. These units are arranged in the form of an array to form the RGB LED lighting system. The datasheets for the hyper red, green and deep blue LEDs have provided the values of forward voltage, rated current drawn and the wavelength of light emitted. Using this data, the power rating of an RGB LED unit can be determined.

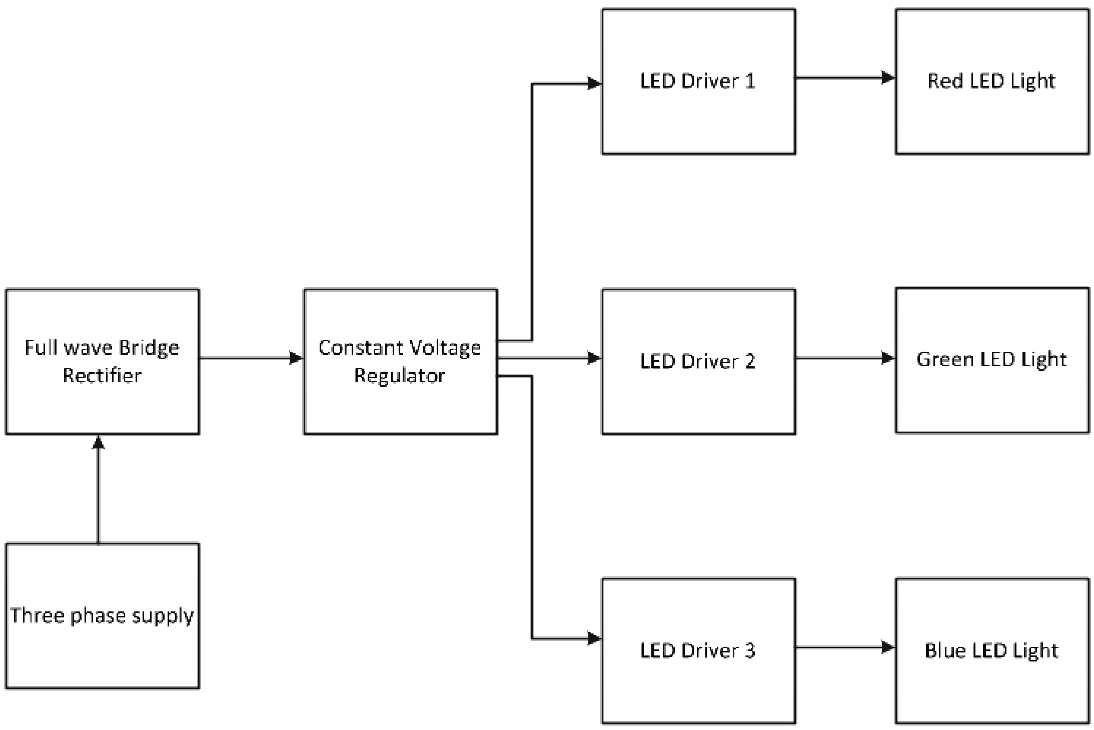



Figure 5.3 Block diagram of the complete setup

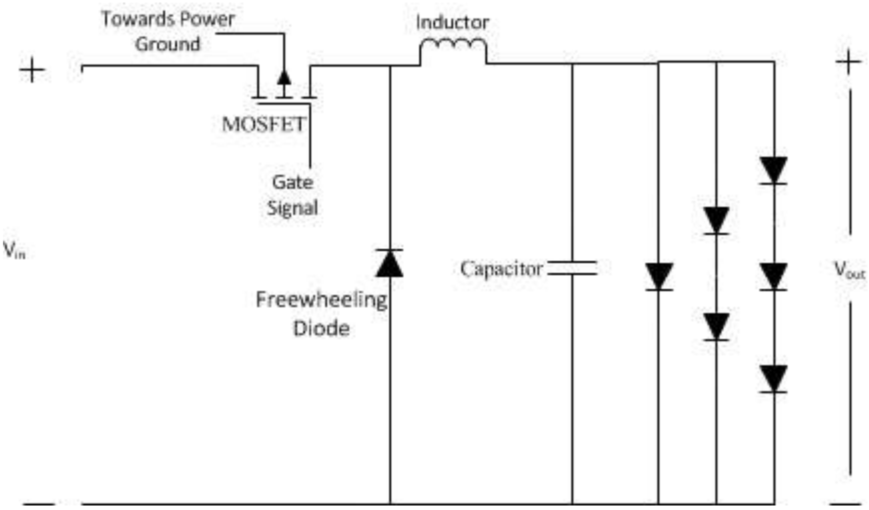



Figure 5.4 The driving scheme for individual color arrays

### 5.2.3 Color Mixing using Variable Dimming Scheme

During the childhood days, everyone is fascinated as to how different colors are formed. It is known that a wide spectrum of colors can be formed by mixing the three base colors. These base colors are red, green and blue. By mixing these colors in different proportions, one can obtain a color of choice. This color mixing property has further been extended in this work where a wide variety of colored lights are required as per figure 5.1. Research has shown that providing intermittent light to the plant S. Platenesis helps in achieving a better growth and performance than using continuous light. Thus, dimming the lights by switching on and off the lights at a very high frequency would result in intermittent lighting without the observation of visible flickering. This property helps in deriving of a driving scheme known as Variable dimming scheme (VDS). VDS means that individual color arrays are supplied with currents at different duty cycles of the buck converter MOSFET. The figure 5.5 shows the color produced on mixing of RGB colors in different proportions. The figure 5.6 shows which material is required for the emission of different colored lights. The range of wavelengths for which the color emitted remains applicable has also been mentioned for each of the VIBGYOR color.

| | <<<= Control 1 - Adjust Hue(Color) =>>> | <<<= Control 2 - Adjust FROM Colour to White =>>> | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | | 6 | | |
| | | R | G | B | R | G | B | R | G | B | R | G | B | R | G | B | R | G | B |
| Red | 23 | 255 | 0 | 0 | 255 | 100 | 100 | 255 | 150 | 150 | 255 | 200 | 200 | 255 | 230 | 230 | 255 | 255 | 255 |
| | 22 | 255 | 100 | 0 | 255 | 110 | 20 | 255 | 120 | 100 | 255 | 165 | 155 | 255 | 230 | 210 | 255 | 255 | 255 |
| Orange | 21 | 255 | 150 | 0 | 255 | 140 | 20 | 255 | 180 | 40 | 255 | 220 | 120 | 255 | 240 | 190 | 255 | 255 | 255 |
| | 20 | 255 | 200 | 0 | 255 | 210 | 20 | 255 | 230 | 100 | 255 | 240 | 150 | 255 | 255 | 200 | 255 | 255 | 255 |
| Yellow | 19 | 255 | 255 | 0 | 255 | 255 | 20 | 255 | 255 | 80 | 255 | 255 | 150 | 255 | 255 | 210 | 255 | 255 | 255 |
| | 18 | 200 | 255 | 0 | 200 | 255 | 20 | 220 | 255 | 80 | 230 | 255 | 150 | 235 | 255 | 180 | 255 | 255 | 255 |
| Chartreuse | 17 | 150 | 255 | 0 | 150 | 255 | 20 | 200 | 255 | 40 | 220 | 255 | 150 | 230 | 255 | 170 | 255 | 255 | 255 |
| | 16 | 100 | 255 | 0 | 110 | 255 | 20 | 150 | 255 | 40 | 200 | 255 | 150 | 230 | 255 | 160 | 255 | 255 | 255 |
| Green | 15 | 0 | 255 | 0 | 100 | 255 | 100 | 150 | 255 | 150 | 200 | 255 | 200 | 225 | 255 | 225 | 255 | 255 | 255 |
| | 14 | 0 | 255 | 100 | 20 | 255 | 150 | 100 | 255 | 180 | 180 | 255 | 210 | 235 | 255 | 220 | 255 | 255 | 255 |
| Aquamarine | 13 | 0 | 255 | 150 | 20 | 255 | 160 | 100 | 255 | 200 | 160 | 255 | 210 | 200 | 255 | 220 | 255 | 255 | 255 |
| | 12 | 0 | 255 | 200 | 20 | 255 | 200 | 40 | 255 | 220 | 140 | 255 | 230 | 200 | 255 | 255 | 255 | 255 | 255 |
| Cyan | 11 | 0 | 255 | 255 | 20 | 255 | 255 | 40 | 255 | 255 | 150 | 255 | 255 | 180 | 255 | 255 | 255 | 255 | 255 |
| | 10 | 0 | 200 | 255 | 20 | 210 | 255 | 40 | 230 | 255 | 60 | 240 | 255 | 170 | 255 | 255 | 255 | 255 | 255 |
| Azure | 9 | 0 | 150 | 255 | 20 | 180 | 255 | 40 | 200 | 255 | 60 | 230 | 255 | 150 | 255 | 255 | 255 | 255 | 255 |
| | 8 | 0 | 100 | 255 | 20 | 150 | 255 | 40 | 180 | 255 | 60 | 200 | 255 | 140 | 255 | 255 | 255 | 255 | 255 |
| Blue | 7 | [illegible] | [illegible] | [illegible] | 20 | 100 | 255 | 40 | 150 | 255 | 80 | 180 | 255 | 160 | 220 | 255 | 255 | 255 | 255 |
| | 6 | 100 | 0 | 255 | 120 | 20 | 255 | 140 | 100 | 255 | 150 | 150 | 255 | 200 | 200 | 255 | 255 | 255 | 255 |
| Violet | 5 | 150 | 0 | 255 | 150 | 50 | 255 | 180 | 100 | 255 | 220 | 140 | 255 | 230 | 180 | 255 | 255 | 255 | 255 |
| | 4 | 200 | 0 | 255 | 200 | 20 | 255 | 220 | 60 | 255 | 240 | 90 | 255 | 255 | 160 | 255 | 255 | 255 | 255 |
| Magenta | 3 | 255 | 0 | 255 | 255 | 60 | 255 | 255 | 100 | 240 | 255 | 150 | 250 | 255 | 180 | 255 | 255 | 255 | 255 |
| | 2 | 255 | 0 | 200 | 255 | 20 | 220 | 255 | 40 | 230 | 255 | 140 | 240 | 255 | 170 | 255 | 255 | 255 | 255 |
| Rose | 1 | 255 | 0 | 150 | 255 | 20 | 200 | 255 | 40 | 200 | 255 | 100 | 200 | 255 | 160 | 240 | 255 | 255 | 255 |
| | 0 | 255 | 0 | 100 | 255 | 20 | 120 | 255 | 60 | 140 | 255 | 100 | 160 | 255 | 140 | 180 | 255 | 255 | 255 |

Figure 5.5 The Color Mixing Chart

Research has shown that providing intermittent light to the plant S. Platensis helps in achieving a better growth and performance than using continuous light. Thus, dimming the lights by switching on and off the lights at a very high frequency would result in intermittent lighting without the observation of visible flickering.

| Color | Wavelength [nm] | Semiconductor material |
|---|---|---|
| Infrared | $\lambda > 760$ | Gallium arsenide (GaAs)<br>Aluminium gallium arsenide (AlGaAs) |
| Red | $610 < \lambda < 760$ | Aluminium gallium arsenide (AlGaAs)<br>Gallium arsenide phosphide (GaAsP)<br>Aluminium gallium indium phosphide (AlGaInP)<br>Gallium(III) phosphide (GaP) |
| Orange | $590 < \lambda < 610$ | Gallium arsenide phosphide (GaAsP)<br>Aluminium gallium indium phosphide (AlGaInP)<br>Gallium(III) phosphide (GaP) |
| Yellow | $570 < \lambda < 590$ | Gallium arsenide phosphide (GaAsP)<br>Aluminium gallium indium phosphide (AlGaInP)<br>Gallium(III) phosphide (GaP) |
| Green | $500 < \lambda < 570$ | **Traditional green:**<br>Gallium(III) phosphide (GaP)<br>Aluminium gallium indium phosphide (AlGaInP)<br>Aluminium gallium phosphide (AlGaP)<br>**Pure green:**<br>Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) |
| Blue | $450 < \lambda < 500$ | Zinc selenide (ZnSe)<br>Indium gallium nitride (InGaN)<br>Silicon carbide (SiC) as substrate<br>Silicon (Si) as substrate—under development |
| Violet | $400 < \lambda < 450$ | Indium gallium nitride (InGaN) |
| Purple | multiple types | Dual blue/red LEDs,<br>blue with red phosphor,<br>or white with purple plastic |
| Ultraviolet | $\lambda < 400$ | Diamond (235 nm)<br>Boron nitride (215 nm)<br>Aluminium nitride (AlN) (210 nm)<br>Aluminium gallium nitride (AlGaN)<br>Aluminium gallium indium nitride (AlGaInN)—down to 210 nm |
| Pink | multiple types | Blue with one or two phosphor layers:<br>yellow with red, orange or pink phosphor added afterwards,<br>or white with pink pigment or dye. |
| White | Broad spectrum | Blue/UV diode with yellow phosphor |

Figure 5.6 Chart depicting color, wavelength and the material of LED substrate

The data for the requirement of the intensities of each of red green and blue color has been taken up from reference [26]. It is suggested that 100% of hyper red for chlorophyll a, 20% of green for trace lights and carotenoids and 70% of deep blue for chlorophyll b is the optimum amount of light required for the perfect growth of Spirulina Platenesis.

## 5.3 Conclusion

In this chapter, a summarized version of what is horticulture and how it is performed optimally using RGB LED lights on a plant species like Spirulina Platenesis has been given. A vivid yet simple scheme for the driving of RGB LEDs has also been presented. Also, the mixing of RGB colored lights to produce light of new colors using variable dimming scheme has been developed.

# CHAPTER 6

# RESULTS AND DISCUSSIONS

## 6.1 Introduction

After completion of the work, it has been decided that results and subsequent discussions should be compiled into a separate chapter. The results hereby have been discussed in the chronological order of the chapters.

## 6.2 Modeling of IV characteristics of LED

The measured curve has been plotted using the (V, I) points of the datasheet. The piecewise Linear approximation has been done with the help of data from Table II. The Maclaurin series expansion based curve has been plotted using the Shockley equation and the parameters as calculated.(All the curves have been plotted using MATLAB and the codes can be referred from Appendix A1 and A2).

From Figure 6.1, it can be seen that the Maclaurin series Expansion based modeled curve resembles the measured characteristics in much more appreciable way as compared to the Piecewise Linear Approximation model. The error between the measured curve and Maclaurin series Expansion based modeled curve is negligible while that for Piecewise Linear Approximation model is a little bit on the higher side.

From figure 6.1, it can be seen that the Maclaurin series Expression based modeled curve resembles the measured characteristics in much more appreciable way as compared to the Piecewise Linear Approximation model. It is also evident from figure 6.1 that the piecewise linear approximation curve would resemble the datasheet plot more accurately as the number of key points taken are increased. This process would become tiring and cumbersome and eventually would defeat the purpose of modeling the curve. The modeling is done so that the voltage and current data can be extracted from the curve without having to actually load the LED. This shows that the Maclaurin series expansion based curve plot is way better than the PLA based curve plot.

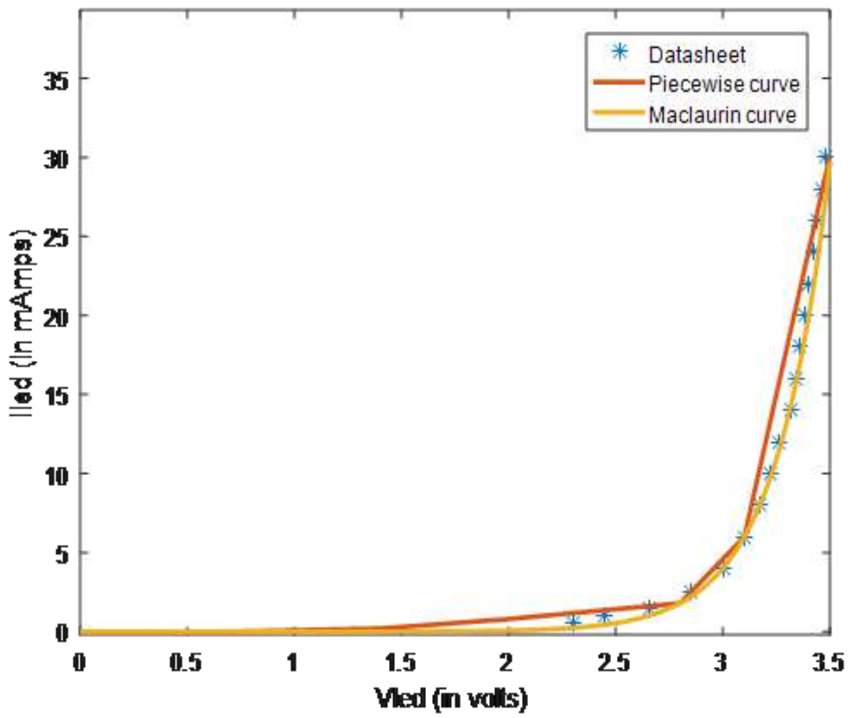



Figure 6.1 Comparison of Measured curve with Piecewise and Maclaurin model curve done in MATLAB 2016a.

The error between the measured curve and Taylor series Expression based modeled curve is very minimal while that for Piecewise Linear Approximation model is not appreciable.

## 6.3 Illumination control using LED lights

This portion of the work has been performed as simulation and later constructed into hardware. The results obtained and a comparison of various parameters have been shown as below:-

### 6.3.1 Simulation Results

The following waveforms were observed on the scopes when the system was subjected to the desired illumination level signal

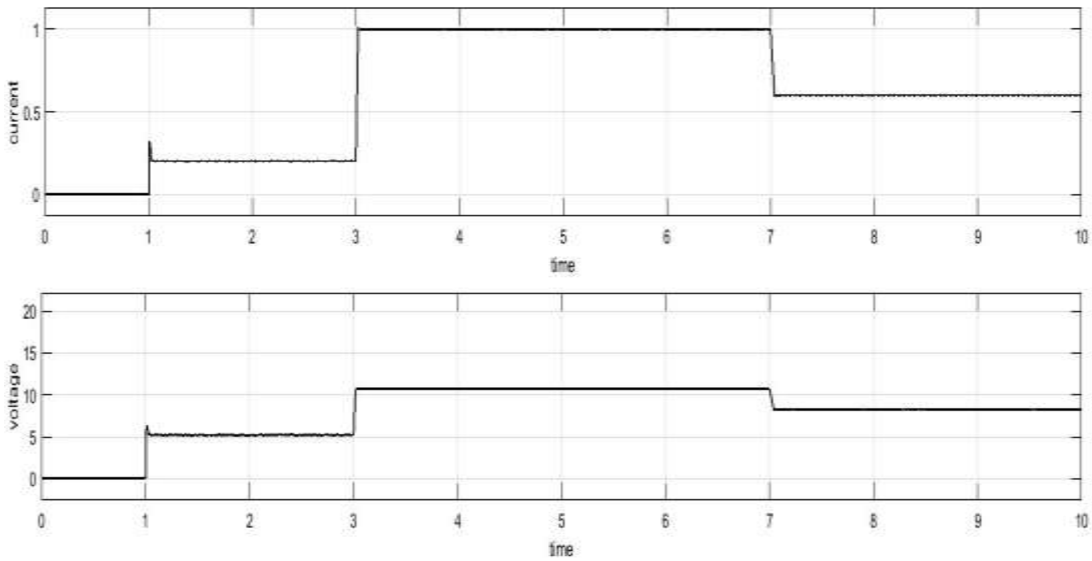
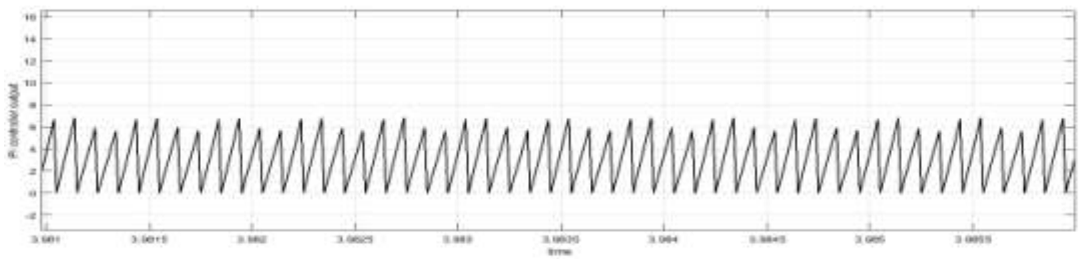


Figure 6.2 Real time plot of LED current(amp) and LED voltage(volts)

- At instance t=1, the set point has been given step increase of 58 lux. The LED responds to it and the current, voltage and light intensity values overshoot to nearly 100% of the desired value.
- These values settle to the steady state value and the steady state error becomes negligible due to the presence of integrator component in the PI controller.
- Similar behavior of the waveforms is observed when the set point value changes at instances t=3 and t=7 as can be seen from figure 6.2


. Figure 6.3 Output from PI controller

- The PI controller is fed with the error signal, which is the difference between the current signal and the set point signal. This error is raised to a proportional value and then integrated.

- Since the integrator sums the error up as time passes, a ramp waveform is generated by the integrator as can be seen in figure 6.3. To stabilize the system, a saturator block is put and it converts this signal to a variable frequency pwm as can be seen in figure 6.4. This pwm signal is then fed to the gate of the MOSFET switch of led driver.

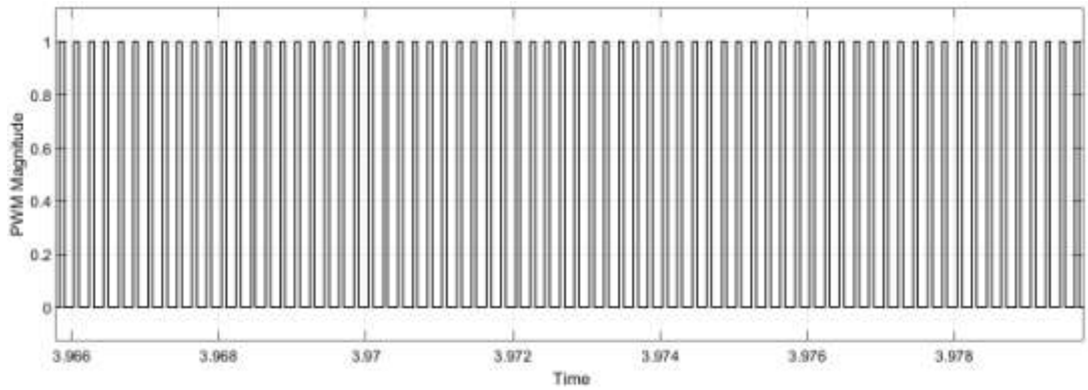



Figure 6.4 Zoomed section of PWM signal generated by the PI controller (after saturator)

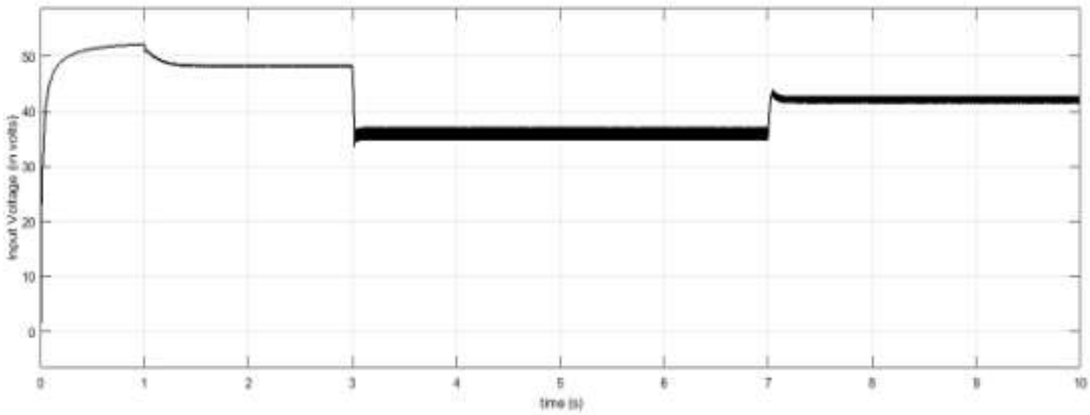



Figure 6.5 Voltage at the input of Buck converter

- The led driver is fed with a dc voltage obtained by ac to dc conversion using a rectifier. As can be seen from figure 6.5, the voltage input to led driver drops down as the LED is made to brighten up.

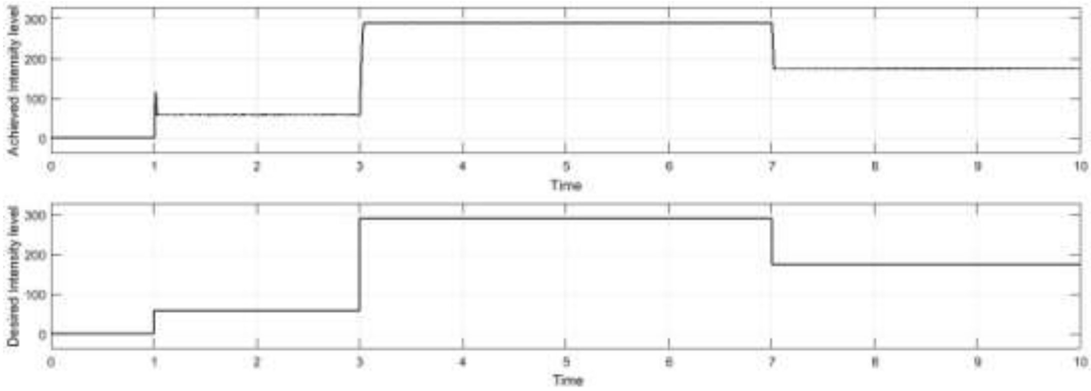



Figure 6.6 Plot of Achieved result against Desired Result

- As can be seen from figure 6.6, the achieved illumination level matches the desired illumination level quite well. Hence, the objective of controlling the illumination level of given closed space has successfully been achieved.

### 6.3.2 Hardware results

The complete setup for this project has been shown in figure 6.7 below.

Figure 6.7 The complete Setup

The illumination level of the given closed space was successfully controlled to a preset value which is evident from the following waveforms observed on the oscilloscope:

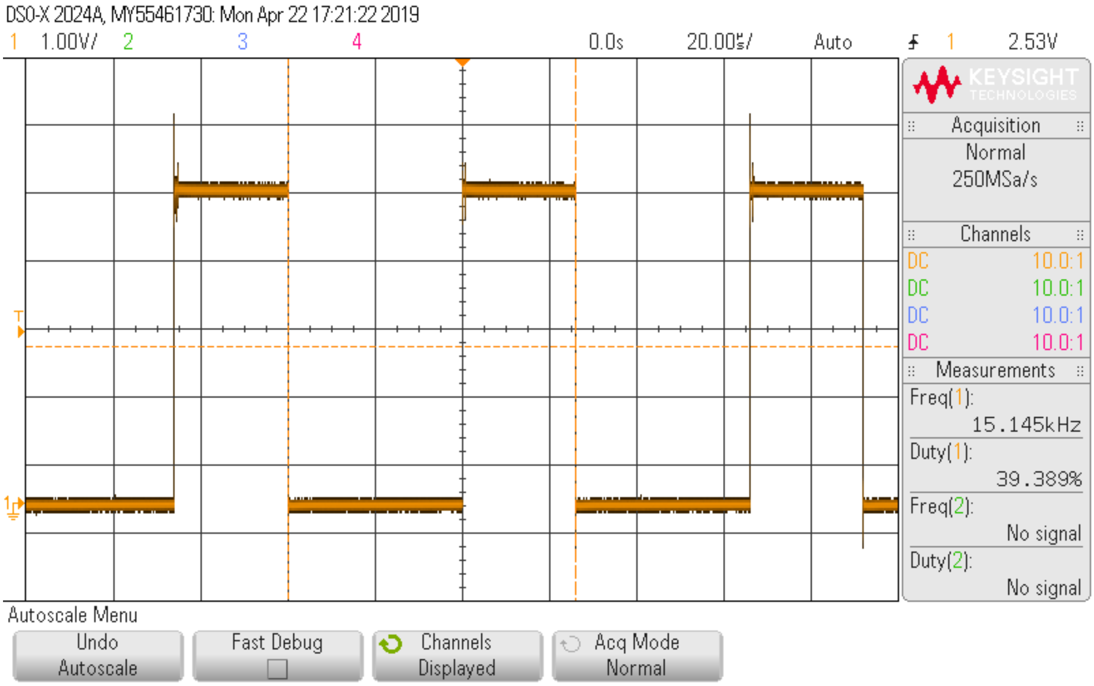



Figure 6.8 PWM wave generated by arduino

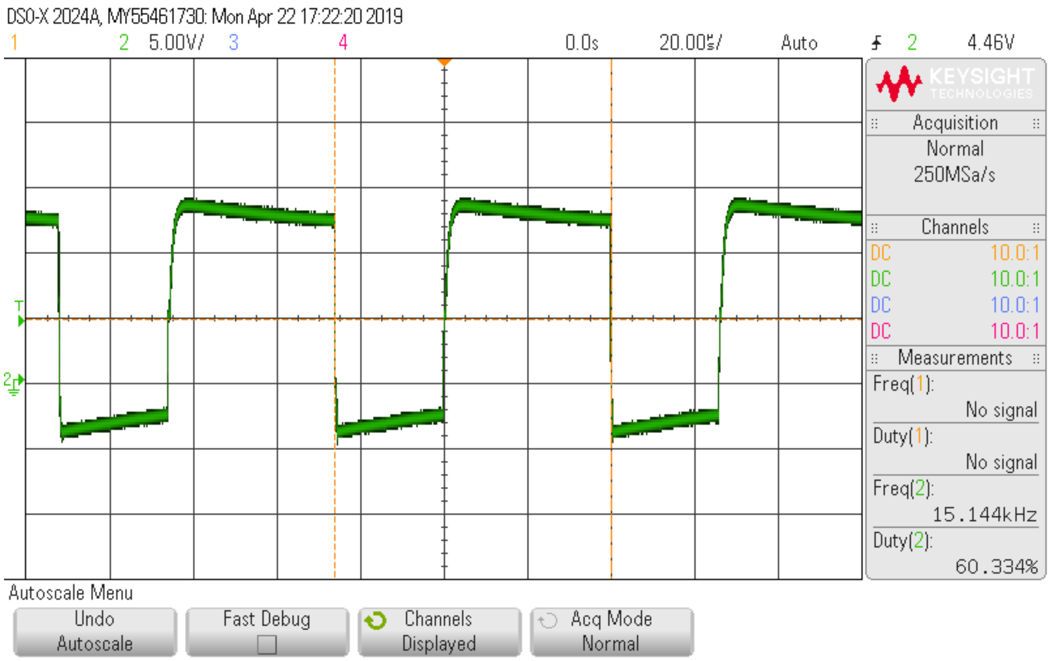



Figure 6.9 Inverted output from IC A6N137

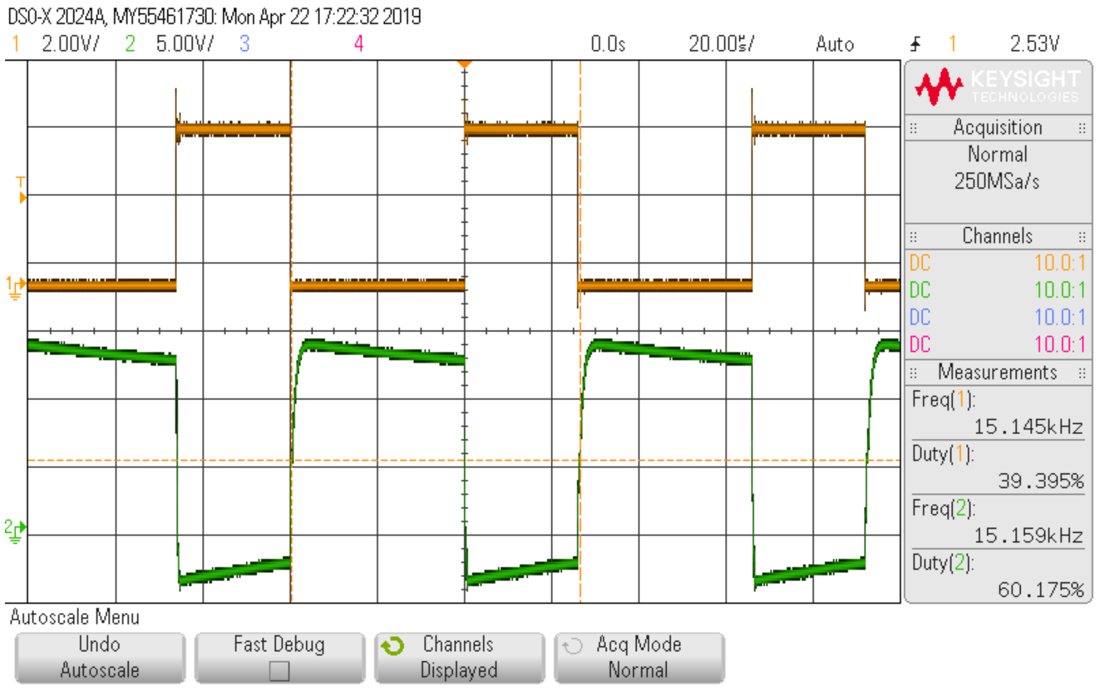



Figure 6.10: PWM output from arduino v/s Inverted output from A6N137.

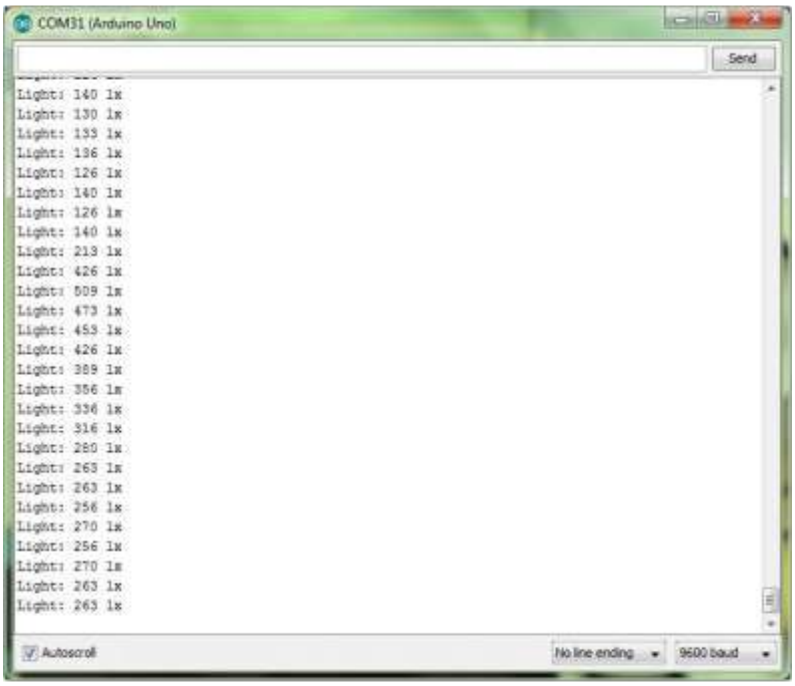



Figure 6.11 Serial monitor displaying the shift from ambient to desired light intensity readings

- 15 kHz frequency wave was coded to facilitate rapid switching of MOSFET and to avoid visible flickering of the LED light.

- The laboratory where the project was setup had an ambient illumination level of around 130 lux. Therefore, any further requirement of illumination would be fulfilled by the LED. A set point of 250 lux of desired illumination has been setup.

- The PWM wave generated by the arduino was at 5 volt level whereas the MOSFET required a 15 volts gating pulse. This was facilitated by the IC A6N137 which acted as an optocoupler and an amplifier.

- The closed loop control was provided by the arduino microcontroller where the feedback signal was the light intensity sensed by lux sensor and the controlled signal was the gate pulse signal.

- The duty cycle of output PWM wave was varied in the range of 25%-95%. The LED was unable to light up below 25% duty cycle due to its knee voltage being around 3.8V. The upper cap of 95% was put to provide overvoltage protection to the LED light.

The automatic control of illumination level of the given closed space to desired levels has therefore been successfully achieved.

### 6.3.3 Comparison of THD values obtained from Circuit Simulation versus The Hardware

In this section, the total harmonic distortion in supply current ($THD_i$) obtained from the simulation circuit has been compared with those obtained from the hardware.

The IEEE standard 519-2014 suggests that the harmonics production is due to the presence of power electronic switches and has also shown some standard waveforms with different setups. For THDv calculation, terms upto 50th harmonic have to be considered. IEC standard 61000-3-2 suggests about the limit for harmonic current emissions into the supply due to lighting loads. For currents less than 16A and loads less than 25W, the permissible THDi should be less than 105%. From table VI as shown below, it is evident that the $THD_i$ values are under the permissible limit throughout the duty cycle range with the maximum value for simulation being 81.92% and that for hardware being 84%.

TABLE VII COMPARISON OF THD$_i$ VALUES

| Duty Cycle (α) (in %) | THD$_i$ Simulation (in %) | THD$_i$ Hardware (in %) |
|---|---|---|
| 95 | 34 | 40.8 |
| 75 | 44.72 | 48.5 |
| 60 | 50.1 | 50.3 |
| 50 | 56.23 | 57.6 |
| 25 | 81.92 | 84 |

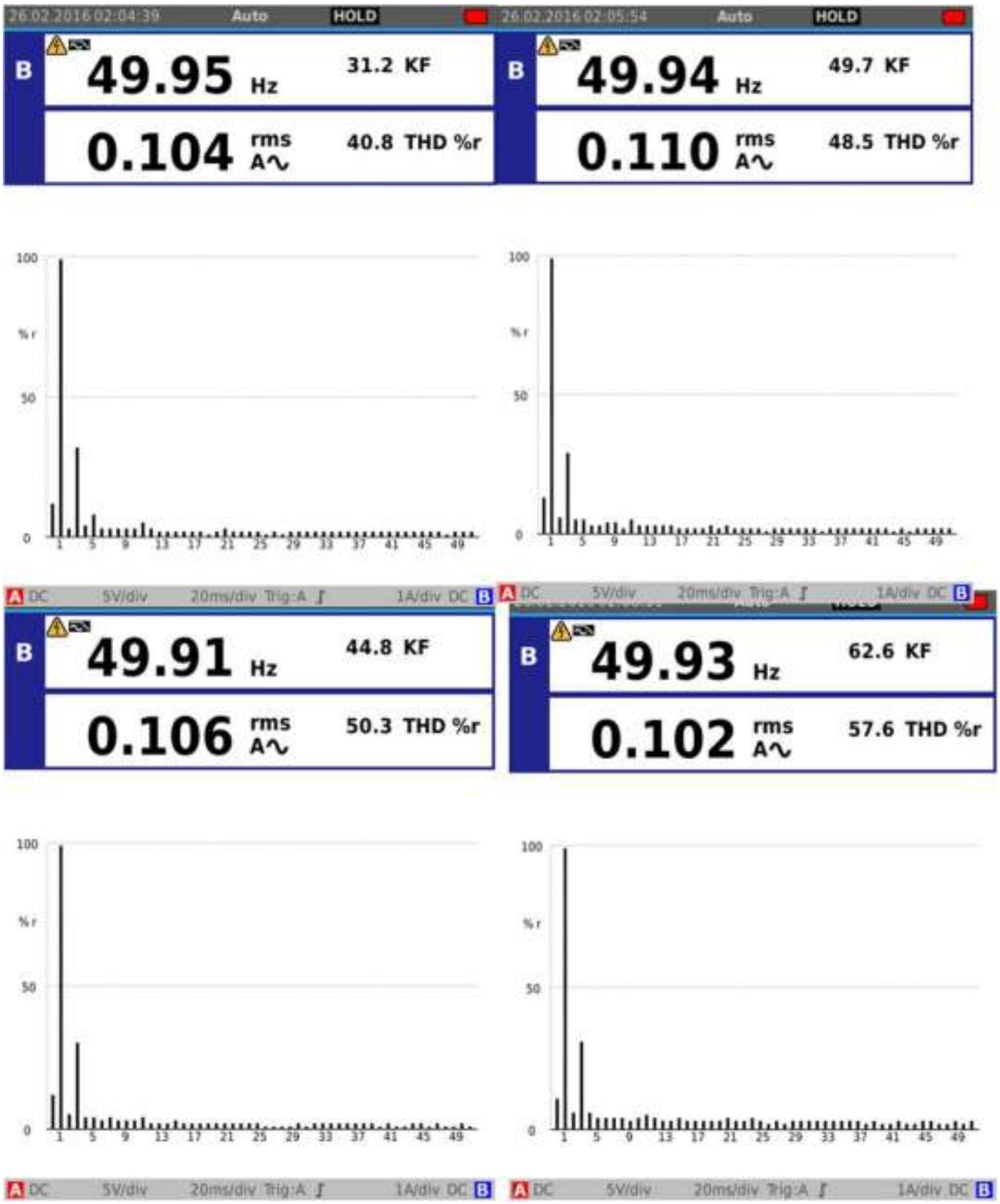



Figure 6.12 THD$_i$ values measured on FLUKE view 2 Scopemeter

### 6.4 Horticulture using RGB LEDs

It has been found that 100%(1.4A) of hyper red for chlorophyll a, 20%(0.28A) of green for trace lights and carotenoids and 70%(0.98A) of deep blue for chlorophyll b is the optimum amount of light required for the perfect growth of Spirulina Platenesis. It has also been observed that intermittent or ON-OFF lighting is suitable for a good growth. The curve for per day light requirement of the plant has been shown in the following three figures.

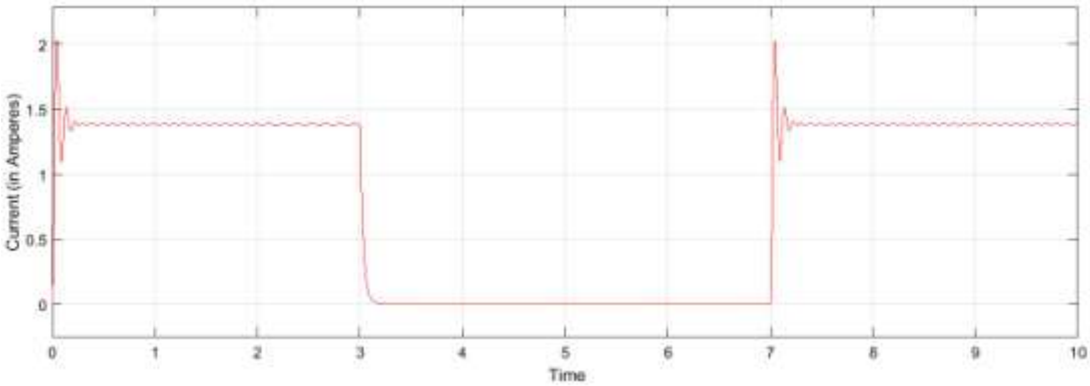



Figure 6.13 Current requirement of hyper red LED per day

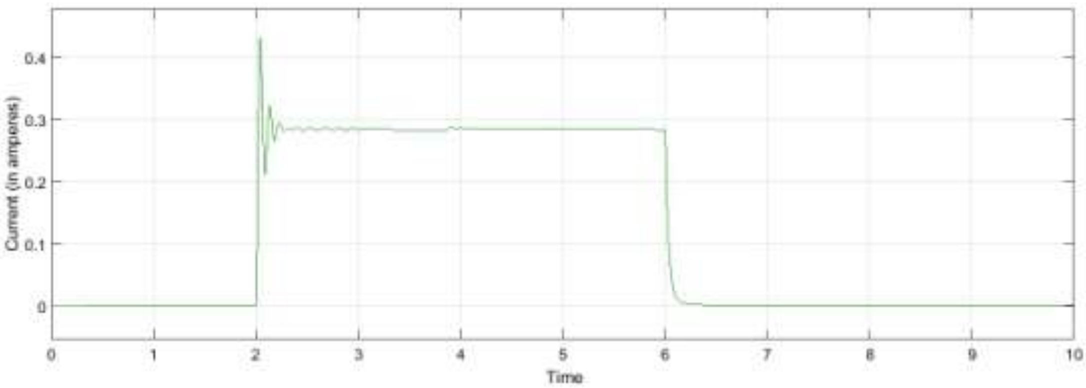



Figure 6.14 Current requirement of green LED per day

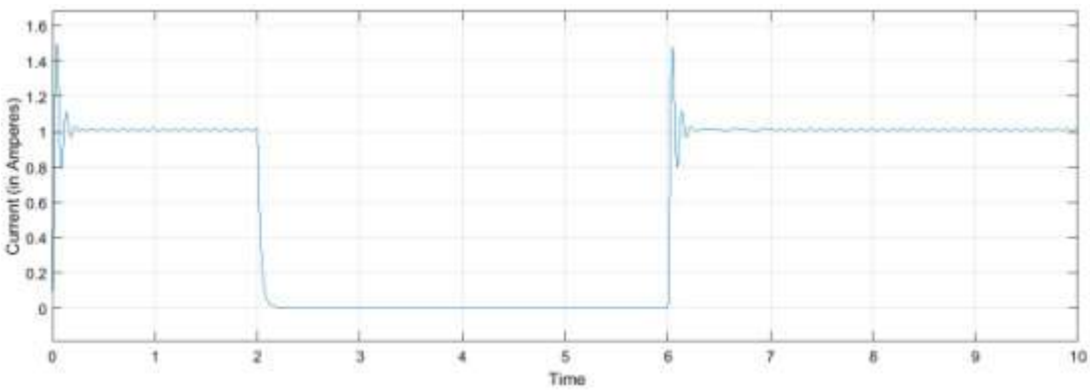



Figure 6.15 Current requirement of deep blue LED per day

It has been found that during initial growth period of S. Platensis, 55% of red, 39% of green and 100% percent of blue light which corresponds to near purple color is required. During the mid growth period, demand of red color increases and the corresponding color required is magenta. During the final stages, the requirement of blue and green color decreases and the corresponding color required is rose red. The following table depicts the RGB color requirements and corresponding single color formed.

TABLE VIII Color Requirement Chart (Assumed)

| **Time** | **Red(%)** | **Green(%)** | **Blue(%)** | **Net Color** |
|---|---|---|---|---|
| Initial stage | 55 | 39 | 100 | Purple |
| Mid stage | 100 | 39 | 94 | Magenta |
| Final stage | 100 | 0 | 39 | Rose Red |

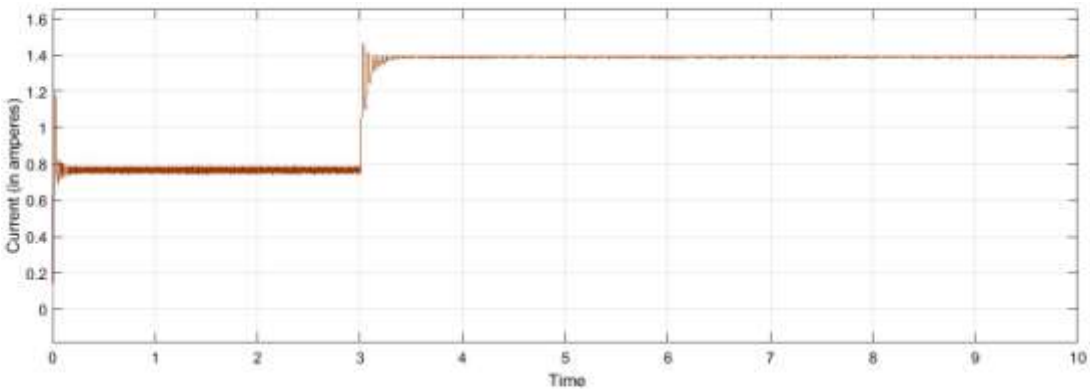



Figure 6.16 Current vs Time curve for hyper red LED

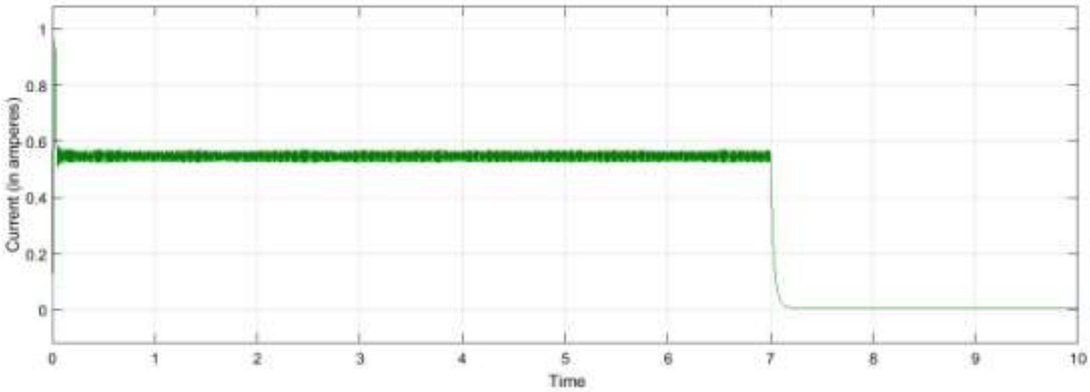



Figure 6.17 Current vs Time curve for green LED

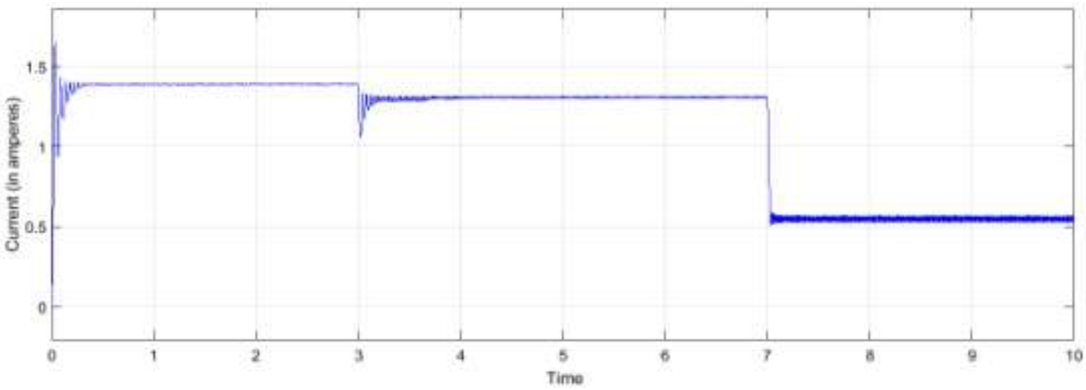



Figure 6.18 Current vs Time curve for deep blue LED

## 6.5 Conclusion

In this chapter, the results and discussion of the work have been taken up. The comparison of the two LED modeling techniques viz Piecewise Linear Approximation and Maclaurin series Expansion has been done and the pros and cons of both the techniques have also been discussed. Then, the illumination control of a given closed space using LEDs has been discussed. A comparison of parameters like THD obtained during simulation and that during the hardware implementation has also been made. Finally, the color mixing of the RGB lights using variable dimming technique has been done for fulfilling the light requirement for proper growth of the plant Spirulina Platensis.

# CHAPTER 7

# CONCLUSION AND SCOPE OF FUTURE WORK

## 7.1 Conclusion

In this work, two methods have been employed to model the I-V characteristics of an LED sample. The PLA technique is the reprise version of the Piecewise linear approximation technique that has been proposed in. It has been observed that the proposed PLA technique is more simplified as compared to Piecewise linear approximation technique. The second method namely, Maclaurin series expansion also has the advantage of saving processor time. The characteristics shown above have been plotted by rigorous coding done in MATLAB software. The results started to converge with the original datasheet plot after merely eight iterations. Moreover, the PLA technique has the disadvantage that to achieve a better accuracy, it has to rely more on the datasheet which is not desirable. The Maclaurin series method, on the other hand, relies only on three datasheet points to get the whole characteristics plotted.

In chapter 4, the primary objective was to control the illumination level of a given closed space as per the desired levels. The desired illumination can range from 40-400 lux as per the general lighting requirement. The objective was successfully achieved in the sense that the LED light source was able to emit light of variable brightness. Since the LED model was not available in the simulink library, the model was developed. The LED was modeled by considering it as a diode for its IV characteristics. The optical properties were taken into account by finding out a relation between LED current and LED intensity. The variable brightness can be attributed to the availability of a controlled PWM wave as the MOSFET gating signal for the employed buck converter. For satisfactory real time response, closed loop control was required which was provided by the collaborated work of the PI controller and the saturator. For real time automation, closed loop control was required which was provided by the collaborated work of the lux sensor (BH1750) and Arduino Uno microcontroller.

In chapter 5, the development of an RGB LED lighting system has been done for the purpose of providing photosynthetic light. A plant Spirulina Platenesis has been considered and the light required for the optimum growth of this plant has been generated using the mixing of RGB colored lights by performing variable dimming of the individual colored light arrays.

### 7.2 Scope of Future Work

The Maclaurin series expansion based model can be used to predict the current flowing through the LED at a particular voltage without actually applying voltage to it. The above work can be extended to model the larger arrays of LED connected in series and parallel and design its power ratings. It can further be used to develop the small signal model of LED which helps in determining the dynamic internal resistance of the LED. It can be of immense help in designing the wireless LED lighting system or designing the LED panels for artificial horticulture which are the two main future prospects of the above carried out work.

The LED model taken into account is a Piecewise Linear Approximation model. Although it models the IV characteristics of the LED quite well, still there is room for improvement. An exponential model of the LED can be devised which takes into account the parameters like saturation current, junction temperature to name a few. As far as the optical properties are concerned, various parameters like luminous intensity, luminous flux, wavelength of light emitted, color, etc can be taken into account for improved performance of the LED driver and achieving better results.

Visible flickering was observed during the intensity control of the given LED light. This was due to the fact that the Arduino uno board used was unable to take serial input and output a pwm wave simultaneously. As such, for the duration when the arduino received input from lux sensor serially, the pwm wave generation was halted. This resulted in the appearance of full voltage across the LED which was evident due to it attaining full brightness for a short period of time. This can be overcome by using a PIC microcontroller or by replacing the lux sensor with a current sensor which would eliminate the issue of serial communication. PWM poses invisible flickering which can cause headache and affect eyesight. This can be overcome by using constant current reduction technique at higher levels of illumination. Manual brightness control of LED is available in the market but automatic brightness control is a breakthrough innovation in the field of LED lighting. With sophisticated encasing of different modules of the project, a commercial product can be developed. Moreover, this project would help in saving electricity and increase the efficiency and life of the lighting source.

The design of LED lighting system for horticultural growth of S. Platensis could not be taken onto the practical application level. This was due to the time constraint of the masters' curriculum and the fact that the time required for the proper growth of S. Platensis would have outlasted the duration of the course.

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# APPENDIX

## A1. MATLAB code for Piecewise Linear Approximation model

```
iled=0:.01:3.5;
vled=0:.01:3.5;
for i=1:351
    if(vled(i)<.7)
        iled(i)=0;
    else
        if(vled(i)<1.4)
            iled(i)=(vled(i)-0.7)/3.5;
        else
            if(vled(i)<2)
             iled(i)=0.2+(vled(i)-1.4)/1;
            else
                if(vled(i)<2.8)
                    iled(i)=0.8+(vled(i)-2)/0.8;
                else
                    if(vled(i)<3.1)
                        iled(i)=1.8+(vled(i)-2.8)/0.0714;
                    else
                            iled(i)=6+(vled(i)-3.1)/0.0166;
                    end
                end
            end
        end
```

```
    end
end
plot(vled,iled)
```

**A2. MATLAB code for Taylor series Expression based model and datasheet plotting.**

```
vled=0:.01:3.5;
Idis=0:.01:3.5;
for i=1:351
    Idis(i)=0;
end
Idis(231)=1;
Idis(246)=1.5;
Idis(267)=2;
Idis(286)=2.5;
Idis(301)=4;
Idis(311)=6;
Idis(316)=8;
Idis(321)=10;
Idis(323)=12;
Idis(325)=14;
Idis(327)=16;
Idis(329)=18;
Idis(331)=20;
Idis(333)=22;
Idis(335)=24;
Idis(337)=26;
```

```
Idis(339)=28;
Idis(341)=30;
plot(vled,Idis,'.')
```

Taylor.m %defining taylor series function%

```
function yt=taylors(x)
yt=0;
for i=0:8
   yt=yt+(x.^i)/factorial(i);
end
end

%%%% Main taylor series code starts here%%%%
isat=1.143;
eta=4.982;
rs=0.01334;
vt=0.025;
y=isat*taylors((vled-3.1)/(eta*vt));
plot(vled,y)
```

**A3a. Code For Pwm Signal Generation Developed Using Arduino IDE**

```
#include <Wire.h>

#include <BH1750.h>

#include <PWM.h>

int brightness = 150;

int32_t frequency = 15000;


BH1750 lightMeter(0x23);

int time=100;

int pwm=3,duty=92;

int setpoint=250, error, ton=45;

uint16_t lux;


void pwm_1()

{


  error= setpoint - lux;

  if(error>10 && duty>21)

  duty-=5;

  else if(error<-10 && duty<235)

  duty+=5;

  else;
```

```
  pwmWrite(pwm,duty);
}


void sensor_1()
{
 Serial.begin(9600);
 Wire.begin();
 lightMeter.begin(BH1750::CONTINUOUS_LOW_RES_MODE);
 lux = lightMeter.readLightLevel();
 Serial.print("Light: ");
 Serial.print(lux);
 Serial.println(" lx");
 Serial.end();
 delay(600);
}


void setup()
{
InitTimersSafe();
bool success = SetPinFrequencySafe(pwm,frequency);
if(success)
 {
  pinMode(13,OUTPUT);
```

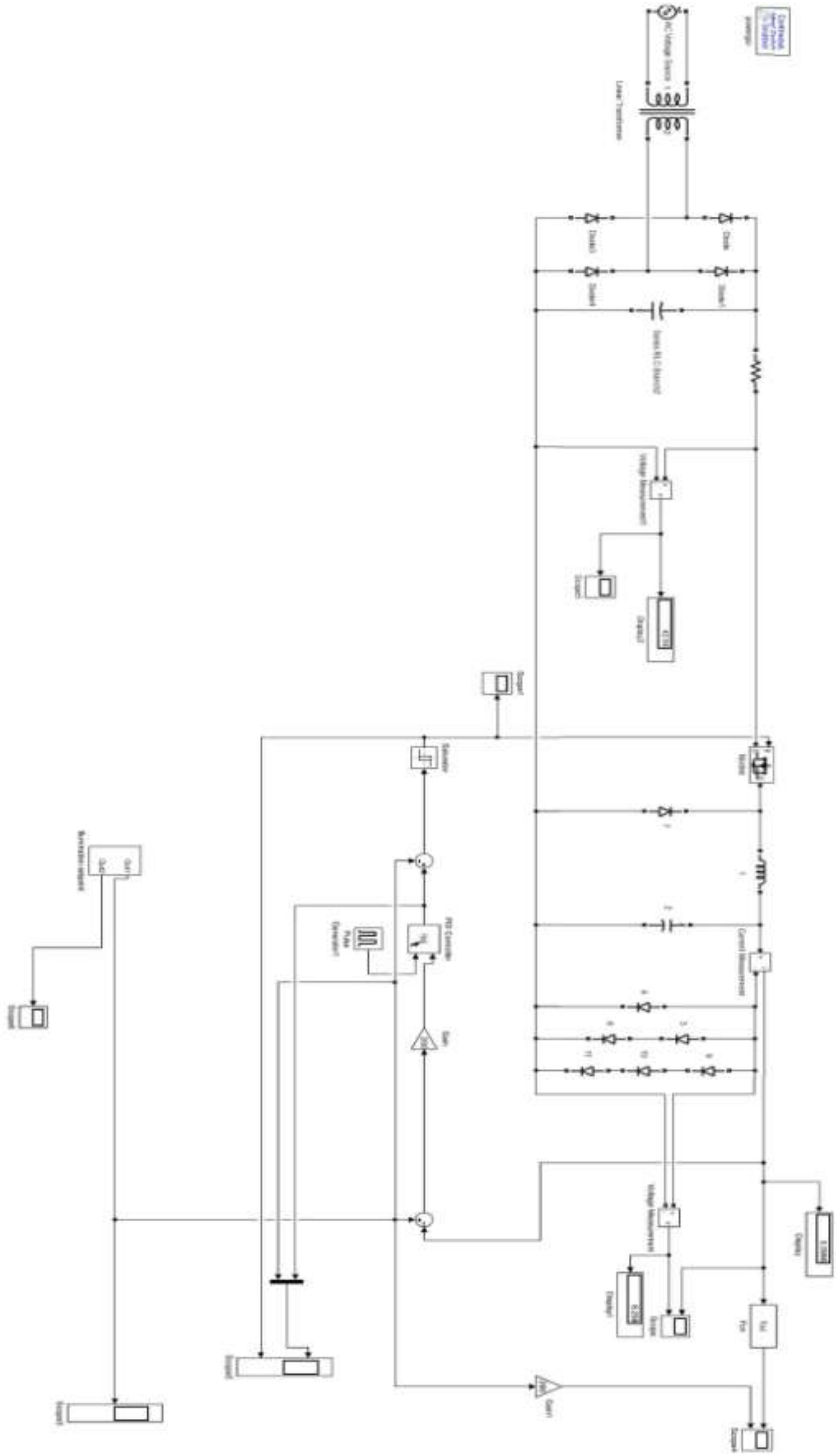
```
  digitalWrite(13,HIGH);
 }
}

void loop()
{
  sensor_1();
  pwm_1.();
}
```

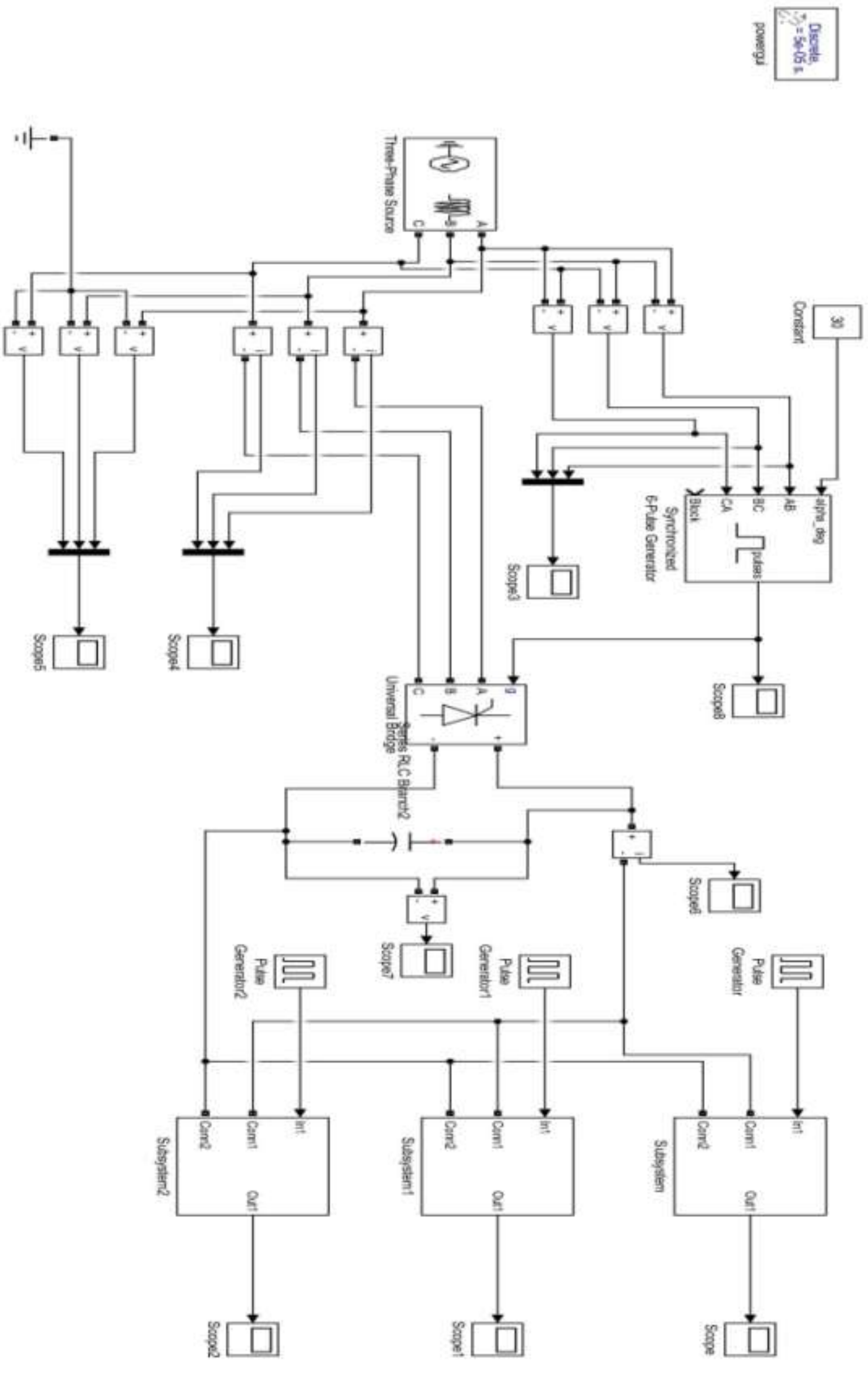
**A3b. List of Components used in the construction of the hardware setup**

| **Component** | **Rating** |
|---|---|
| Resistance Box | 5Ω, 33 Ω, 260 Ω, 330 Ω |
| Tranformer | 220 volts to 36volts (18-0-18 centre tap) |
| LED light | 12 volts, 1 ampere |
| MOSFET (IRFZ640N) | 15V gating pulse |
| Optocoupler (A6N137) | 0-5 volts input and 0-15 volts output |
| Diode (IN4007) | 50volts, 2amperes |
| Capacitor | 47µF, 50volts and 100µF, 100 volts |
| Inductor | 500 µH |
| Voltage Regulator (LM7812) | 12 volts output |
| Microcontroller (ATMega328) | - |
| BH1750 Lux sensor | 0-65536 lux range, works on I2C |
| Breadboards | - |
| Connecting wires | - |

## A4. Complete Simulink Model for Illumination Control using LED Lights



## A5 The Complete Simulink Model for LED lighting System for Horticulture



# LIST OF PUBLICATIONS

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