Development of Linear Regression Based Maximum Power Point Tracking (MPPT) Controller for Solar PV Systems

A thesis submitted in partial fulfillment of the requirements for
the award of the degree of

Bachelor of Technology

in

Electrical and Electronics Engineering

By

K. CHARITESH RAJA (EE19B1021)
K. SRAVAN KUMAR REDDY (EE19B1023)
S. SAMEER (EE19B1041)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY PUDUCHERRY
KARAIKAL – 609609
APRIL 2023

BONAFIDE CERTIFICATE

This is to certify that the project titled

Development of Linear Regression Based Maximum Power Point Tracking (MPPT) Controller for Solar PV Systems

is a bonafide record of the **EE402 Project Phase II** work done by

K. CHARITESH RAJA (EE19B1021)
K. SRAVAN KUMAR REDDY (EE19B1023)
S. SAMEER (EE19B1041)

in partial fulfillment of the requirements for the award of the degree of **Bachelor of Technology** in **Electrical And Electronics Engineering of** the **NATIONAL INSTITUTE OF TECHNOLOGY PUDUCHERRY,** during the year 2022-2023.

Dr.A.VENKADESAN
Head of the Department (i/c)

Dr.K.NAVIN SAM
Project Guide

Project viva-voice held on ___________

Internal Examiner

External Examiner

ABSTRACT

The human activities contribute to the global warming of the planet. As a result, every country strives to reduce carbon emissions. The world is facing not only the depletion of fossil fuels, but also rising its prices which causes the worldwide economic instability. Numbers of efforts are being undertaken by the Governments around the world to explore alternative energy sources and to achieve pollution reduction. Solar electric or photovoltaic technology is one of the biggest renewable energy resources to generate electrical power and the fastest growing power generation in the world.

The thesis describes the application of Multi Variate Linear Regression (MLR) technique for Maximum Power Point Tracking (MPPT) in solar Photo Voltaic (PV) panels. The model used in the project work is trained and tested with the help of collected data.

MLR is a Machine Learning (ML) algorithm, an Artificial Intelligence (AI) technique used to predict the value of a variable based on the value of another variable. Compared to conventional techniques, AI techniques have been extensively used for MPPT in solar PV panels. AI based MPPT techniques exhibit fast convergence speed, less steady state oscillations and high efficiency.

A boost converter is a DC (Direct Current) to DC converter which steps up the input voltage level. The output voltage level depends on the Duty cycle. In this study, a machine learning algorithm for the boost converter using the Linear Regression technique is developed in MATLAB and the developed model is then coded into Arduino UNO With the help of Arduino IDE software and validated the performance of the modelled controller for various irradiance and temperatures at uniform shading condition.

Keywords: MPPT, MLR, ML, Boost converter, Duty cycle.

ACKNOWLEDGEMENT

This project consumed good amount of work, research and dedication. Still, implementation would not have been possible if we did not have the support of many individuals. Therefore, we would like to extend our sincere gratitude to all of them.

We are grateful to **Dr.A.Venkadesan**, Head of the Department, Electrical and Electronics Engineering for provision of expertise, and technical support in the implementation. The success of this project would not have been possible without his support.

We would like to express our deep and sincere gratitude to our supervisor **Dr.K.Navin Sam,** Assistant Professor, Department of Electrical and Electronics Engineering for his continual effort in this thesis work. His guidance, encouragement and suggestions have contributed immensely to the evolution of our idea on the topic and without him, this work would not have been possible.

Many thanks to **Dr**.**Rajvir Kaur**, Assistant Professor, Department of Electrical and Electronics Engineering, Project Coordinator who devoted her time and knowledge in guiding us throughout this project work. We are very much pleased to acknowledge all Teaching and Non-Teaching staff members of the Department of Electrical and Electronics Engineering for their support and guidance in carrying out this project work in spite of their busy schedule.

Nevertheless, we express our gratitude towards our families and colleagues who kept us on track and provided hours of entertainment and stimulating conversation.

CONTENTS

LIST OF SYMBOLS

D – Duty cycle

L – Inductance

C – Capacitance

R – Resistance

T – Time Period

V_{mpp} – Voltage at Maximum Power Point

I – Current

P_{mpp} – Power at Maximum Power Point

% - Percentage

LIST OF ACRONYMS

PV – Photo-Voltaic

MPPT –Maximum Power Point Tracking

IC- Incremental Conductance

MPP-Maximum Power Point

FLC – Fuzzy Logic Control

ANN – Artificial Neural Network

ANFIS – Artificial Neuro Fuzzy Interface System

ACO – Ant Colony Optimization

FA – Firefly Algorithm

GA – Genetic Algorithm

MLR – Multivariate Linear Regression

MATLAB – Matrix Laboratory

MOSFET – Metal Oxide Semiconductor Field Effect Transistor

PWM – Pulse Width Modulation

DC – Direct Current

RMSE -Root Mean Square Error

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Preamble

The basic necessity of a human being is electricity. Electrical energy is essential for us to do our daily activities without encountering any difficulties. Electrical energy may be obtained from a variety of sources, including wind, fossil fuels, hydro power plant, solar power, nuclear and coal power. Renewable and non-renewable energy are the two forms of energy.

Due to the massive consumption of fossil fuels in recent decades, global warming and the energy crisis had a significant impact on government economic policy, climatic conditions, and energy security issues, motivating the development and use of alternative, sustainable, and clean energy sources to replace current energy production. The entire world was focusing on the utilization of renewable energy resources in order to avoid an emergency power outage, cut CO_2 emissions, and maintain pollution control. However, equipping such energy resources is a significant challenge, and as a result, we cannot entirely rely on the amount of renewable energy generated for the national power grid. One way to reduce future greenhouse gas emissions is to employ solar energy. Photovoltaic (PV) may offset 50% of all future development in thermal energy generation, reducing yearly worldwide carbon dioxide emissions by 10% in 20 years and 32% in 50 years, compared to predicted increase.

The use of solar PV panels is increased due to its reliability and cost-effective. Despite its advantages, the output power from solar power system varies according to the solar irradiance and operation temperature. The output from the PV cell ascends with the rise in solar irradiance and descends with the rise in temperature. But the solar irradiance is not same throughout the day hence the output from the PV panel is not constant.

This necessitates the use of some technique to track down the maximum power output from the PV panel. Maximum Power Point Tracking (MPPT) is algorithm that included in charge controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which PV module can produce maximum power is called maximum power point (or peak power voltage). Maximum power varies with solar radiation, ambient temperature, and solar cell temperature.

There are various MPPT techniques exist like Perturb & Observe and Incremental Conductance (IC) are the most prevalent conventional methods. These methods require PV panel voltage and current to track the Maximum Power Point (MPP) by calculating the required change in voltage. Mathematical-based methods, such as the curve-fitting algorithm, offer an indirect method to track the MPP using the panels power-voltage curve. Constant-parameter algorithms like fractional open-circuit voltage require periodic open-circuit voltage values by periodic isolation of the load. On the other hand, the fractional-short circuit current algorithm requires a periodic short-circuit current value by periodic short-circuit of the load in terms of power loss and a reduction in efficiency. Trial-and-error-based methods such as gradient descent, calculate the adjacent local MPP using the gradient function. Intelligent prediction algorithms like Fuzzy Logic Control (FLC), which is a rule base control, and Artificial Neural

Network (ANN), predicts the anonymous data from the existing data by adjusting the weights of different layers through training process. An Artificial Neuro-Fuzzy Interface System (ANFIS) is a type of ANN. Optimization methods, such as Ant Colony Optimization (ACO), Firefly Algorithm (FA), Genetic Algorithm (GA), and Grey Wolf Optimization (GWO), attempt to optimize a function or variable. These algorithms are forced to operate the PV panel such that the maximum available power will be extracted and delivered to the load.

Machine learning algorithms can accurately predict unknown data from known data. A machine learning algorithm is converted into a machine learning model by adequately training with some of the existing data and testing the model with the remaining data. Generally, 80% of the data is utilized for training, and the remaining 20% of the data is used for testing the model.

The irradiance and temperature vary continuously at a fast rate. Thus, the tracking speed of MPP is an essential factor in the MPPT technique. It is possible to improve the tracking speed of the MPP in solar PV systems by applying machine learning algorithms. These algorithms are not iterative and eliminate the controller requirement. In this project, a new technique i.e., Multi-variate Linear Regression (MLR) machine learning algorithm is applied to track the MPP of a PV panel. The developed model from MATLAB is implemented into Arduino UNO through Arduino IDE software and the pulses generated from the Arduino are fed to the gate driver circuit and the pulses from the gate driver circuit is given to the MOSFET gate terminal. Based on the change in inputs the pulse width changes i.e., duty cycle.

1.2 Objective of Thesis

The use of PV panels is dominating in the renewable energy market today. The rise in PV application is mainly due to the improved PV panel efficiency and its low marginal costs. Along with this surge of PV application in today's electronic industry, the need for more efficient DC-DC converters that integrate with the PV panels are also in demand. In order to achieve a higher efficiency as well as high power density in DC-DC converter circuits play an essential role.

The objective of this project, is to develop an MPPT controller for the DC-DC Boost Converter. There are multitude MPPT algorithms that are well-established in literature. Among them, this study has focused on the Multi-Variate Linear Regression (MLR) algorithm. The MLR algorithm can be deployed in the controller by using analog circuitry or it can be coded digitally by using a microcontroller unit as the controller for the DC-DC converter. This work shows the development of MLR algorithm in Arduino UNO software.

In this project work, a boost converter is modeled with the designed values of inductance, capacitance, etc... and validated the performance of the boost converter for various switching frequencies by calculating the efficiency. Moreover, the developed MLR algorithm in Arduino UNO software's output is verified for various certain irradiance and temperature by calculating the actual value and also additionally the code is modified by maintaining the temperature as constant and varying certain irradiance with a delay in between their occurrence. Gate driver circuit is modeled for the designed boost converter to control the switching of power device (MOSFET). Gate driver's primary function is to take the low current PWM pulse generated by the Arduino and amplifies it to a higher current level that can effectively drive the gate of the MOSFET. To validate the final experimental setup, potentiometers are used as irradiance sensor temperature sensors and the value from the potentiometer is read by the Arduino and multiplied with a proper calibration factor for the actual value of irradiance and temperature the corresponding duty cycle is generated from Arduino UNO. The generated Pulse Width Modulation (PWM) pulse with a proper duty cycle is taken as input to the gate driver circuit and the output PWM pulse from the gate driver is given to the boost converter's MOSFET gate terminal. The result proved the MLR model performance, and the controller design developed in hardware shows that the MLR algorithm works under various irradiance and temperature i.e., under dynamic conditions the controller responds to the change and generates proper duty cycle.

1.3 Literature Survey

There are various literature surveys exist in MPPT controller but linear regression was not applied. Hence this gave a motivation for this project to apply a machine learning technique to MPPT controller i.e., Linear Regression. Without pre knowledge on MPPT controller would be difficult to carry out the study. Hence to carry out this project work, there were a lot of research papers referred and the knowledge gained from it were applied into this project to develop the hardware model of MPPT controller. Some of the researcher's names, their research work area and the knowledge gained by reading to those research papers will be discussed.

1.Yuvarajan et al. (2008) presented a fast and accurate maximum power point tracking (MPPT) algorithm for a photovoltaic (PV) panel that uses the open-circuit voltage and the short circuit current of the PV panel. The mathematical equations describing the nonlinear V-I characteristics of the PV panel are used in developing the algorithm. The MPPT algorithm is valid under different irradiance, temperature, and level of degradation. The algorithm is verified using MATLAB and it is found that the results obtained using the algorithm are very close to the theoretical values over a wide range of temperature and illumination levels.

2. Norazlan Hashim (2018) presented a DC-DC Boost converter design for MPPT controllers in solar PV systems. The mathematical equations describing the calculation of dutycycle, inductor and capacitor for Boost converter.

3.Byamakesh Nayak(2017) , presented a paper on selection criteria of dc-dc converter and control variable for MPPT in solar PV systems. Made comparisons between Buck and Boost Converters and with the help of SIMULINK results in his paper he stated that Boost Converter is more efficient.

4. P. Venkata Mahesh (2022) provided a review on multivariate Linear Regression in MPPT controller for solar pv system. The stated algorithm can predict the maximum power available at the panel and the voltage corresponds to this maximum power for specific values of irradiance and temperature. The MATLAB/SIMULINK results illustrate that as time progress the PV panel is forced to operate at the MPP predicted by MLR algorithm, yielding an efficiency of more than 96% in the steady state operation of the PV system.

5. Adedayo M. Farayola (2018) presented a review on optimization of PV systems using Linear Regression techniques (Multivariate Linear Regression (MLR), Bagging, Boosting techniques). The proposed techniques is designed and simulated in MATLAB/SIMULINK to test its performance for different operating conditions. Simulation results have proved that MLR trains the data in less time and have R2 as 1 but RMSE (Root Mean Square Error) of MLR is greater than other techniques. Simulation results of MLR have proved that it gives faster response compared to other techniques.

1.4 Organization of Thesis

The remainder of this thesis is organized as follows:

Chapter 2 details the system description of photovoltaic systems and types of solar panels. This chapter also presents the details of the electrical specifications of the solar panel chosen for this study, modelled gate driver circuit and the boost converter and its hardware model.

Chapter 3. details the background of MPPT algorithms and principles of the most common MPPT methods developed and used. This chapter presents present-day MPPT methods. Lastly, it briefs the concept of Multi-Variate Linear Regression (MLR).

Chapter 4 deals with the concept of Multi-Variate Linear Regression (MLR) and briefs about the Arduino and deals with the developed hardware model and the flowchart of algorithm.

Chapter 5 deals with the results of the developed hardware model**.**

Chapter 6 concludes this thesis and gives a summary of the research.

CHAPTER 2

DESCRIPTION OF SYSTEM

2.1 Introduction

Solar energy begins with sun. Solar panels (PV panels) are used to convert light from sun, which is composed of particles of energy called photons into electricity that can be used to power electrical loads.

Russel Ohl, an American inventor on the payroll of Bell laboratories, patented the world’s first silicon solar cell in 1941. Ohl’s invention led to the production of first solar panel in 1954 by the same company. Solar panels found their first mainstream used in space satellites. For most people, the first solar panel in their life was probably embedded in their new calculator.

2.2. Photovoltaic Systems

The process of converting light (photons) to electricity (voltage) is called the solar photovoltaic (PV) effect. Photovoltaic solar cells convert sunlight directly into solar power (electricity). They use thin layers of semi-conducting material that is charged differently between the top and bottom layers. The semi-conducting material can be encased between a sheet of glass and/or a polymer resin. The conversion is achieved via thin semiconductor devices called photovoltaic cells, which are also sometimes called solar cells or PV cells. PV cells are basically flat light-sensitive diodes comprised of the same or similar materials as those used in transistors, 13 computer chips, and related technology. A PV cell functions as follows: A semiconductor absorbs enough energy from a light photon to transfer it to electrons. The high-energy electrons would then pass their energy to the semiconductor material, and in so doing create heat through recombining with the positively-charged “holes” formed by the light. An internal electrical field then emerges as a result of the PV cell’s junction that exists between the two forms of the semiconductor. When the electric field channels the charged electrons to one side of the cell (to prevent them from creating heat), a difference in voltage is thus formed between the opposite cell sides. An electric current is then able to be drawn from the cell through the contacts on the two sides.

A PV cell creates electricity like how a chemical battery cell does (i.e., as a direct current [DC]). The electrical power created is limited by the amount of received light (irradiance), as well as the cell’s temperature and the PV cell’s connections.

When exposed to daylight, electrons in the semi-conducting material absorb the photons, causing them to become highly energised. These move between the top and bottom surfaces of the semi-conducting material. This movement of electrons generates a current known as a direct current (DC). This is then fed through an inverter, which converts the power to alternating current (AC) for use in your home.

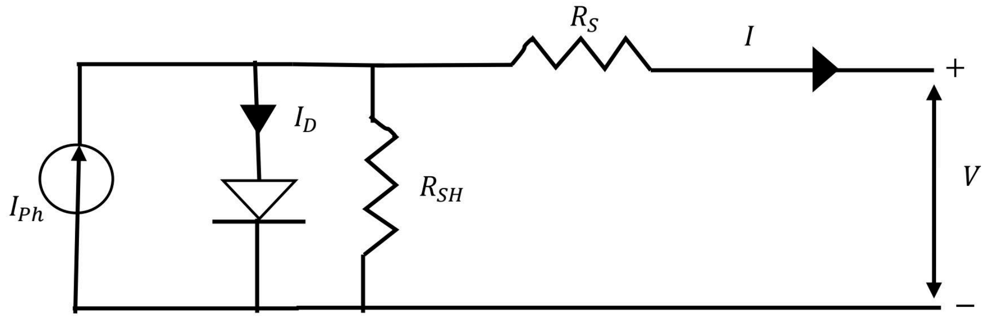

Fig.2.1 PV cell modelled as diode circuit

2.2.1 Types of Solar Panels

Different types of solar PV installations require slightly different components. The solar panel is the key component of any solar photovoltaic system, which takes the sun's energy and converts it into electricity. There are three main types of solar panel currently in commercial production, all of which are based on silicon semiconductors:

1. Monocrystalline Solar Cells

2. Polycrystalline Solar Cells

3. Amorphous Solar Cells

1.Monocrystalline Solar Cells: -

This type of solar cell is made from thin wafers of silicon cut from artificially-grown crystals. These cells are created from single crystals grown in isolation, making them the most expensive of the three varieties (approximately 35% more expensive than equivalent polycrystalline cells), but they have the highest efficiency rating – between 15-24%.

2. Polycrystalline Solar Cells: -

This type of solar cell is also made from thin wafers of silicon cut from artificially grown crystals, but instead of single crystals, these cells are made from multiple interlocking silicon crystals grown together. This makes them cheaper to produce, but their efficiency is lower than the monocrystalline solar cells, currently at 13-18%

3. Amorphous Solar Cells: -

These are the cheapest type of solar cell to produce, are relatively new to the market and are produced very differently to the two other types. Instead of using crystals, silicon is deposited very thinly on a backing substrate.

There are two real benefits of the amorphous solar cell: firstly, the layer of silicon is so thin it allows the solar cells to be flexible, and secondly, they are more efficient in low light levels (like during winter). They have the lowest efficiency rating of all three types, approximately 7% – 9%, requiring approximately double the panel area to produce the same output. In addition, as this is a relatively new technique, there is no agreed industry- so they are not as robust as the other two types.

2.2.2 Factors Affecting the Performance of Solar PV Panels

Solar power systems are considered a key tool in the energy supply for the present and future generations. Several factors have promoted the development of photovoltaics such as environmental concerns, incentives and tax deductions, a more performing and less expensive technology, and the need to replace carbon fossil energy systems with renewables to ensure compliance with the objectives set by the Paris Agreement (took place in 2015) to reduce global warming and to reduce global temperature by 1.5 ° C.

A solar cell or photovoltaic cell is a device that converts the sunlight into usable energy. The amount of sunlight that can be converted into electricity is referred to as solar cell efficiency. There are some factors that should be taken into consideration to guarantee the optimal efficiency of the solar panels.

1. Temperature: -

The temperature influences the efficiency of the photovoltaic cell due to the intrinsic characteristic of the semiconductor material. The efficiency of the solar panels increases when the temperature drops and decreases in high temperatures, as the voltage between the cells drops.

2. Solar Shadings: -

Solar PV panels are very sensitive to solar shadings. Total or partial shading conditions have a significant impact rate on the capability of delivering energy and may result in lower output and power losses. Cells in a solar panel are usually connected in series to get a higher voltage and therefore an appropriate production of electricity.

But when shading occurs, this structure presents some limitations. In fact, when a single solar cell is shaded, the current of all the units in the string is determined by the unit that produces the least current. When a cell is shaded, the whole series is virtually shaded too. To prevent the loss of energy, the installation usually includes bypass diodes.

Bypass diodes are wired in parallel to the solar cells. When a solar cell is shaded, the bypass diode provides a current path that allows the string of connected solar cells to generate energy at a reduced voltage.

3. Energy Conversion Efficiency: -

The solar module has a different spectral response depending on the kind of the module. Therefore, the change of the spectral irradiance influences the solar power generation. The energy conversion efficiency is increased by reducing the reflection of the incident light.

4. Operation and Monitoring: -

Operation & Monitoring services help with the management of the implementation of certain processes to avoid or mitigate potential hazards. Operations mainly consist of the remote monitoring and control of the PV power plant conditions and performance. Monitoring software provides access to all data collected, which can be used for different purposes: defect detection, performance analysis, improvement, predictive maintenance, and security. A good monitoring system will provide information on the production, alarms, and analytical data, in a timely, efficient, and precise manner to detect any anomaly of the PV plant.

2.3 Electrical Characteristics of Solar PV Panel

The PV cell characteristics are usually described by using I-V (Current-Voltage) and P-V (Power-Voltage) curves. By multiplying the output current and voltage from the I-V curve, the output power can be calculated. Due to the limited efficiency of the PV cell and to their non-linear characteristics PV systems are always required to operate close to MPP in order to gain maximum energy harvesting. However, the performance of solar PV cells can be easily affected by environmental conditions. The short-circuit current depends linearly on the solar irradiance level while the open-circuit voltage shows a strong dependence on the cell temperature. Consequently, the operating point which satisfies the MPP condition also varies with the environmental conditions. Thus, it is essential to have a Maximum Power Point Tracking (MPPT) mechanism, which is a control algorithm that can track the MPP continuously during the operation in order to maximize the power production of PV systems.

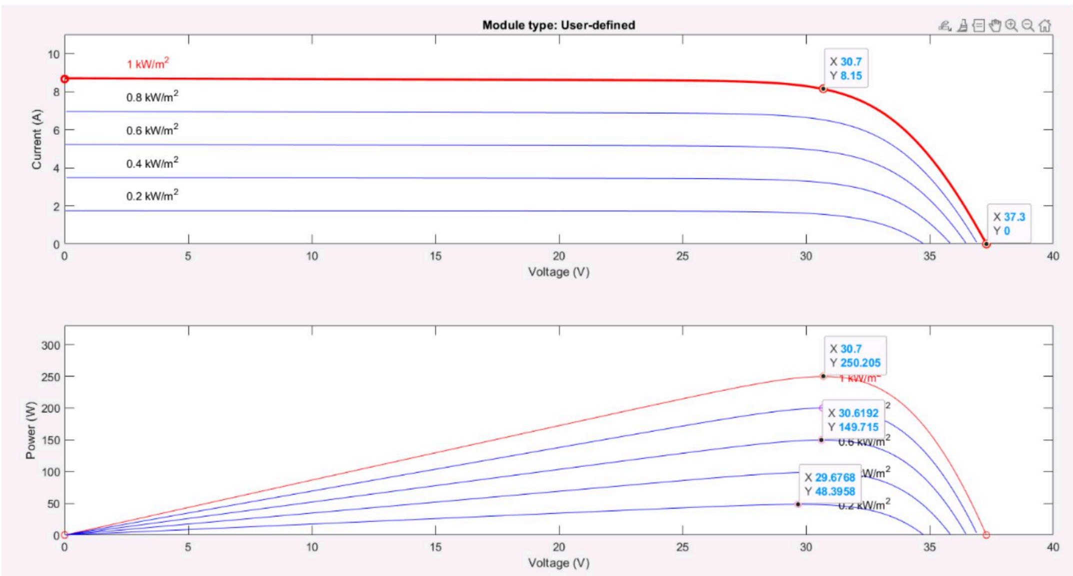

Fig.2.2 I-V and P-V Characteristics of Solar Panel for Various Irradiances and at a Constant Temperature of 25°C

2.3.1 Electrical Specifications of Solar PV Panel

The solar panel used in this project is zytec panel is made of 72 solar cells in series and provide 250 W of nominal maximum power. The maximum power point's voltage is 30.7 V and current delivered at maximum power point is 8.15 A. The electrical parameters of the zytec panel are given in table 2.1 and these parameters are helped to validate the performance the proposed MPPT algorithm. The values of electrical parameters are as follows : -

Characteristics	Value
Short Circuit Current (I_{SC})	$8.66A$
Open circuit Voltage (V_{OC})	$37.3V$
Current at MPP ($I_{P(\max)}$)	$8.15A$
Voltage at MPP ($V_{P(\max)}$)	$30.7V$
Voltage Temperature Coefficient	-0.36901
Irradiance (G)	$1000W/m2$
Temperature (T)	25^0C
Current Temperature Coefficient	0.086988

Table.2.1 Solar PV Panel Specifications

2.4 MOSFET Gate Driver Circuit

MOSFET gate drive circuits have progressed from basic resistance selection to more complex dynamic modulation of the gate drive resistance during the switching event. Using these improved techniques, switching power loss can be minimized while collector current and voltage overshoots during MOSFET switching events can be reduced. This makes it possible to increase the MOSFET -based inverter circuits' efficiency. Newer MOSFET modules are also intended to survive short circuit circumstances in the load. The MOSFET collector current can increase to several times its steady state value during a load short circuit. By cutting off the fault current, extremely high dI/dt can result, which can cause significant voltage overshoots in stray inductances.

SL. NO	COMPONENTS	SPECIFICATIONS
1	Resistance	220ohm
2	Optocoupler	TLP250
3	Capacitance	1000µF
4	Diode	1N4007

Table.2.2 Design Parameters of the Gate Driver Circuit

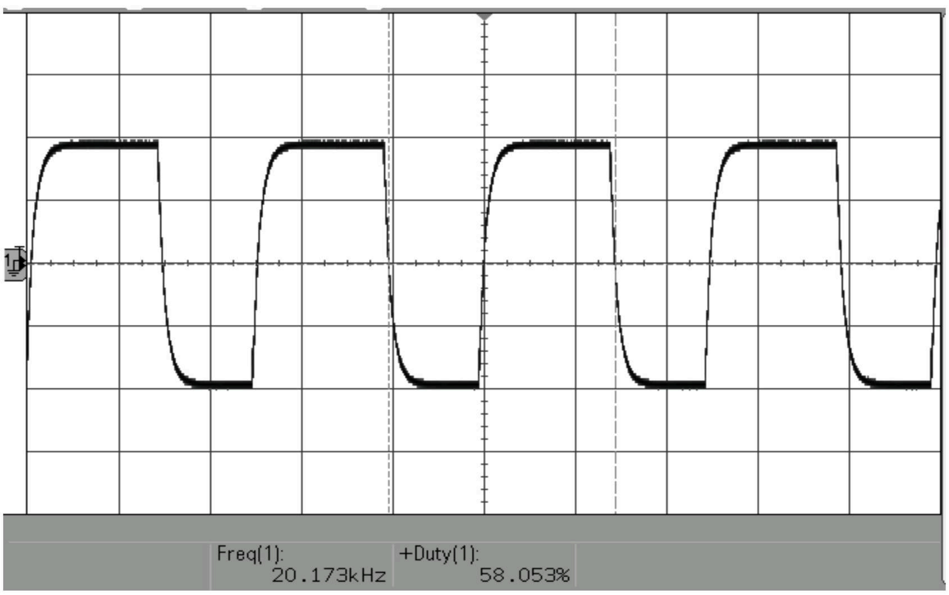

Fig.2.3 Gate driver circuit Output PWM Pulse for a Switching Frequency of 20kHz with a Duty Cycle of 58%

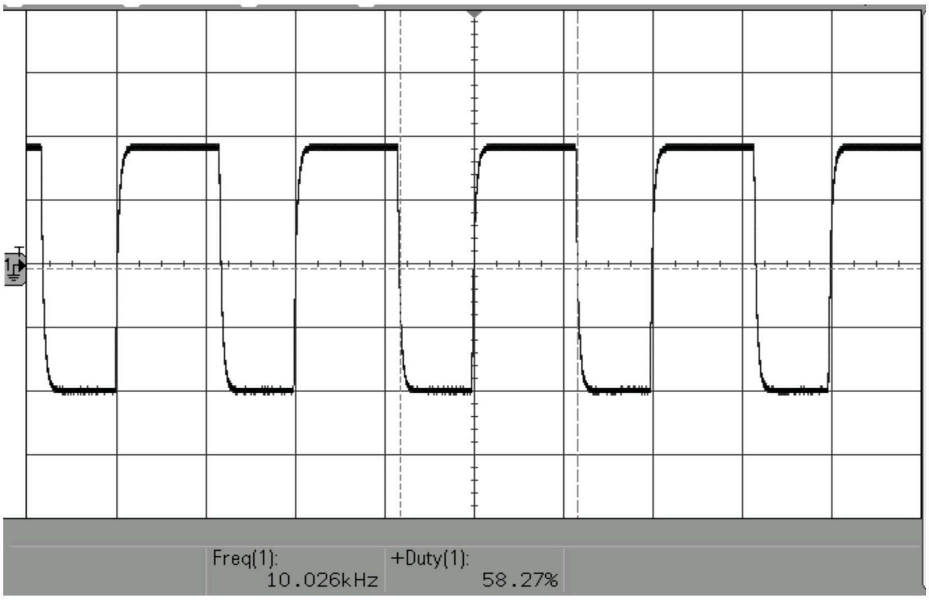

Fig 2.4 Gate Driver Circuit Output PWM Pulse for a Switching Frequency of 10kHz with a Duty Cycle of 58%

2.5 Boost Converter

DC-DC (Direct Current) converters are also known as Choppers. Boost converter is also known as step-up chopper which increases the input DC voltage to a specified DC output voltage.

The main purpose of the DC-DC is to convert the DC input from the PV into a higher DC output. The maximum power point tracker uses the DC-DC converter to adjust the PV voltage at the maximum power point. The boost topology is used for stepping up the low voltage input from the PV. A boost type converter steps up the PV voltage to high voltage necessary for the battery. A typical Boost Converter is shown below:

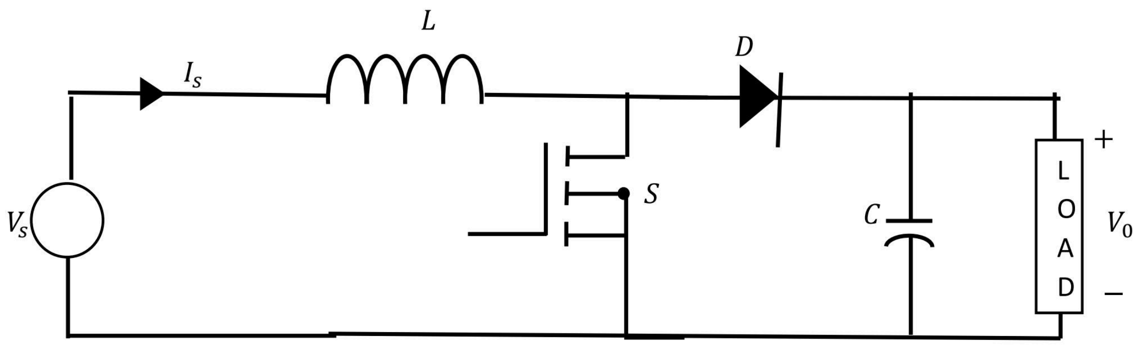

Fig.2.5 Boost Converter Circuit Diagram

Figure 2.5 shows the Boost converter. The DC input voltage is in series with an inductor L that acts as a current source. A switch T is in parallel with the current source that turns on and off periodically, providing energy from the inductor and the source to increase the average output voltage.

The capacitor C is large enough to keep a constant output voltage, and the inductor provides energy when the switch is open, boosting the voltage across the load.

The duty cycle from the MPPT controller is to control the switch of the boost converter. It is a gate signal to turn on and off the switches by pulse width modulation.

Mode I: Switch is ON, Diode is OFF

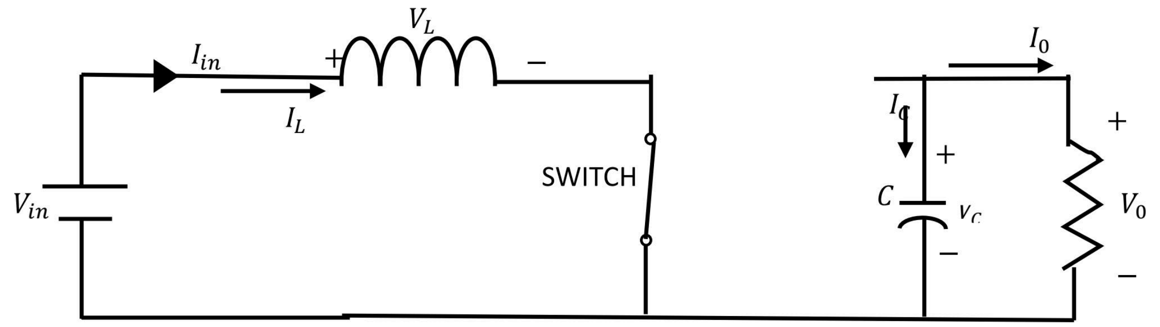

Fig.2.6 Boost Converter During Mode I Operation

The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and back to the DC input source. Let us say the switch is on for a time T_{ON} and is off for a time T_{OFF}. We define the time period (T), as:

$$T = T_{ON}+T_{OFF}$$

and the switching frequency as:

$$f_{switching} = 1/T$$

the duty cycle (D) be:

$$D=T_{ON}/T$$

Analysing the Boost converter in steady state operation for this mode using Kirchhoff Voltage Law (KVL).

$$Vin=V_L$$

$$V_L=L(di_L/dt) = Vin$$

$$di_L/dt = Vin/L$$

Since the switch is closed for a time T_{ON}=D

$$(\Delta i_L)_{closed} = (\frac{V_{in}}{L})DT$$

Mode II: Switch is OFF, Diode is ON

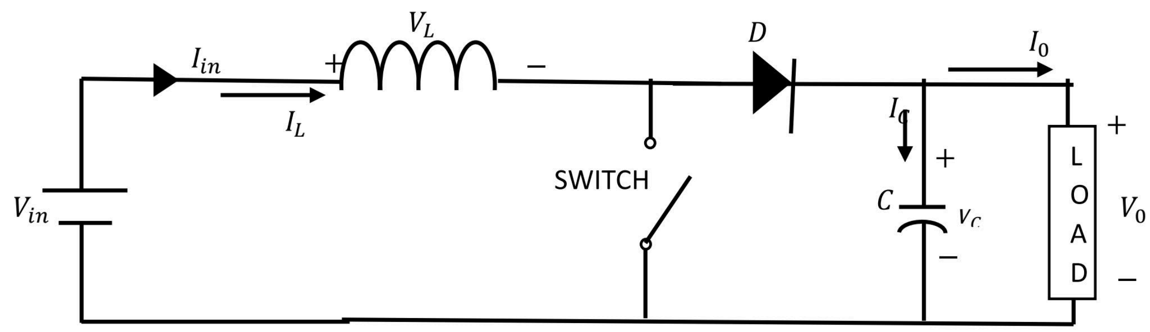

Fig.2.7 Boost Converter During Mode II Operation

In this mode, the polarity of the inductor is reversed. The energy stored in the inductor is released and is ultimately dissipated in the load resistance, and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source. But for analysis, we keep the original conventions to analyse the circuit using KVL.

Let us now analyse the **Boost converter** in steady state operation for Mode II using KVL.

$$V_{in} = V_L + V_o$$

$$V_L = L\frac{di_L}{dt} = V_{in} - V_o$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_{in} - V_o}{L}$$

Since the switch is open for a time,

$T_{OFF} = T - T_{ON} = T - DT = (1-D)T$

We can say that,

$\Delta t = (1-D)T$

$$(\Delta i_L)_{open} = (\frac{V_{in} - V_o}{L})(1-D)T$$

It is already established that the net change of the inductor current over any one complete cycle is zero.

$(\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$

$$\left(\frac{V_{in} - V_o}{L}\right)(1-D)T + \left(\frac{-V_o}{L}\right)DT = 0$$

$$\frac{V_o}{V_{in}} = \frac{1}{1-D}$$

2.5.1 Selection of Inductor

The input inductor values can be calculated based on the energy discharged during ton and toff times and the current ripples. In photovoltaic system, the boost converter functions in the discontinuous and continuous modes of conduction. The conduction mode of the converter could change depending on the atmospheric conditions. The inductor is then calculated based on the maximum inductor current and at maximum input power. Generally, the inductor value is chosen based on the desired ripple current. The inductor of the boost converter is given by

$$L= \frac{V_{mpp} \times D_{mpp}}{2 \times \Delta I_{out} \times f_s}$$

2.5.2 Selection of Capacitor

The capacitor in parallel with the load is the DC link capacitor. The value of the capacitor depends on the minimum ripple voltage. It is given in by:

$$C= \frac{V_{out} \times D_{mpp}}{2 \times \Delta V_{out} \times f_s \times R_L}$$

The output voltage of the PV array depends on the variation of temperature and insolation. To compensate the variation of the output voltage of the PV, a dc link capacitor is installed between the PV and the inverter. It helps to reduce the voltage ripple and provides energy storage for a short period and for a rapid change of the PV voltage.

2.5.3 Role of Boost Converter in Solar PV Panels

A boost converter is a type of DC-DC converter that is commonly used in solar PV panels to track the maximum power point (MPPT). The MPPT is the point at which the solar panel produces the maximum power output, and it varies depending on the environmental conditions such as temperature, shading, and solar irradiance.

The boost converter is used to increase the voltage of the output of the solar panel to a higher level, which is more suitable for charging batteries or feeding power into the grid. The boost converter achieves this by converting the DC voltage from the solar panel into a higher DC voltage by using a switching element and an inductor.

The MPPT tracking function is implemented by varying the duty cycle of the switching element (i.e., MOSFET) in the boost converter. The duty cycle is the percentage of time that the switching element is on during each switching cycle. By adjusting the duty cycle, the boost converter can maintain the output voltage at the maximum power point of the solar panel.

The boost converter with MPPT tracking capability helps to maximize the energy output from the solar PV panel by allowing the panel to operate at its maximum power point, even under changing environmental conditions. This results in improved system efficiency and higher energy yield, which is beneficial for both residential and commercial solar applications.

2.5.4 Use of High Switching Frequency

In a boost converter, the switching frequency refers to the rate at which the switching element (typically a MOSFET) turns on and off. A high switching frequency has several benefits in the modelling and operation of a boost converter:

1. Smaller passive components:

A higher switching frequency allows for the use of smaller inductors and capacitors in the boost converter circuit, which reduces the size and cost of the overall system.

2. Faster transient response:

A higher switching frequency allows the boost converter to respond more quickly to changes in the input or output voltage, resulting in improved transient response and stability.

3. Reduced electromagnetic interference (EMI):

A high switching frequency reduces the magnitude of the current and voltage spikes that occur during switching, which reduces the electromagnetic interference (EMI) generated by the converter.

4. Improved efficiency:

A higher switching frequency can lead to improved efficiency in the boost converter, particularly at low loads, due to reduced switching losses.

2.5.5 Hardware Model of Boost Converter

The Boost Converter used in this study has been developed as a hardware on dart board by soldering inductor, capacitor and diode as per the circuit diagram of boost converter (Fig. 2.3). The above formulas are helped to chose proper inductor and capacitor values with their corresponding voltage and current stress. The Fig 3.5.3 shows the modelled boost converter hardware.

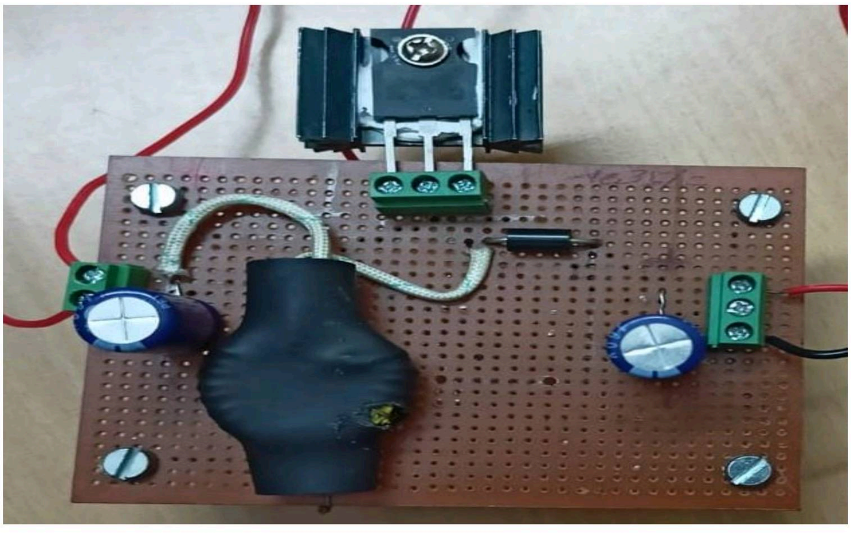

Fig 2.8 Hardware Model of Designed Boost Converter

2.5.6 Boost Converter Results:

Below tables, table no. 2.3 and table no. 2.4 shows the efficiency and output voltage for different input voltages for switching frequencies of 20kHz and 10kHz with a duty cycle of 58% of the modeled boost converter.

For a switching frequency of 20kHz and with a duty cycle of 58%

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	V_{out} (Cal) (V)	Efficiency (%)
5	0.4	2	10.94	0.15	1.6	11.94	80
10	1.14	11.4	22.4	0.4	8.96	23.8	78.59
15	0.73	10.95	30.06	0.25	7.51	35.7	68.58

Table.2.3 – Input and Output Voltage, Current, Power and Efficiency of Boost Converter for a Switching Frequency of 20kHz

For a switching frequency of 10kHz and with a duty cycle of 58%

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	V_{out} (Cal) (V)	Efficiency (%)
5	0.37	1.85	9.6	0.16	1.53	11.94	82.7
10	1.68	16.8	22.6	0.62	14.01	23.8	83.40
15	1.34	20.1	32.8	0.41	13.44	35.7	68.98

Table.2.4 –Input and Output Voltage, Current, Power and Efficiency of Boost Converter for a Switching Frequency of 10kHz

2.5.7 Boost Converter's Input and Output waveforms:

Duty Cycle: 58%

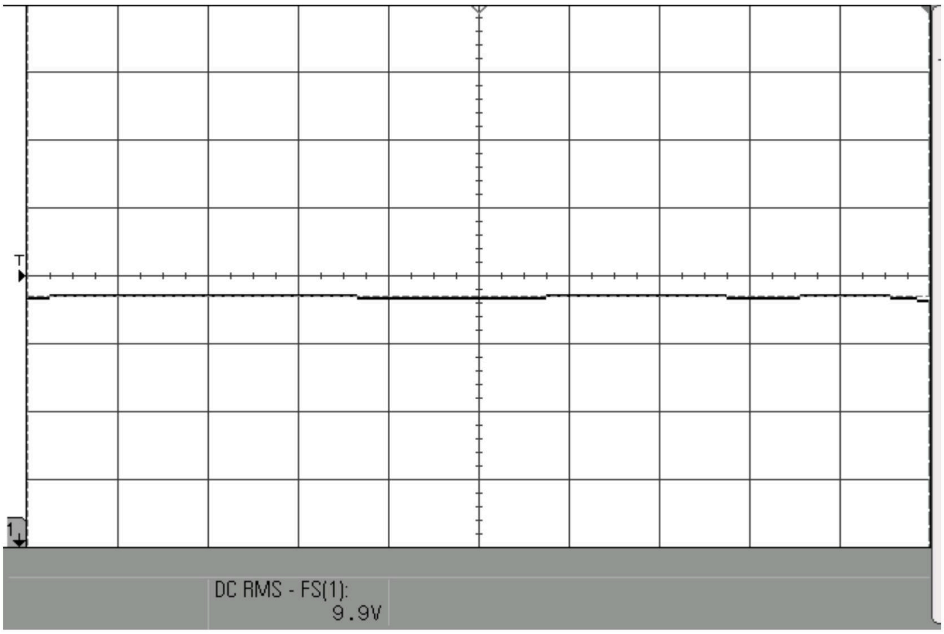

Fig 2.9 Input Voltage Waveform for 10V

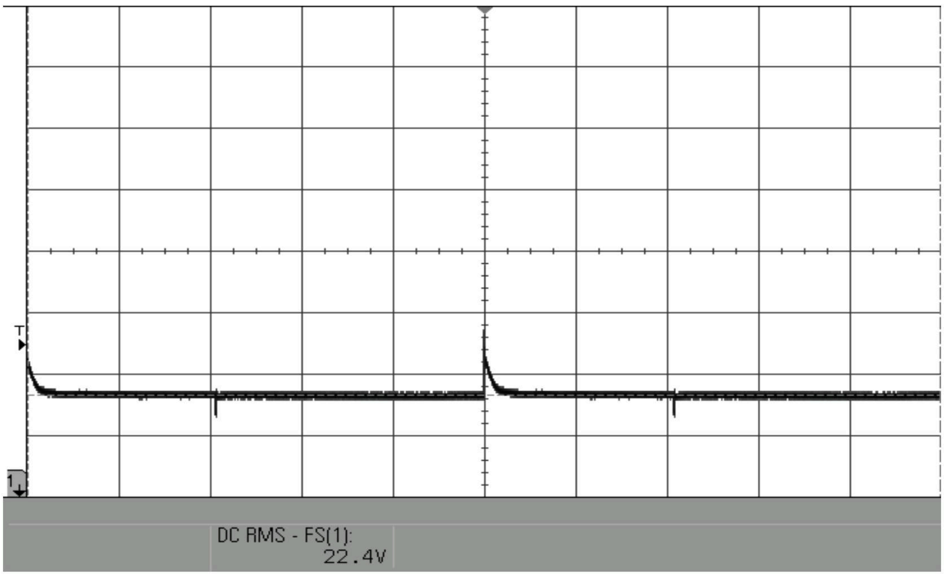

Fig 2.10 Output Voltage Waveform of 22.4V for a Switching Frequency of 20kHz

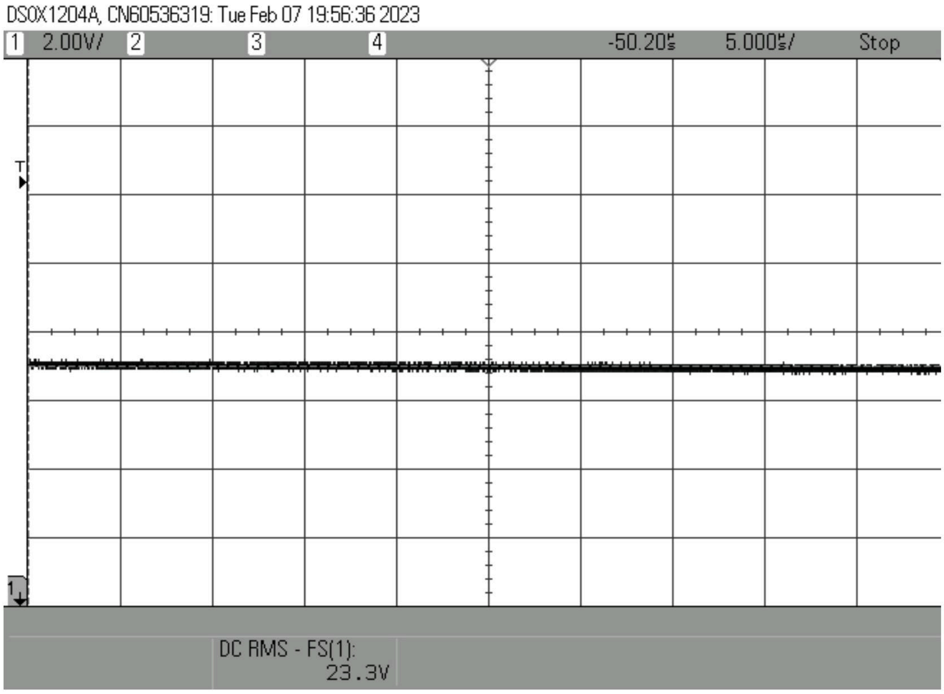

Fig 2.11 – Output Voltage Waveform of 23.3V for a Switching Frequency of 10kHz

CHAPTER 3

MAXIMUM POWER POINT TRACKING (MPPT) CONTROLLER

3.1 Solar Charge Controllers

Charge controllers, control the energy coming from the solar panels. It adjusts the current and the voltage and then sends it to the batteries. Charge controllers prevent over charge and over-discharge of the batteries. Therefore, it protects the system. Each solar energy system requires a charge control device. There are two main types of solar charge controllers,
Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) that can be used to charge batteries from a solar array/panel. Both technologies are widely used in the off-grid solar industry and are both great options for efficiently charging battery.

3.1.1 Pulse Width Modulation (PWM)

Pulse width modulation (PWM) is a technique used in solar charge controllers to track the maximum power point of a solar panel and adjust the voltage and current to optimize the power output. In PWM, the controller switches the solar panel current on and off at a high frequency (typically between 1kHz to 10kHz). The ratio of the on-time to the total time is called the duty cycle. By adjusting the duty cycle, the controller can maintain the solar panel output voltage at the level that maximizes the power output.

To track the MPP using PWM, the controller measures the voltage and current output of the solar panel and calculates the power output. The controller then adjusts the duty cycle to increase or decrease the voltage and current output to track the MPP. This process is repeated continuously to ensure that the MPP is tracked under changing weather conditions.

PWM charge controllers can be explained as an electrical switch between batteries. The switch can be quickly switch on and switch off. Therefore, desired voltage can be obtained to charge the batteries. The charged current will be slowly decreased as the batteries charged.
Features of PWM technique : The pulse width modulation (PWM) technique has several features that make it useful for regulating the charging process in solar charge controllers:

1. Efficiency: PWM controllers are more efficient than simple 1 or 2 stage controllers, as they can adjust the charging voltage to the battery by rapidly turning the charging current on and off, thereby maintaining a constant battery voltage.

2. Battery protection: PWM controllers prevent overcharging of the battery by maintaining a constant battery voltage, which helps to extend the life of the battery.

3. Simple design: PWM controllers have a simple circuit design, which makes them easy to manufacture and maintain
4. Cost-effective: PWM controllers are relatively inexpensive compared to other charge controller technologies.

5. Wide availability: PWM controllers are widely available and can be used with a variety of solar panel and battery types.

6. MPP tracking: PWM controllers can be used to track the maximum power point (MPP) of the solar panel and adjust the voltage and current to optimize the power output, improving the charging efficiency.

7. Durability: PWM controllers are durable and can operate in a wide range of temperatures and weather conditions.

3.1.2 MPPT Controller

MPPT stands for Maximum Power Point Tracking. The major principle of MPPT is to extract the maximum available power from PV module by making them to operate at the most efficient voltage (maximum power point). MPPT checks output of PV module, compares it to battery voltage then fixes what is the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. Solar panels show changeable outputs according to weather conditions. MPPT charge control devices can match the solar panel voltage with battery voltage to maximize the charge efficiency.

MPPT is most effective under these conditions: -

1. Cold weather, cloudy or hazy days: Normally, PV module works better at cold temperatures and MPPT is utilized to extract maximum power available from them.

2. When battery is deeply discharged: MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

Features of a MPPT solar charge controller: -

1. The MPPT charge controller corrects the solar cell's voltage and current variation.

2.It ensures that maximum energy is drawn from the solar panels.

3. This controller can be used in wind-power turbines and small water turbines.

4. It eases the system's complex operation.

3.2 An Overview of MPPT Controller Algorithms

Numerous MPPT algorithms already exist which include a variety of different techniques, methodologies, and approaches. This section will give an overview of the most popular ones since going over all the existing MPPT techniques and algorithms is out of the scope of this thesis. Most of the algorithms developed are more than a decade old; the newer ones are primarily a variation, combination, or adoption of the principles used in the older MPPT techniques. This section will also briefly present a few recent MPPT algorithms that have been developed and focus in-depth about the Multi Variate Linear Regression (MLR) algorithm, which is the primarily used algorithm in this project work.

3.2.1 Problem Overview

A PV cell or array can only produce its maximum power at a particular level of voltage or current corresponding to the solar insolation on it. Usually, the voltage level at maximum power point and current level is denoted as V_{mpp} and I_{mpp}, respectively, and the maximum power point as P_{mpp}. As seen in Figure 2.1, the output characteristics of a PV panel show that the panel will not be at P_{mpp} if its operating voltage or current falls below or rises above V_{mpp} or I_{mpp}, respectively.

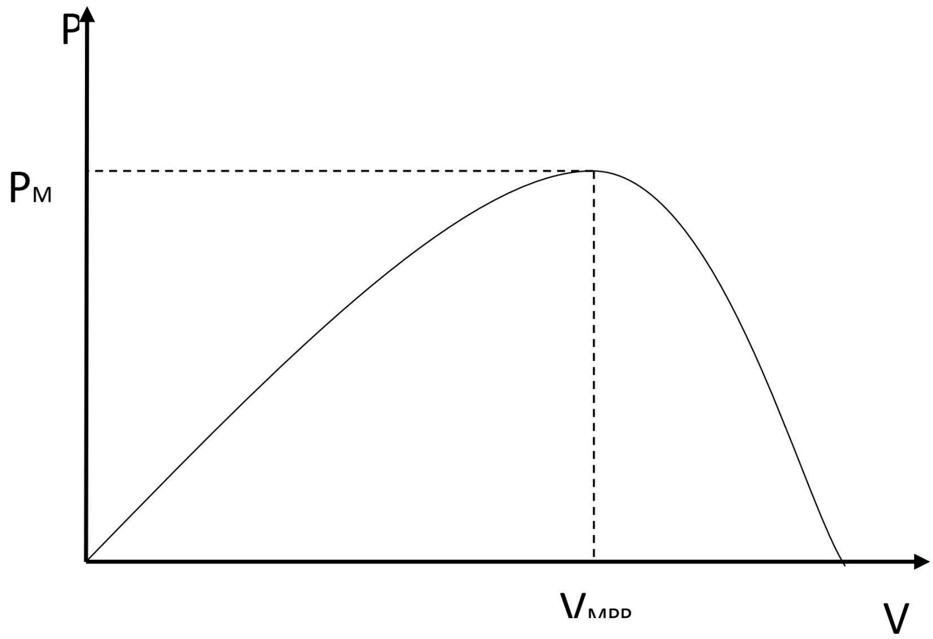

Fig.3.1 Characteristics of PV Array

MPPT is the solution to the problem of automatically finding the V_{mpp} or I_{mpp} of the PV panel at which the PV panel will be at its P_{mpp} at the given solar irradiance and temperature level.

3.2.2 Common MPPT Algorithms

Perturb and Observe (P&O), and Hill-Climbing methods are one of the most popular MPPT technique used. In this technique, the panel voltage and current are initially measured, and then the corresponding panel power, P1. Then, a small perturbation in the voltage (ΔV) or duty cycle (Δd) of the DC-DC converter is performed in one direction, and the corresponding power, P2, is calculated. P2 is then compared to P1, and if it is observed that P2 > P1, the perturbation was in the correct direction, and it continues. But if P1 > P2, then the perturbation direction is reversed. By continuously repeating this, the P_{mpp} is eventually realized. The popularity of P&O can be credited to its many advantages such as, it is PV array independent, it is easy to implement, and can be performed by using both analog and digital systems. Despite its advantages, P&O has a few major issues, it keeps oscillating about the MPP at steady state, and its tracking efficiency is not accurate under rapidly changing solar irradiance.

Incremental Conductance (Inc Cond) method works using the fact that the slope of the output power characteristic curve of a PV array as shown in Figure 2.1 will be zero at the MPP, positive on the left of MPP, and negative on the right of MPP. It can be summarized as follows:

$$dP/dV = 0, \ at\ MPP$$

$$dP/dV < 0, \ at\ right\ of\ MPP$$

$$dP/dV > 0, \ at\ left\ of\ MPP$$

Another domain of MPPT techniques can be realized by using high-performance microcontrollers. These are the intelligent MPPT techniques. They are primarily based on fuzzy logic and artificial neural networks. The Fuzzy Logic (FL) Control based MPPT method normally consists of three steps: fuzzification, a fuzzy rule algorithm or look-up table, and defuzzification. It takes in two inputs which are the error signal (E) and change in error signal (ΔE) and gives a single output. The two input variables at the k th sampled time are defined in Equation (2.4) and (2.5). The block diagram of the fuzzy logic MPPT interface is shown in Figure 2-2.

$$E(k) = dP/dV\ (k) - dp/dv(k-1)$$

$$\Delta E = E(k) - E\ (k-1)$$

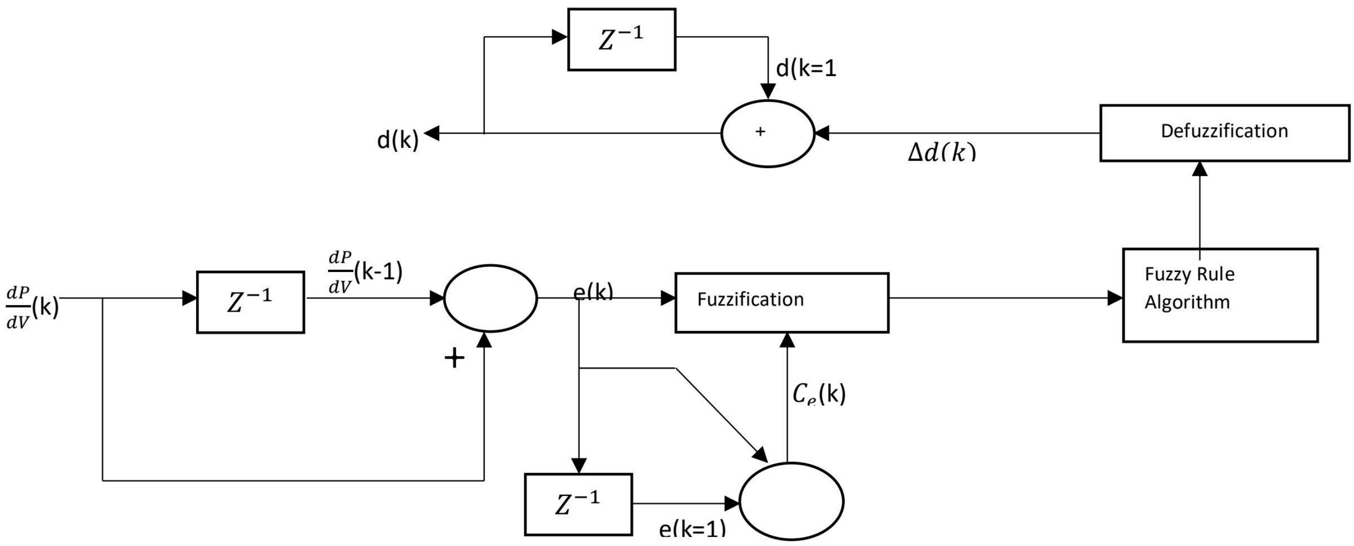

Fig.3.2 Block diagram of Fuzzy Logic MPPT Technique

Artificial Neural Network (ANN) based MPPT technique is also well adapted for microcontrollers. ANN typically has an input layer, a hidden layer, and an output layer, as shown in Figure 2-3. The effectiveness of the controller will depend on the algorithm utilized in the hidden layer and how well the neural network was trained. The input variables can be the PV array voltage, current, solar irradiance, temperature, and other atmospheric data. The output signal is usually the duty ratio, which will drive the DC-DC converter close to MPP.

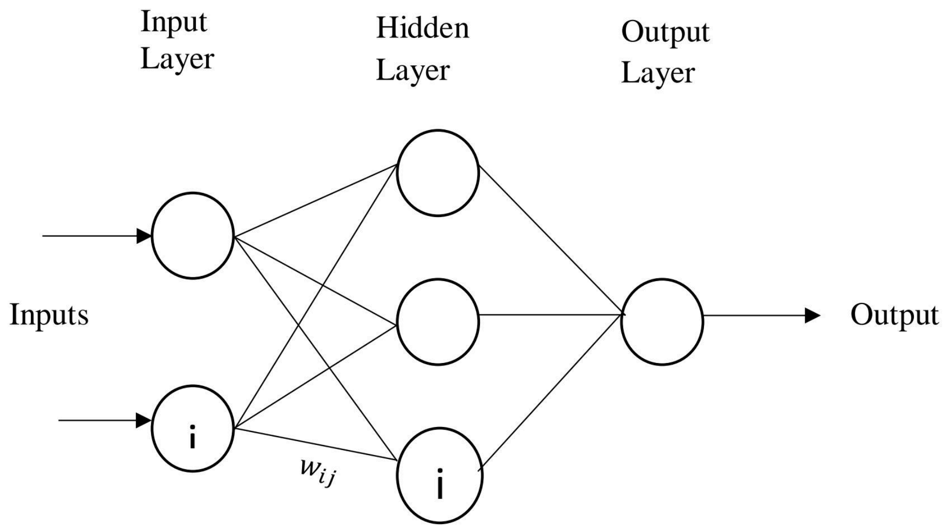

Fig.3.3 Neural Network Example

Both these intelligent MPPT methods (FLC & ANN) have similar advantages. They achieve good tracking efficiency at fast response times with minimal fluctuations at steady state. For the Fuzzy Logic Control, no prior knowledge of the PV array is needed. But for ANN it requires prior data on the specific PV panels that are going to be used in order to train the neural network. A disadvantage that both shares is that the FLC or ANN implementation is complex and costly.

The linear regression machine learning technique is simple and best suitable for predicting a real number from the existing data. It predicts the unknown data, commonly known as dependent data, from the features popularly known as independent data. If the data has a single feature, then the univariate linear regression algorithm gives a straight line to predict the data in a two-dimensional space. If the data has multiple features, then Multi Variate Linear Regression (MLR)can be used, it provides a plane with multi-dimensional space. MLR is a proposed MPPT technique used to predict the voltage or current of the PV panel in order to drive it to the MPP. In MLR the independent variables are irradiance and temperature and the dependent variable can be voltage or current of PV panel. In MLR it models an equation with the help of trained data and it predicts the corresponding value for new value. The MLR algorithm drives the PV panel voltage and current to its MPP. Among many, one of the advantages of MLR is that it models an equation to predict the voltage which takes less time and a faster convergence. The general form of the multi variate linear regression is as follows: $y=b_0+b_1x_1+b_2x_2+\ldots\ldots\ +b_nx_n$

CHAPTER 4

DESCRIPTION OF SYSTEM

4.1 Introduction to Linear Regression

Machine Learning (ML) is the field of study that gives computers the capability to learn without being explicitly programmed. ML is one of the most exciting technologies that one would have ever come across. As it is evident from the name, it gives the computer that makes it more like humans: The ability to learn. Machine learning is actively being used today, perhaps in many more places than one would expect.

Linear regression was developed in the field of statistics and is studied as a model for understanding the relationship between input and output numerical variables, but has been borrowed by machine learning. It is both a statistical algorithm and a machine learning algorithm.

Linear regression is a linear model, e.g., a model that assumes a linear relationship between the input variables (x) and the single output variable (y). More specifically, that y can be calculated from a linear combination of the input variables (x).

When there is a single input variable (x), the method is referred to as simple linear regression. When there are multiple input variables, literature from statistics often refers to the method as multiple linear regression.

4.1.1 Data in Linear Regression

Machine Learning Algorithms learn from data. They find relationships, develop understanding, make decisions, and evaluate their confidence from the training data they are given. And the better the training data is, the better the model performs.

Data: It can be any unprocessed fact, value, text, sound, or picture that is not being interpreted and analysed. Data is the most important part of all Machine Learning, Artificial Intelligence. Without data, we can’t train any model and all modern research and automation will go in vain.

Information: Data that has been interpreted and manipulated and has now some meaningful inference for the users.

Knowledge: Combination of inferred information, experiences, learning, and insights. Results in awareness or concept building for an individual or organization.

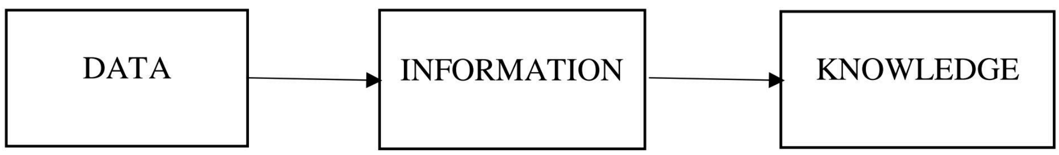

Fig.4.1 Learning of Model

4.1.2 Linear Regression Model Representation

Linear regression is an attractive model because the representation is so simple.

The representation of linear regression is a linear equation that combines a specific set of input values (x) the solution to which is the predicted output for that set of input values (y). As such, both the input values (x) and the output value are numeric.

Mathematical equations for simple and multi linear regressions is as follows:

$$y=b_0+b_1x$$

$$y=b_0+b_1x_1+b_2x_2+\ldots\ldots\ldots+b_nx_n$$

were,

y=Predicted output

b_0, b_1, b_2…., b_n=regression co-efficient

x_1, x_2, x_3,…., x_n=inputs

4.2 Arduino UNO

Arduino Uno is a microcontroller board that is part of the Arduino family of boards. It is a popular and widely used board due to its affordability, ease of use, and versatility.

The Arduino Uno board is based on the ATmega328P microcontroller, which is the heart of the board. The ATmega328P is an 8-bit microcontroller with 32KB of flash memory, 2KB of SRAM, and 1KB of EEPROM. It also has 14 digital input/output pins, six analog input pins, and several other features that make it a powerful and flexible microcontroller.

One of the most significant advantages of the Arduino Uno board is its ease of use. The board comes with a pre-loaded bootloader, which allows users to easily upload new code to the board without the need for an external programmer. Additionally, the board can be programmed using the Arduino Integrated Development Environment (IDE), which is a simple and intuitive programming environment that is easy to learn.

The digital input/output pins on the Arduino Uno board can be used to connect to various electronic components, including LEDs, motors, and sensors. These pins can be programmed to either output a voltage or to read a voltage input. Additionally, the board has six analog input pins, which can be used to read analog signals from sensors and other electronic components.

One of the most powerful features of the Arduino Uno board is its ability to communicate with other devices. The board has a USB port, which can be used to communicate with a computer and to upload new code to the board. Additionally, the board has several other communication interfaces, including I2C, SPI, and UART. These interfaces allow the board to communicate with a wide range of other devices, including sensors, displays, and other microcontrollers.

Fig.4.2 Arduino Uno Board

In this project work, potentiometers are used as irradiance and temperature sensors and their corresponding values within 5V signal read by the analog input pins in the Arduino UNO i.e., A0, A1, A2, A3, A4, A5. The read analog input is multiplied with a proper calibration factor to obtain the actual value of the irradiance and temperature. Using the actual values of irradiance and temperature the linear regression algorithm predicts the duty cycle by making certain calculations. The predicted duty cycle value of a certain switching frequency PWM pulse is generated through Arduino using PWM pins i.e., pins 3,5,6,10,11. The output from the Arduino is fed to the gate driver and the output from the gate driver circuit is fed as gate pulse to the MOSFET switch. The boost converter boosts the input voltage to the required voltage.

4.3 Flowchart of Algorithm

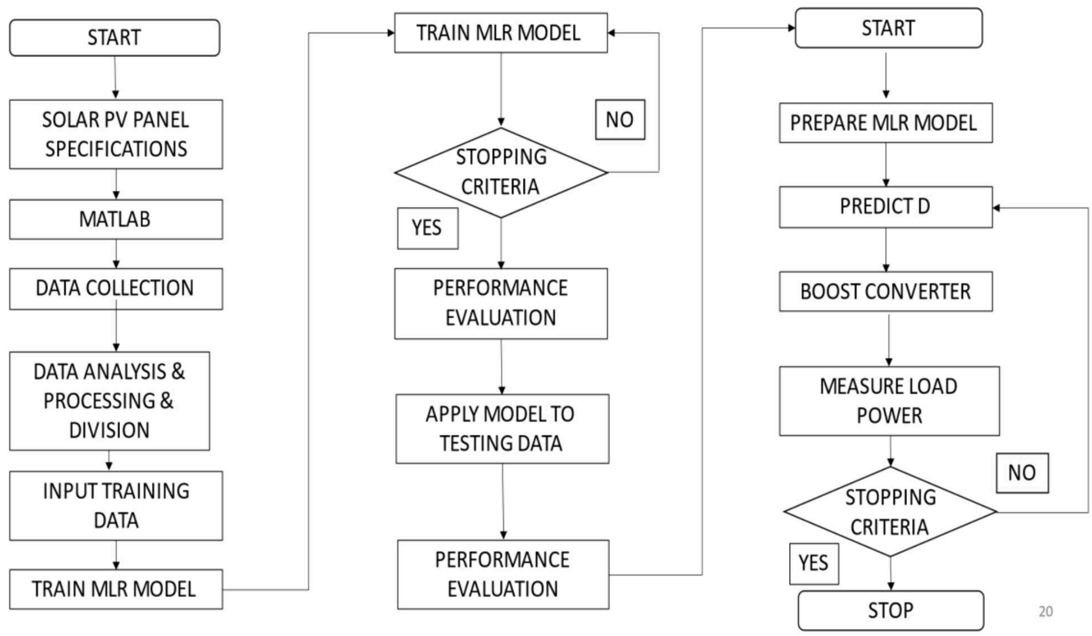

Fig.4.3. Flowchart of Algorithm

CHAPTER-5

RESULTS

5.1 Hardware Model

The modelled MPPT controller using Linear regression algorithm and Boost converter were used to build circuit in SIMULINK. The circuit is as follows:

Fig.5.1 Developed Hardware Model

5.2 Hardware Results

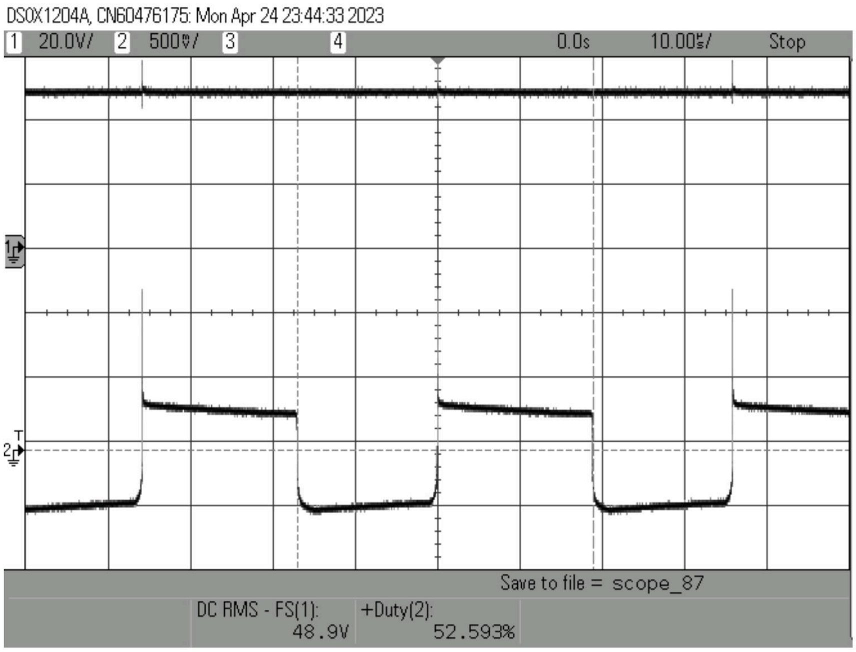

Fig.5.2 Output Voltage from the Boost Converter and PWM Pulse from Arduino for an Irradiance of 800W/m^2

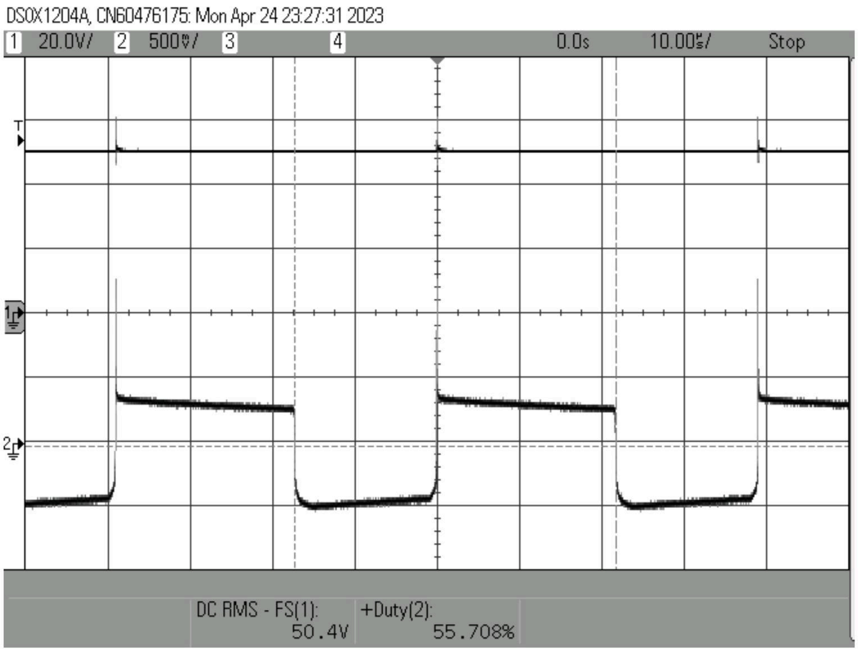

Fig.5.3 Output Voltage from the Boost Converter and PWM Pulse from Arduino for an Irradiance of 600W/m^2

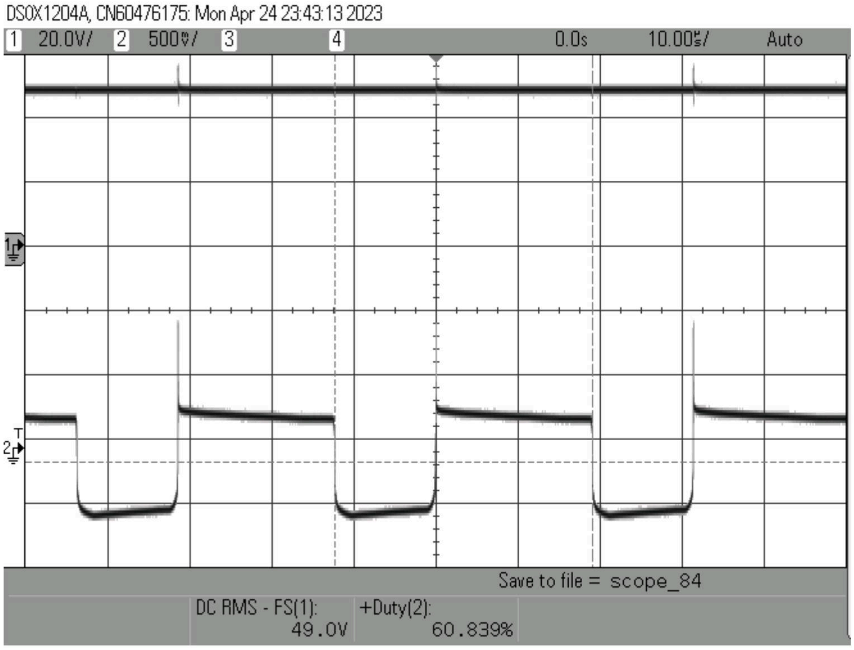

Fig.5.4 Output Voltage from the Boost Converter and PWM Pulse from Arduino for an Irradiance of 500W/m^2

Irradiance (W/m^2)	Duty ratio (%)	Input Voltage to the Boost Converter (V)	Output Voltage (V_{out}) (V)
800	52.59	23.65	48.9
600	55.70	22.41	49.2
500	60.83	19.92	49.8
400	64.2	17.92	50.2
200	67.4	16.43	50.6

Table 5.1 Performance of Boost Converter with the MLR MPPT Control for Various Irradiance and at a Constant Temperature of 25°C

CHAPTER-6

SUMMARY AND CONCLUSION

6.1 Summary

This thesis established a new algorithm for maximum power point tracking (MPPT) controller using linear regression. Although the concept of MPPT is not new, modern society demands more power to energize its enhanced equipment and instruments and also to reduce global warming. With photovoltaics (PV) as the primary source of electricity production, it becomes even more necessary for power converters to have MPPT controllers. The main component of a DC-DC converter is a MOSFET. This device utilized in the converter must be able to handle high voltage and current stress and switch at high frequency with minimal losses. Detailed background on MPPT techniques is given briefing the most common ones.

6.2 Conclusion

The MLR model that has been generated from MATLAB has been implemented into Arduino UNO. Based on the calculated parameters of the boost converter a boost converter is modeled on a dart board by properly soldering the components based on the circuit diagram. As we know that the pulses generated from Arduino are not sufficient and cannot able to switch on the MOSFET switch hence it requires a gate driver circuit. A gate driver circuit has been modelled using TLP250. The model performance has been validated with the evaluation metrics. The trained and tested model is used to make predictions and the predicted output is fed to boost converter. The MPPT is achieved using the MLR model. The power output is validated with theoretical values. The MLR algorithm reaches the MPP in about 0.02 seconds and less oscillations.

REFERENCES

[1] P. Venkata Mahesh, S. Meyyappan, A New Multivariate Linear Regression MPPT Algorithm for Solar PV System with Boost Converter. Ecti transactions on electrical engineering, electronics, and communications vol.20, no.2 june 2022.

[2] D. Khodair, M.S. Salem, Application of Modified MPPT Algorithms: A Comparative Study between different types of solar cells. https://doi.org/10.3103/S0003701X20050084

[3] J. A. Carballo, J. Bonilla, M. Berenguel, J. FernándezReche, and G. García, "Machine learning for solar trackers," AIP Conference Proceedings, vol. 2126, 2019, Art. no. 030012.

[4] Norazlan Hashim (2018) & Zainal Salam. DC-DC Boost Converter Design for Fast and Accurate MPPT Algorithms in Stand-Alone Photovoltaic systems. https://doi.org/10.3103/S0003701X20050084

[5] Telbany, M. E. E., Youssef, A., & Zekry, A. A. (2015). Intelligent Techniques for MPPT Control in Photovoltaic Systems: A Comprehensive Review. Proceedings - 2014 4th International Conference on Artificial Intelligence with Applications in Engineering and Technology, ICAIET 2014, 17–22.

[6] Younis, M. A., Khatib, T., Najeeb, M., & Mohd Ariffin, A. (2012). An improved maximum power point tracking controller for PV systems using artificial neural network. Przeglad Elektrotechniczny, 88(3 B), 116–121.

[7] Yuvarajan, S., & Shoeb, J. (2008). A fast and accurate maximum power point tracker for PV systems. https://doi.org/10.1109/APEC.2008.4522717

[8] Phan, Q. D., Le, D. K., Hong, H. L., Le, M. P., & Vu, N. T. D. (2010). The new MPPT algorithm using ANN-based PV.2010 International Forum on Strategic Technology, IFOST 2010, September 2014, 402–407.

[9] Karanjkar, D. S., Chatterji, S., Shimi, S. L., & Kumar, A. (2014). Real-time simulation and analysis of maximum power point tracking (MPPT) techniques for solar photo-voltaic system. 2014 Recent Advances in Engineering and Computational Sciences, RAECS 2014, 6–8.