SOLAR CHARGE CONTROLLER FOR ENHANCED PV SYSTEM PERFORMANCE

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CERTIFICATION

This is to certify this project titled "Solar Charge Controller for Enhanced PV System Performance" carried out by **Njoku Francis Kennedy, Obhiozele Ehiabhili Donald, Okoh Elijah Olusola** and **Oriarewo Ehimen Kelvin** in the Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Benin, Benin City. For the requirement of the award of Bachelor of Engineering (B.Eng.) Degree in Electrical and Electronics Engineering.

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DEDICATION

This project is dedicated to Almighty God for his given wisdom, grace, strength, guidance and ever-flowing mercy throughout this important chapter of our lives

This is also dedicated to our supervisor, Engr. Dr. T. A. Aika for his invaluable support and insightful guidance that made any of this possible.

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We wish to use this this medium to express our deepest gratitude to the Almighty God for giving us strength, wisdom and endurance to complete our project successfully.

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A very special thanks goes to our family members, guardians, friends, course mates and well-wishers. Your constant support either financially or through words of encouragement gave us the necessary boost to make this project a reality.

ABSTRACT

This research project touches on the simulation, design and applications of a Solar Charge Controller to enhance the performance of a Photovoltaic system.

Solar charge controllers are devices that helps regulate the flow of voltage and current from solar panels in order to prevent over-charging or over-discharging of the batteries acting as a regulator.

They are essential to the management of the charge and discharge of batteries through the regulation of their currents and voltages in order to increase and improve the lifespan and efficiency of batteries.

This study explores the design, simulation, implementation, test and evaluation of a solar charge controller including calculations for its voltage, current, power, capacitance and inductance. A detailed description of various components used to design the solar charge controller is also provided as well as the simulation and test results on the solar charge controller.

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ABBREVATIONS

PV-	Photovoltaic
PWM-	Pulse Width Modulation
MPPT-	Maximum Power Point Tracking
DC-	Direct Current
LCD-	Liquid Crystal Display
MOSFET-	Metal Oxide Semiconductor Field Effect Transistor
CAD-	Computer Aided Design
DIY-	Do It Yourself
IC-	Integrated Circuit
IoT-	Internet of Things
I^2C-	Inter-Integrated Circuit
GPIO-	General Purpose Input/Output
TVS-	Transient Voltage Suppressor
LED-	Light Emitting Diode
IGBT-	Insulated-Gate Bipolar Transistor
MPP-	Maximum Power Point

CHAPTER ONE

INTRODUCTION

1.1 Background To the Study

Photovoltaic cells are a fundamental component of renewable energy technology as they offer a clean and robust way to generate electricity directly from the sun. This device converts light energy into electrical energy through the photovoltaic effect which is the generation of voltage and electric current in a material when it is exposed to light. The demand for high efficiency in using renewable energy resources is increasing and this can be resolved by utilizing more reliable Photovoltaic (PV) charge controllers.

Charge controllers, also known as charge regulators are electronic devices that manage the charging and discharging of batteries, particularly in renewable energy systems such as solar and wind power setups in order to prevent overcharging of batteries. But in specific terms, PV charge controllers are devices used in solar power systems to regulate the voltage and electric current coming from the panels to the batteries.

The very essence of using charge controllers cannot be overemphasized as they serve a high ordeal in voltage and current regulation as well as others which includes:

- Prevention of battery damage.
- Optimizing battery performance.
- Better handling of load control.
- Preserving Battery lifespan

1.1.1 Types of Charge controllers

The charge controller consists of two major types:

1. Pulse Width Modulation (PWM) Controller: These are simpler and less expensive charge controllers and they basically use a constant voltage

algorithm by switching the power flow from the solar panels on and off while adjusting the pulse width to maintain the charge.

2. Maximum Power Point Tracking (MPPT) Controller: These are the more efficient and sophisticated charge controllers as they work by adjusting the input voltage drawn from the solar panels to extract its maximum power output at any given time, which is especially useful in varying environmental conditions by utilizing the MPPT algorithm.

1.1.2 Advantages of Charge controllers

1. Efficiency: Especially with MPPT controllers, they can optimize the energy harvested from solar panels, increasing overall systems efficiency.
2. Safety operation: Charge controllers are usually safe to work with as they are incorporated into circuits in order to minimize the destruction of components and other connected devices.
3. Battery protection: Charge controllers prevent overcharging, deep discharging, extending the battery lifespan and maintaining its performance.

1.1.3 Disadvantages of charge controllers

1. Cost: The cost of charge controllers can vary depending on output range it can serve and they can be quite expensive as well.
2. Complexity: The design of charge controllers can be so robust and complex
3. Heat Dissipation: The amount of heat usually give out by charge controllers can be very high which is usually as a result of the amount of current they are capable of driving.
4. Maintenance: Charge controllers often need to be serviced as to evaluate their performance overtime and this is not always an easy task to perform.

This project proposes a charge controller circuit that is used to extract maximum power from solar panels for effective utilization by batteries or output load devices. Under reduced conditions of sun intensity which can arise from several weather conditions, the power emanating from the solar panels is usually not adequate for energy consumption, but with the availability of a charge controller, even the low power generated by the solar panels can be made more useful.

In this project, a Photovoltaic MPPT charge controller is designed based on microcontroller Arduino Nano, with a number of other electronic components for highly efficient monitoring and regulation. The project uses a DC-DC buck converter which has been simulated using Proteus electronic CAD software. PWM and MPPT algorithms are also being implemented by using the Arduino Nano to control the duty cycle, voltage and current in the PV system and it is programmed with the Arduino C/C++ code. The Liquid Crystal Display (LCD) is used to display the voltage and current of both the solar panel and the battery. The essence of this project is for the improvement of photovoltaic energy consumption which usually depends on programmed control and system adjustment.

1.2 Problem Statement

The world is experiencing a rapidly increasing demand for energy which is basically driven by population growth, urbanization and industrialization and as traditional fossil fuel energy sources depletes and the environmental impact of the fuels become less apparent, there is a significant shift towards renewable energy sources, especially in the area of photovoltaic power systems which are steadily on an increase across the globe.

This shift is motivated by the need for sustainable, clean and reliable energy that does not cause adverse effects on society. And in using these renewable energy sources like solar panels, there is the need for efficient power generation for effective consumption which can be made possible by employing suitable PV charge controllers.

1.3 Aims And Objectives

The aim of this project is to design a Maximum Power Point Tracking solar charge controller, and the objectives are:

1. To design a charge controller.
2. To simulate the charge controller.
3. To implement the charge controller design.
4. To test and evaluate the performance.

1.4 Methodology

This project will be carried out with the following methods;

1. Use electrical circuit theory to calculate the output of the charge controller.
2. The charge controller will be simulated using CAD software Proteus.
3. The design will be implemented on circuit board i.e. Veroboard.
4. A solar system (panels) will be used to test the design

1.5 Scope Of Study

This design will utilize the MPPT charge controller algorithm and it will be limited to a pulse width modulated square signal waveform with its voltage range of $12V_{DC}$, $24V_{DC}$ and $48V_{DC}$ with a current of 10A I_{DE}.

1.6 Relevance Of the Project

A charge controller is a crucial component in a renewable energy system, particularly in solar and wind power setups. Its relevance lies in several key functions:

1. Regulate the voltage and current from solar panels.
2. Prevent the overcharging and deep discharging of batteries.
3. Optimize battery performance.

4. Load control
5. It can help evaluate the difference between DIY charge controllers and already-made charge controllers in terms of their cost while having same operating conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Description Of the Charge Controller

Usually, a solar panel will generate different voltages which is basically dependent on;

1. The amount of available sunlight,
2. The temperature of the solar panel, and
3. The connected load at the output.

These parameters in turn are also essential in determining the efficiency of the system and hence helps to maximize the power generated by the solar panel and hence brings about the need for a charge controller which is a device used in systems that involve the generation, storage, and utilization of electrical energy, especially in renewable energy setups like solar power systems.

The primary function of the charge controller is to regulate and control the flow of electric charge from a power-generating source, such as a solar panel or wind turbine to a battery bank, ensuring that the batteries are charged efficiently and safely. Without a charge controller, batteries could be overcharged, leading to degradation, reduced lifespan, or even damage, or they could be undercharged, resulting in inefficient energy storage.

Some of the key functions of a charge controller includes;

1. Overcharging Prevention: The charge controller monitors the battery voltage and prevents it from exceeding a safe level. Overcharging can cause excessive heat, gas production (in the case of lead-acid batteries) and irreversible damage to the battery's internal structure, severely reducing its longevity. A charge controller ensures that when the battery voltage reaches a specified maximum, the charging current of the battery is reduced or cut-off for its protection.

2. Over-discharging Prevention: Modern charge controllers often include a feature to prevent over-discharging, which occurs when the battery is drained beyond its safe discharge limit. Over-discharging can damage the battery's chemical composition, leading to permanent capacity loss. The controller may disconnect the load or sound an alarm when the battery reaches a low-voltage threshold to avoid this scenario.
3. Regulate Voltage and Current: Charge controllers regulate both the voltage and the current going into the battery. The power generated from renewable energy sources can fluctuate due to environmental factors and the charge controller stabilizes these fluctuations, ensuring that the battery is charged consistently with the correct voltage and current levels. This regulation is vital for maintaining battery health and optimizing charging efficiency.
4. Power Conversion and Maximum Power Point Tracking (MPPT): More advanced charge controllers, especially those used in Photovoltaic systems, often include Maximum Power Point Tracking technology. MPPT charge controllers dynamically adjust the voltage and current to extract the maximum possible power from solar panels. This technology significantly increases the efficiency of the energy transfer from the solar array to the battery, especially under varying environmental conditions. MPPT charge controllers are particularly beneficial in colder climates or low-light situations, where they can still optimize energy harvesting.
5. Load Control: Some charge controllers provide load control features, meaning they can directly manage the connection between the battery and the electrical load (e.g., lighting, appliances, or other devices drawing power from the battery). Load control helps in automating systems such as switching off the load when the battery level is too low or turning it on when the battery is sufficiently charged, ensuring efficient energy use and battery protection.

2.2 Components In a Solar Charge Controller

The main components of a charge controller work together in a synchronized manner to regulate and manage the flow of electrical energy from a power source (like solar panels or wind turbines) to a battery bank, ensuring the system operates efficiently and safely.

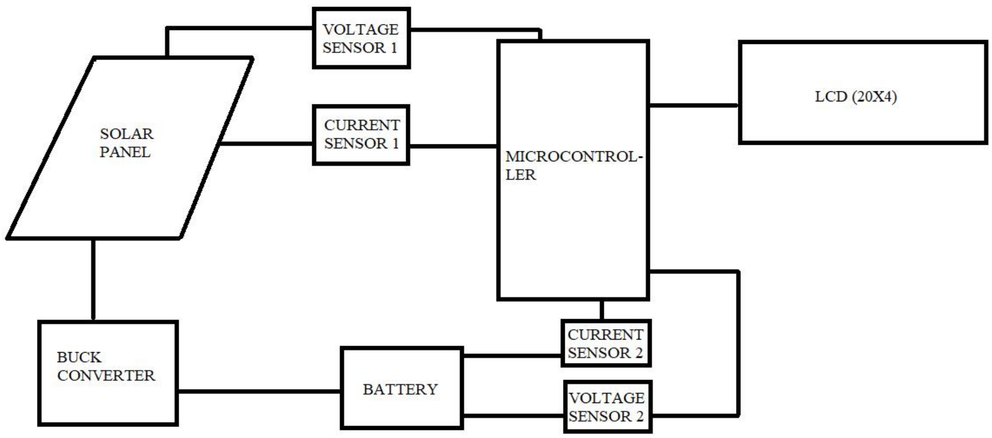

Figure 1: Block Diagram of a Charge Controller

How the main components of a charge controller collaborate together is described below:

1. Input Stage (Source): This stage is characterized by power generating sources (i.e. solar panel) which receives the impending energy and directs it to the charge controller. It receives varying voltage and current levels which is usually dependent on the environmental conditions like sunlight or the positions of clouds in the case of solar panels. The input stage of a solar charge controller comprises of the solar panels which delivers power to the controller and also other system components (e.g. regulators, converter) that begins the process of stabilizing and optimizing the energy for storage. If the system uses an MPPT charge controller, this input stage plays a critical role in ensuring that the maximize power available from the source is captured.

2. Voltage and Current Sensors: This stage comprises of the voltage and current sensors which helps to sense the corresponding input and output voltage and current and send the information to the microcontroller which processes these readings and helps maximize the flow of energy between the input and output stages.
3. Microcontroller: This is the brain of the charge controller and it is responsible for coordinating all activities within the charge controller system, ranging from monitoring the voltage and current levels of both the input and output stages, regulating the power flow the battery, turning on/off switches like MOSFETs, controlling the charging phases of the battery bank, generate PWM signals to regulate power converters to displaying relevant data to the LCD screen for real time monitoring and other performance tracking.
4. Buck Converter: Often referred as a step-down converter, it is a type of DC-DC converter that steps down a higher input voltage to a lower output voltage, making it ideal for use in charge controllers where the input voltage from the source like a solar panel might be higher than the battery voltage.

   The buck converter comprises several components interconnected together to serve a single function which is to convert higher input voltage to a lower output voltage which in turn increases the output current due to the reduced output voltage.

   From power equation,

$$P = V \times I$$

   This shows that for a given power, a decrease in voltage results in an increase in current, and vice versa due to the inverse relationship. This is important for the operation of the buck converter. Some of its several components are:

   - **Switching Element**: The main component of a buck converter is a high-speed switch (Usually a MOSFET), which rapidly turns ON and OFF. When the switch is ON, current flows from the input source to the inductor which makes it store energy in magnetic fields.

- **Inductor**: The inductor plays a crucial role in smoothing the current. When the switch is OFF, the inductor releases the stored energy, maintaining current flow to the load (the battery in the charge controller)
- **Diode**: A freewheeling diode is placed across the load. It provides a path for the inductor's current when the switch is off, ensuring continuous current flow to the battery.
- **Capacitor**: A capacitor helps to filter out voltage ripples, smoothing the output voltage to a stable load.
- **PWM Control**: The buck converter uses pulse-width modulation (PWM) to regulate the output voltage. The microcontroller controls the MOSFET switching frequency and duty cycle (ratio of ON-time to OFF-time) to adjust the output voltage based on the input voltage and load requirements.

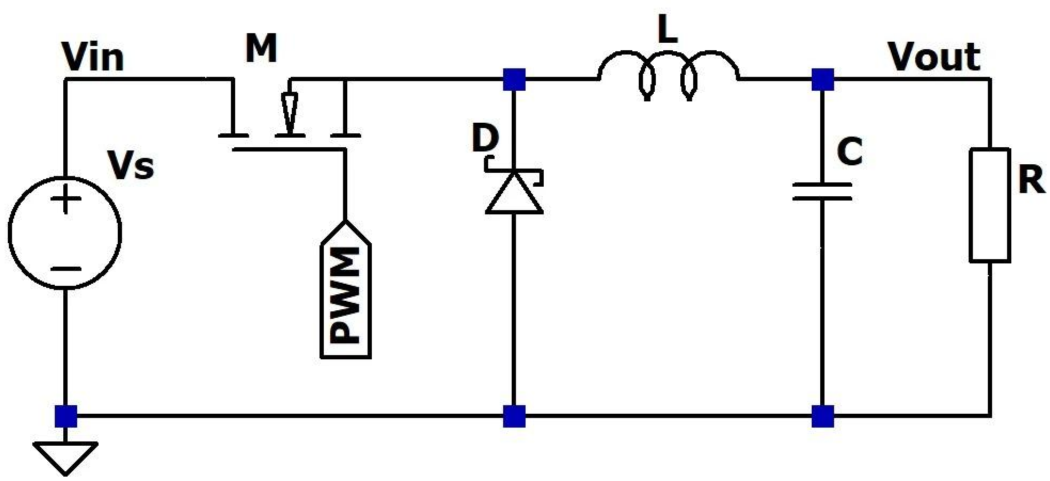

Figure 2: Basic Buck Converter Circuit

The buck converter plays an important role in managing proper distribution of power within the charge controller through the coordination of the microcontroller. So, there are several calculations associated in the bulk converter that helps in determining the output voltage, current, power and system efficiency produced.
Some of the calculations used are:

2.2.1 Output Voltage of a Buck converter (Step-down converter)

The output voltage of a buck converter can be calculated based on the duty cycle of the pulse-width modulation (PWM) signal which usually controlled by the microcontroller based on the input and output parameters of the charge controller. The output voltage is given by:

$$V_{out} = D \times V_{in}$$

where:

V_{out} is the output voltage of the charge controller to the battery,

D is the duty cycle to the PWM (ratio of ON-time to total time), and

V_{in} is the input voltage (From the solar panel or other sources).

2.2.2 Output Current

Assuming high efficiency, the output current of the buck converter is given by:

$$I_{out} = \frac{P_{in}}{V_{out}} = \frac{V_{in} \times I_{in}}{V_{out}}$$

where:

I_{out} is the output current,

P_{in} is the input current,

V_{in} is the input voltage,

I_{in} is the input current, and

V_{out} is the output voltage.

2.2.3 Power Output

The power delivered to the battery by the charge controller can be calculated as:

$$P_{out} = V_{out} \times I_{out}$$

where:

P_{out} is the power delivered to the battery,

V_{out} is the output voltage and

I_{out} is the output current.

2.2.4 Battery Charging Current

To determine the charging current of the battery, the following formula is used:

$$I_{charge} = \frac{P_{in \times \eta}}{V_{bat}}$$

where:

I_{charge} is the current supplied to the battery,

P_{in} is the input power from the source,

η is the efficiency of the charge controller,

V_{bat} is the battery voltage.

2.2.5 Efficiency of the charge controller

The overall efficiency of the charge controller can be calculated as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

where:

η is the efficiency of the charge controller,

P_{out} is the power delivered to the battery or load,

P_{in} is the power from the input source.

2.2.6 Maximum Power Point Tracking (MPPT) Efficiency

This particular calculation is usually incorporated in charge controllers that incorporate MPPT functionality, the power transfer efficiency from the solar panel to the battery can be approximated as:

$$\eta_{MPPT} = \frac{P_{bat}}{P_{panel}} \times 100$$

where:

η_{MPPT} is the MPPT efficiency,

P_{bat} is the power delivered to the battery,

P_{panel} is the maximum power produced by the solar panel.

These various formulas will help estimate the performance and output of the charge controller.

5. LCD Screen: This is the display part of the charge controller that provides the user interface that allows monitoring, control, and management of the system's performance in real time. The LCD provides real-time feedback on critical parameters like:
    1. Input Voltage from the power source (i.e. solar panel)
    2. Battery voltage and charging current
    3. Battery status and health
    4. System efficiency

    In essence, the LCD serves as a crucial interface between the user and the system, providing essential feedback on performance, safety and efficiency. It ensures that the system can be monitored, configured, and maintained with ease.

2.3 Description Of Components Used

A PV charge controller regulates the voltage and current coming from the solar panels to the batteries, preventing overcharging and ensuring safe operation and also it enables proper load control. This section of the chapter discusses the various components that have been used in this project, highlighting their basic functions and some of their images.

They include the following;

1. Current Sensor (ACS712): ACS712 is a Hall-effect-based linear current sensor that measures current in a circuit. It outputs an analog voltage proportional to the current flowing through a charge controller, it monitors the current flowing into or out of the battery to ensure it stays within safe limits.

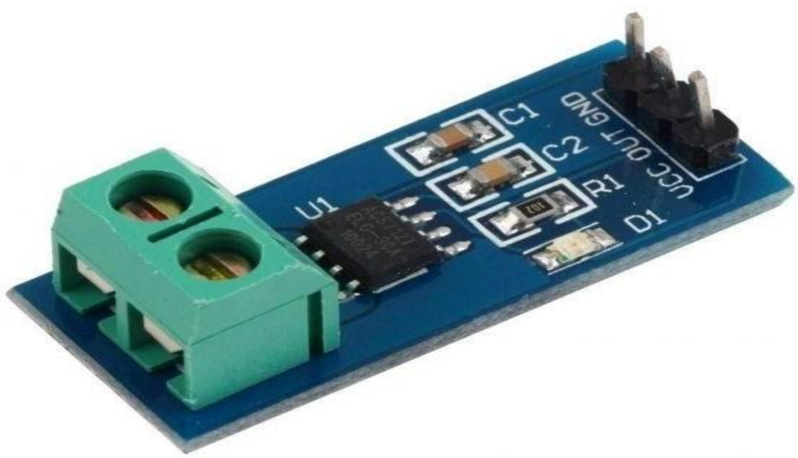

Figure 3: ACS712 Current Sensor

2. Voltage Sensor: A voltage sensor detects and measures the voltage level of a system and provides a corresponding output signal. It basically consists of a pair of voltage divider which is used to measure the voltage and scale its value to that readable by the microcontroller.
3. MOSFET Driver: A MOSFET driver is a circuit that provides the appropriate gate drive voltage and current to control MOSFETs efficiently, enabling high-speed switching with minimal power loss. The IR2104 MOSFET driver have

been utilized in this project. Now, let's take a brief overview into a MOSFET driver:

- **IR2104**: The IR2104 is a versatile and widely used half-bridge gate driver designed to control N-channel MOSFETs in high-side and low-side configurations. It is a dip 8 IC socket, and particularly well-suited for DC-DC conversion.

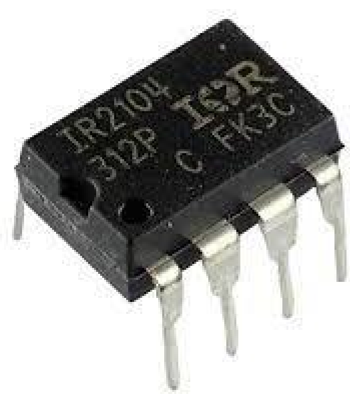

Figure 4: IR2104 MOSFET Driver

4. Arduino Nano: The Arduino Nano is an 8-bit microcontroller based on the ATMEGA328P (or ATMEGA168 for older versions) microcontroller which uses the AVR architecture developed by ATMEL (now part of Microchip Technology). It is widely used in embedded systems, including applications like charge controllers, IoT devices, and sensors. It is the brains of the charge controller as it performs various functions within the charge controller.

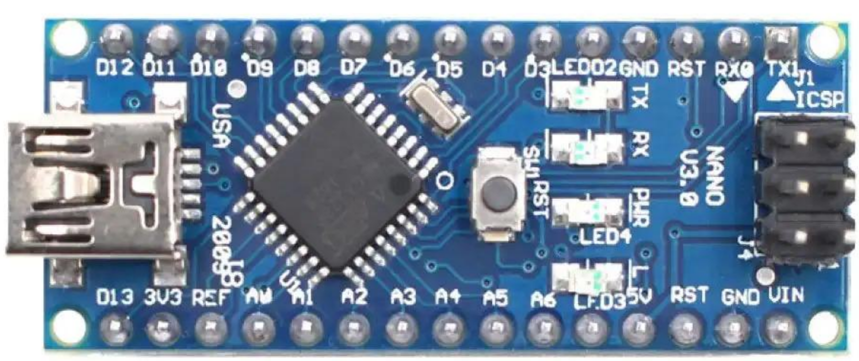

Figure 5: Arduino Nano Micro-controller

5. MOSFETS: MOSFETs are essential components in power electronics due to their fast-switching speed, low conduction losses, and ability to handle high currents and voltages. The IRFZ44N MOSFET has been utilized for this project, it is an N-channel MOSFET commonly used in power applications due to its affordability, robust performance, and availability.

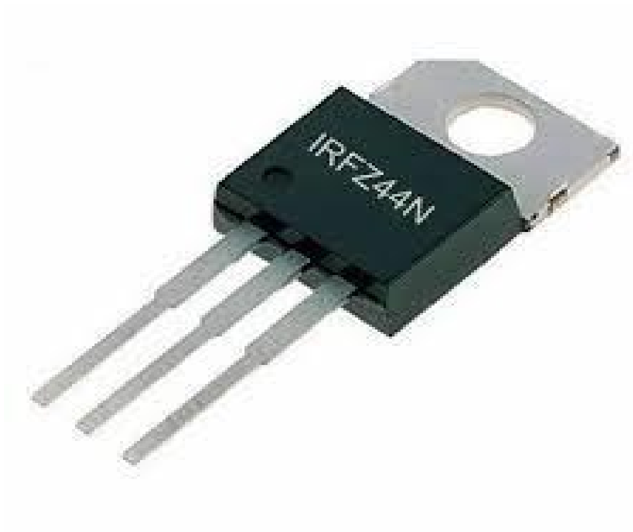

Figure 6: IRFZ44N MOSFET

6. LCD: The LCD is the unit of the charge controller that provides a visual platform for displaying system information parameters. it serves as a user interface, providing real-time information about the system's operational status, performance, and settings. The 20x4 LCD display has been integrated in this project.

Figure 7: LCD (20x4)

7. I^2C LCD Interface: This is an adapter module that is used to simplify the connection and control of the LCD display and it is done with the use of the Inter-Integrated Circuit (I^2C) communication control. It helps to allow easy integration of LCD screens by reducing the number of required General Purpose Input/Output (GPIO) pins on the microcontroller and simplifying the wiring process. It is typically used with 16x2 and 20x4 character LCDs.

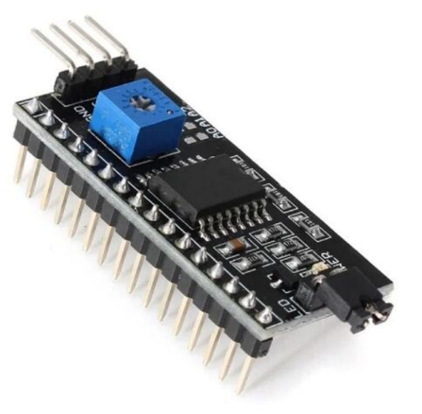

Figure 8: I^2C LCD Module

8. Relay: A relay is an electrically operated switch that uses an electromagnetic coil to control the opening and closing of electrical contacts. In charge controllers,

relays play a vital role in managing power flow and ensuring system protection. A 5V relay has been used for the project for the load control.

Figure 9: 5V Relay

9. Fuse: A fuse is a passive safety device designed to protect electrical circuits by interrupting the flow of current when it exceeds a specified limit. In charge controllers, fuses play a critical role in safeguarding components, batteries, solar panels, and loads from damage due to over-current or short-circuit conditions.
10. TVS diode: A TVS (Transient Voltage Suppression) diode, such as the P6KE200A, is a specialized diode designed to protect electronic circuits from transient voltage spikes caused by events like lightning, power surges, or inductive load switching. The P6KE200A is commonly used in charge controllers to safeguard sensitive components from over-voltage condition.

Figure 10: P6KE200A TVS Diode

11. Diode: The diode plays several functions in the charge controller which includes the blocking of reverse currents, surge protection, over-voltage protection etc. In this project, several diodes which serve different functions has been utilized to provide better syestem protection like the 1N4148 diode has been used as a freewheeling diode to the power input of the MOSFET driver to protect the MOSFET driver and surrounding circuitry from voltage spikes and transients that can occur when he MOSFET is switching on and off. Also, the FR154 fast recovery diode with a current rating of 15A has been utilized as the diode for the buck converter circuit which is aimed at managing currents up to 10A within the charge controller.

Figure 11: A 1N4148 Diode

Figure 12: A FR154 Diode

12. Capacitor: Capacitors are essential components when it comes to electronic circuit and particularly in the case of charge controllers where they perform

various functions like filtering, smoothing, voltage regulation and energy buffering. In this project, the electrolytic and the ceramic capacitors have been used due to their respective applications. The values of the capacitors include 100uF, 470uF, 22uF, 0.1uF etc.

13. Resistor: Resistors play a very crucial role in charge controller design, they are used in voltage divider pairs to measure the voltage, they also serve the purpose of limiting current flow in certain parts of the charge controller circuit.
14. LED: The light emitting diodes (LEDs) serve the function of power indication in the charge controller, they also help to display the charging status of the battery.
15. Buttons: Buttons are integral components of the charge controller as they perform a few functions which ranges from mode selection to system configuration.
16. Crystal Oscillator: The crystal oscillator is component of the charge controller that helps to provide a stable clock signal for the micro-controller. The crystal oscillator that has been integrated with the micro-controller operates at a frequency of 16MHz.

Figure 13: 16MHz Crystal Oscillator

17. Potentiometer: The potentiometer is a variable resistor that provides a way to adjust and fine-tune various parameters like voltage and current flow within the charge controller circuit.
18. Voltage Regulator: The voltage regulator is used to regulate the amount of voltage flowing within the charge controller, and providing a stable voltage for the charge controller. Here we are making use of the LM2596 buck converter module to supply a stable 5V to the microcontroller, and also other circuit

components that utilize a voltage up to about 12V from the 7812-voltage regulator.

Figure 14: A LM2596 Buck Converter Voltage Regulator

19. Transistor: The transistor acts as a switch to control the relay, which in turn connects or disconnects the load from the output voltage. It is used to amplify the control signal from the microcontroller to drive the relay. The BC337(NPN) transistor has been used as the transistor for the relay control.
20. Inductor: The inductor is a passive electronic device that plays a key role in the charge controller, it serves various functions like filtering, energy storage, and voltage regulation. It is incorporated in the buck converter circuit to provide a stable and efficient power to the battery.
21. Heat sinks: The heat sink is also an important component of the charge controller that helps to dissipate heat generated by the power electronic components, such as MOSFETs and diodes.

Figure 15: Heat Sink for thermal management

2.4 Review of Related Work

PV charge controllers are crucial components in photovoltaic systems, responsible for regulating the power flow from solar panels to batteries. By ensuring batteries are charged efficiently and protected from overcharging or deep discharging, charge controllers significantly affect the overall efficiency and longevity of solar energy systems. Various types of charge controllers, including PWM and MPPT, have been developed over the years to improve the performance of PV systems. This review explores the technological advancements in PV charge controllers and highlights critical research contributions that have shaped the current state of the field.

2.4.1 Types of Charge Controllers

1. On/Off Controllers: "Eric P. Usher and Michael M. D. Ross” in their work “Recommended Practices for Charge Controllers” describes these types of controllers as a switch where during charging, the controller will allow all current from the PV to flow to the battery and it turns off when the voltage reaches the upper threshold. These controllers were highly inefficient due to their inability to manage charging dynamically. "O. S. Ejiofor, D. Nnadi, O. Uche and U. Celestine" in their work "Design and Development of a Charge Controller for a Photovoltaic System" (2018) detailed the limitations of early

controllers, emphasizing poor battery performance due to uncontrolled charging cycles.

2. Pulse-Width Modulation (PWM) Charge Controllers: PWM charge controllers marked the first significant improvement by providing continuous regulation of power delivered to the battery. "M. LokeshRaddy et al." in their 2017 study, "Comparative Study on Charge Controller Techniques for Solar PV System" highlighted how PWM charge controllers improved battery charging by modulating the power input, leading to reduced stress on the battery and increased charging efficiency. PWM technology became the industry standard for many small-scale PV applications due to its cost-effectiveness and simplicity in design. However, PWM controllers often fell short of extracting maximum power from solar panels under varying environmental conditions, thus creating the need for more advanced control techniques.
3. Maximum Power Point Tracking (MPPT) Charge Controllers: MPPT technology represents the most significant advancement in PV charge controllers. Unlike PWM, MPPT controllers dynamically adjust the load on the solar panel to ensure it operates at its maximum power point, irrespective of environmental changes such as temperature and irradiance levels.

   "R. Faranda and S. Leva" in their seminal paper, "Energy Comparison of MPPT Techniques for PV Systems" (2008), provided a comprehensive analysis of various MPPT algorithms, including Perturb and Observe (P&O) and Incremental Conductance. Their work demonstrated that MPPT controllers could improve system efficiency by 20-30% compared to PWM, especially in large-scale PV systems.

   Similarly, "S. Jain and V. Agarwal" in "A Single-Stage Grid Connected Inverter Topology for Solar PV Systems with MPPT" (2007) discussed advanced MPPT algorithms designed for grid-tied PV systems. The authors concluded that while MPPT technology has improved overall system efficiency, issues such as response time and complexity in partial shading conditions remain challenges for future research.

2.4.2 Maximum Power Point Tracking (MPPT) Solar Charge Controller

The Maximum Power Point Tracking (MPPT) Charge Controller is what is being used in this project. According to "Muhammad Riazul Hamid et.al" in their paper "Design and Development of MPPT Charge Controller for PV Power Generation System", MPPT charge controllers are very cost effective as in a short term, not using any charge controller will cause higher installation cost for replacement of damaged batteries and solar panels which will further increase in time causing up to 30 to 50 percent more spending even when using an average charge controller.

The key component of a MPPT charge controller is the DC-DC converter where its switch mode is used to regulate the input voltage at the photovoltaic Maximum Power Point (MPP) and provides a load matching for the maximum power transfer ensuring the battery receives maximum power in any weather condition.

"Tulika Majaw et.al" mentioned on their paper; "Solar Charge Controllers Using MPPT and PWM: A Review" that there are three factors to consider in order to extract the maximum amount of power from a solar panel:

1. Irradiance: This is the density of sunlight radiation incident to the solar panel and varying irradiance can change the solar panel current operating point
2. Temperature: The voltage operating point can change depending on how hot or cod the solar panel is
3. Load: The load at the end of the charge controller is used as a refrence for the current and voltage that is required to be supplied.

To ensure maximum power is being transferred to the battery, the MPPT charge controller typically passes through three or four distinct stages:

1. Bulk Stage: Here the controller delivers maximum current to the battery until it reaches a specific voltage usually around 80mpercent charge
2. Absorption Stage: The current is then decreased with the voltage held constant to bring the battery to a full charge
3. Float Stage: The voltage is then slightly reduced to maintain the charge to avoid over-charging of the battery

4. Equalization: In this optional stage, so controllers apply a higher-than-normal voltage to the battery for a short period of time to stir up the electrolyte in flooded lead-acid batteries preventing stratification and prolonging the battery life.

2.4.3 Control Strategies in MPPT Controllers

1. Perturb and Observe (P&O): The P&O method, one of the simplest and most widely used algorithms, adjusts the operating voltage in small steps and observes the impact on output power. “Djimbi Makoundi et.al.” in their work “Comparative Study of MPPT and PWM Charge Controller” described it as an algorithm that perturbs the PV panel voltage and observes the effect on power. However, ". Xiao et al." in "Optimal Design of Photovoltaic Arrays Under Partial Shading Conditions" (2009) pointed out that P&O can be inefficient in rapidly changing conditions, leading to oscillations around the MPP.
2. Incremental Conductance (IncCond): This method overcomes some limitations of P&O by using the derivative of power concerning voltage to directly find the MPP. “Djimbi Makoundi et.al.” in their work “Comparative Study of MPPT and PWM Charge Controller” described it as an algorithm that calculates the derivative of power with respect to voltage and compares this value to the instantaneous conductance. "T. Esram and P. Chapman" in their highly cited paper, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques" (2007), concluded that IncCond offers better performance in dynamic environments but at the cost of increased computational complexity.

2.4.4 Efficiency and Performance Improvements

1. As solar energy systems have become more widespread, there has been increasing interest in improving the overall efficiency of PV charge controllers. "R. Ramaaprabha and B. Mathur" in "Impact of Partial Shading on Solar PV Performance: Simulation and Experimental Analysis" (2009) discussed how shading conditions can drastically reduce the efficiency of MPPT controllers,

and they explored methods to mitigate these effects. Their work has led to advancements in algorithms that can handle partial shading more effectively, such as adaptive P&O and distributed MPPT techniques.

2. In terms of hardware improvements, "F. Lov and F. Blaabjerg" in "Power Electronics for Renewable Energy Systems" (2009) discussed the use of advanced power electronics components, such as GaN MOSFETs and high frequency transformers, in reducing losses in charge controllers. They highlighted that future advancements in material science could further improve the efficiency of PV charge controllers.

2.4.5 Challenges and Future Directions

Despite the progress made in PV charge controllers, several challenges remain. The efficiency of MPPT controllers in low-irradiance conditions, response time during rapid environmental changes, and the cost-effectiveness of intelligent control techniques are areas that require further research.

There is a growing need for more robust, reliable, and cost-effective solutions for rural and off-grid PV systems. And it should be noted that recent innovations such as hybrid controllers that combine the benefits of PWM and MPPT are likely to dominate future markets.

2.4.6 Conclusion

The evolution of PV charge controllers, from simple on/off regulators to sophisticated MPPT systems, has been critical in improving the efficiency of solar energy systems. Research over the past two decades has focused on refining MPPT algorithms, optimizing hardware designs, and integrating intelligent control strategies to enhance performance under diverse environmental conditions. Despite these advancements, future research must address remaining challenges, particularly in areas like low-cost intelligent controllers and improved performance under partial shading conditions.

CHAPTER THREE

METHODOLOGY

3.1 Design Analysis of a Solar Charge Controller

This section provides a comprehensive overview of the design process for a solar charge controller, breaking down each major component and explaining the rationale and methodology behind their selection and optimization.

The solar charge controller is designed to manage and regulate power from an independent source (in this case the solar panels) to charge a battery efficiently and safely. The project consists of several major blocks.

A visual representation of the block diagram of the solar charge controller circuit as shown in Figure 3 illustrate the sequential flow of energy from the charge controller source i.e. a solar panel or wind turbine.

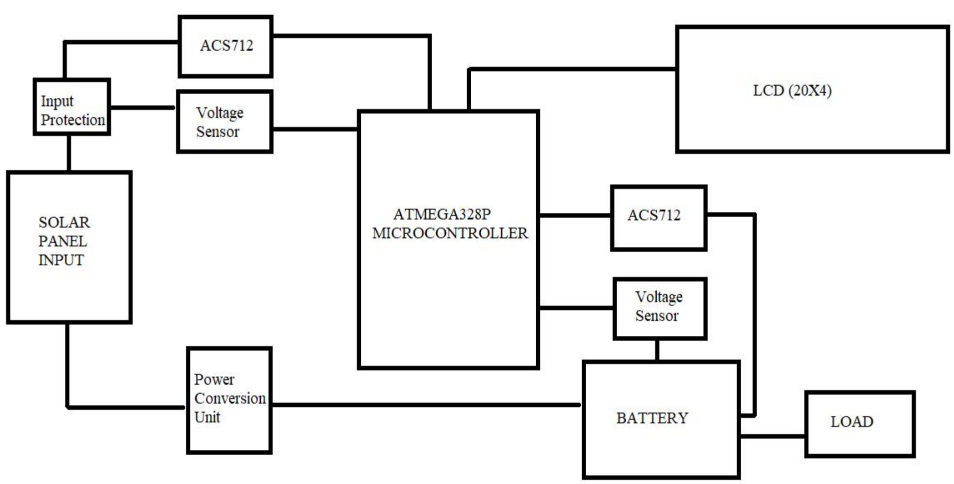

Figure 16: Block Diagram of PV Solar Input Charge Controller

3.1.1 Design Specifications

Inputs

- Input Sources: Solar panel and auxiliary input (e.g., wind turbine or grid power).
- Input Voltage (V_{in}): 24V (Nominal, assume range of 20V to 28V)
- Current Handling Capacity: Up to 20A per source.

Outputs

- Output Voltage: Adjustable, range of 12V to 36V
- Output Current: 10A max
- Switching frequency: 100kHz
- Ripple current (ΔI_L): 20% of max current i.e. 4A

Microcontroller

- Model: Arduino Nano.

Display

- LCD Type: 20x4 character LCD.
- User Interface: Two toggle screens for displaying input/output voltages, currents, and status messages, navigated using a push button.

Sensors and Protection

- Current Sensors: ACS712, for real-time current measurement.
- MOSFET Driver: IR2104 for efficient control of high-current MOSFETs.
- MOSFETs Used: IRFZ44N (3 in parallel for enhanced current handling).
- Protection:
- Over-voltage and over-current protection.
- TVS diodes rated for 450–500W to safeguard against voltage spikes.

Circuit Design

- Veroboard
- Power Management: Efficient handling of high currents with low power dissipation.

Efficiency and Performance

- Boost Features: Circuit optimized for minimal losses.
- Power Delivery: Reliable up to 10A output.

3.2 Subsystem Of the Charge Controller

3.2.1 The Input Source

The input source for your solar charge controller consists of a singular power input i.e. the solar panel input or an auxiliary input source (wind turbine or alternate DC source). The solar panel or auxiliary source supplies electrical energy to charge the battery. Input sources typically deliver power at varying voltages, like in the case of solar panels which delivers power in varies with the intensity of the sun.

3.2.2 Input Protection

The input protection of a charge controller is designed to safeguard both the controller and the input sources (such as solar panels or auxiliary power supplies) from potential damage due to electrical faults or adverse conditions. The input protection circuitry usually comprises a fuse which helps to prevent over-current spikes, and a transient voltage suppressor (TVS) diode which is a device used to protect unexpected over-voltages and surges caused by static electricity and power supply fluctuations.

3.2.3 Current Sensor

The current sensor is used to measure the amount of current that is generated by the input source. The current sensor detects the incoming current from the input source and also the battery, and sends detected value to the microcontroller which further processes the current signal and then performs other operations.

3.2.4 Voltage Sensor

The voltage sensor is used to detect and measure the voltage generated by the input source and battery. It records the voltage values of the input source and also the battery and sends these readings to the microcontroller for further processing.

3.2.5 Power Conversion Unit

The power conversion unit is the block that comprises the circuitry that manages the entire power within the charge controller, it consists of a DC-DC converter circuit that includes components such as power switches (i.e. MOSFETs, IGBTs), diodes, inductors, capacitors. Figure 4 shows the block diagram for the power conversion unit and their inter-related connections.

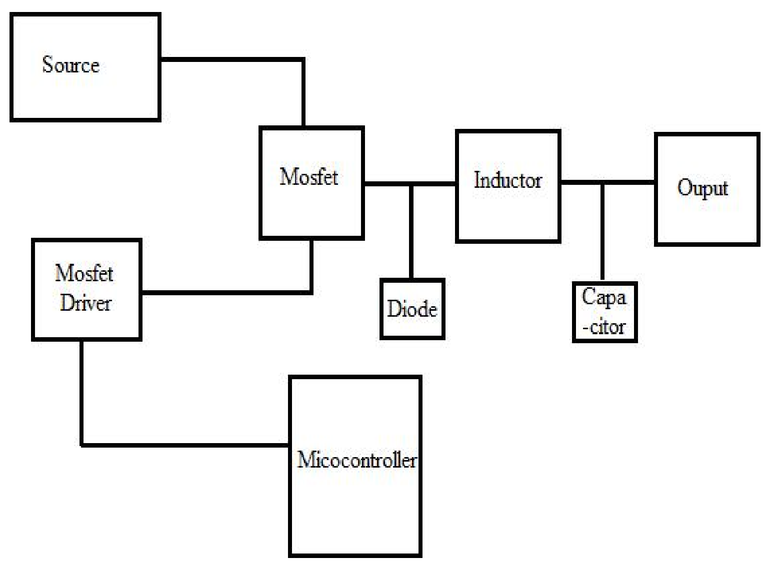

Figure 17: Power Conversion Unit Block Diagram

3.2.6 MOSFET Selection

The charge controller utilizes IRFZ44N N-channel MOSFET with a high current (I_D = 49A) handling capability and a maximum drain to source voltage (V_{DS} = 55V) within the operation of the charge controller.

3.2.7 Inductor Selection

The value of the inductor L is critical for maintaining continuous current flow and minimizing ripple.

For a buck converter;

$$L = \frac{V_{in}(1 - D)}{\Delta I_L \times f_s}$$

Where:

V_{in} = Output voltage

D = Duty cycle = $\frac{V_{out}}{V_{in}+V_{out}}$

V_{out} = Output voltage

ΔI_L = Inductor current ripple (usually 20-40% of the maximum output current) f_s = Switching frequency of the MOSFET

For V_{out} = 36V, V_{in} = 24V, ΔI_L = 4A, f_s = 100kHz and D = 0.6;

$$L = \frac{24 \times (1 - 0.6)}{(100 \times 10^3) \times 4} = 24\mu H$$

3.2.8 Capacitor Selection

The capacitor is given by the relation;

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{out}}$$

Where:

ΔV_{out} is the allowable ripple voltage (Usually 1% of the V_{out}, i.e. 0.36V)

Hence from the previous example, using the same parameters;

$$C = \frac{4}{8 \times (100 \times 10^3) \times 0.36} = 138.9\mu F$$

The closest capacitor that can cover for the 138.9uF is the 220uF(50V) electrolytic capacitor.

3.2.9 Diode Selection

The voltage rating for the power converter circuit is given as 1.2 x $V_{out.}$

For V_{in} = 36V, the voltage rating is given as: 1.2 x 36V = 43.2V.

Also, the current rating for the diode is given as:

$$\frac{I_{out} + \Delta I_L}{2}$$

Hence, it has been calculated to be 22A.

In order for better efficiency and power management, we will select a diode of slightly higher value (i.e. 30A, 50-60V)

3.2.10 Microcontroller

The microcontroller is basically the brains of the charge controller, it plays many crucial roles such as monitoring and measurement of sensor data, execution of control algorithms to regulate the charging process, ensuring safe and efficient energy transfer, detection and prevention of overcharging and over-discharge, provide platform for user interfacing and overall system communication.

3.2.11 LCD

The liquid crystal display (LCD) is an essential component in the charge controller that provides a visual interface for users to monitor and interact with the system. It shows the current state of the charge controller, displays charging parameters such as voltage, current, and power. It also allows users to navigate to menus to view more system parameters.

3.2.12 Battery

The battery is another crucial component in the charge controller, as it stores the energy generated by the sources. It also provides power to the load when the primary power source is not available.

3.4 Circuit Design

The simulation modelling for this project discusses the connection of the various circuit components of the charge controller and includes the overall circuit diagram that incorporates all the components working together. In this project, the circuit diagram has been designed using Proteus CAD software.

3.4.1 Circuit Diagram

The solar controller circuit diagram as shown in Figure 18 shows the specific circuit components as utilized for this project and how each of these components are connected to one another to perform efficiently in the charge controller.

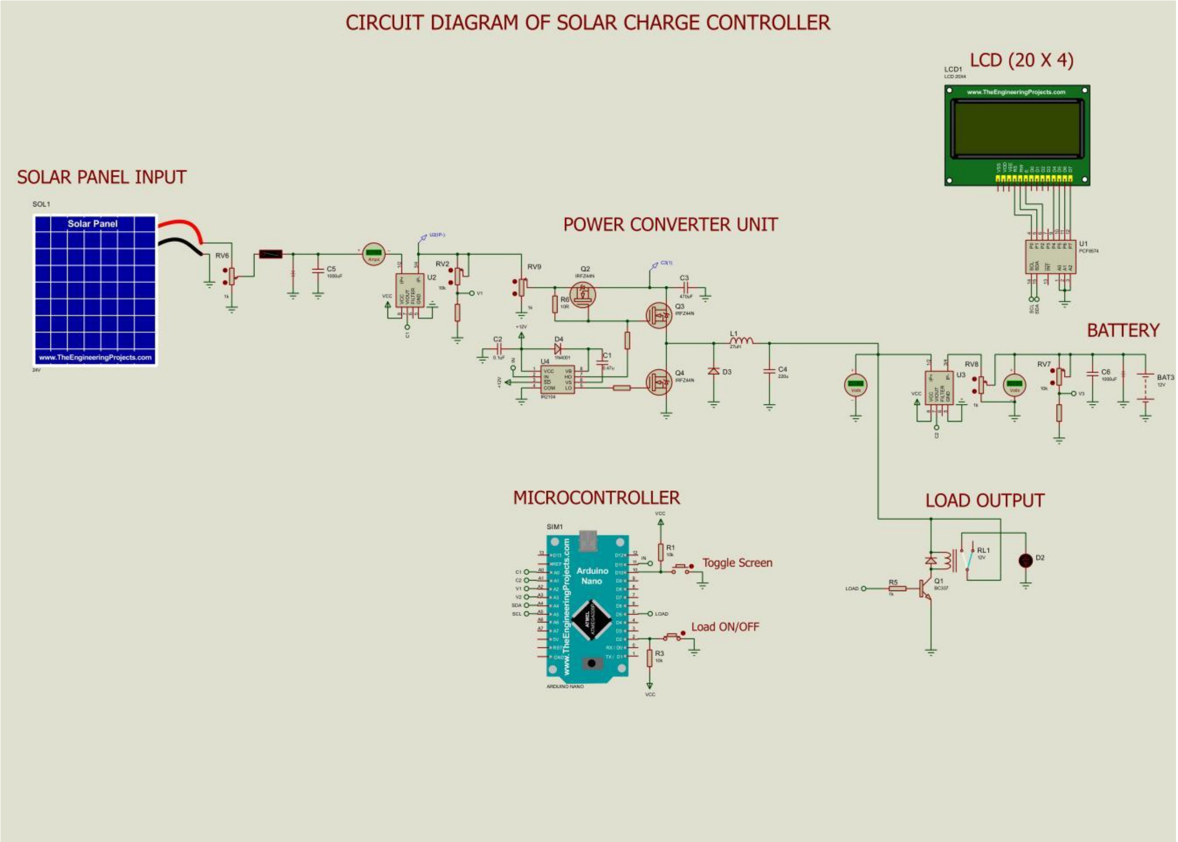

Figure 18: Solar Charge Controller Circuit

3.4.2 Circuit Implementation

The physical arrangement and implementation of Figure 18 can be seen in Figure 19 and the packaging is shown in Figure 20 where each of the various components on Figure 18 with heat sinks are placed, soldered to the Veroboard and connected with each other successfully.

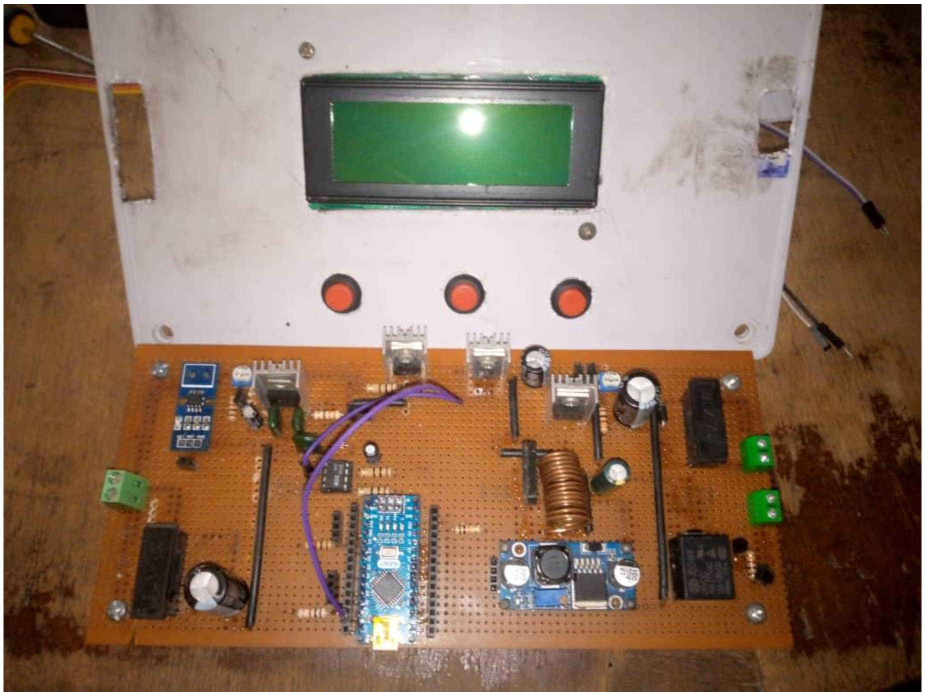

Figure 19: Solar Charge Controller on the Veroboard

Figure 20: The Protetive Cover of The Charge Controller

CHAPTER FOUR

TESTING, RESULT AND ANALYSIS

4.1 Introduction

This chapter provides the experimental results, analysis and evaluation of the solar charge controller. The major focus is on using MPPT tracking algorithm, voltage and current regulation, power conversion efficiency, and circuit response to varying solar conditions. The results have been recorded and compared with theoretical expectations, and possible design improvements are discussed.

4.2 System Performance Testing

4.2.1 No-Load Testing

This procedure aims at evaluating the performance of the charge controller without any external load connected to the output. This test is used to verify the solar charge controller's functionality, voltage regulation and overall health. The no-load test was carried out both digitally in simulation and in real-life physical testing. The simulation result showed that the expected output for an input voltage of 24V is 23.6V, as the controller was designed to regulate it's output voltage for battery charging. The simulation result proved that the controller maintained a steady voltage of 23.6V under no-load conditions with minimal fluctuations. Also, the design was tested using a 12V solar panel which produces up to 17V under open circuit conditions and it produced a output value of 10.6V which below the expected value and this was mainly attributed to different voltage drops within the charge controller components. The simulation result confirms the proper functioning of the charge controller, while the actual real-life result suggest that the system components are not ideal.

4.2.2 Load Testing (Battery Charging Performance)

In simulation, the charge controller was connected to a 12V battery to analyze its performance under charging conditions. The following parameters where recorded at different charge levels:

1. Battery voltage over time: The battery voltage increased gradually, indicating effective charging, and the battery mode changed overtime from bulk mode to float mode as the battery voltage increased.
2. PWM Signal: The PWM Signal value reduced gradually as the battery voltage increased during charging, indicating less charging current.
3. External load: A 12V dc motor was connected across the output load terminal in simulation, and when turned, the system was able to power it.

4.4 Discussion of Results

The experimental results demonstrate that the solar charge controller when utilized effectively in MPPT mode extracts maximum power from the solar panel, efficiently regulates voltage and current, and provides stable charging. The MPPT algorithm performed well under dynamic conditions, ensuring optimal power transfer.

4.5 Conclusion

The MPPT charge controller successfully met its design objectives by:

Efficiently tracking maximum power point and adapting to sunlight variations.

Providing a stable output voltage of 23.6V in simulation and 10.6V in real-testing under no load condition. And under load conditions, the simulation result produced sufficient voltage needed to charge the 12V battery from the 24V input solar panel.

Incorporating effective protection features to safeguard against electrical faults.

The overall performance aligns well with expectations, with minor areas for improvement. Future optimizations could focus on higher efficiency MOSFETs, buck converter design upgrade, improved thermal management, and faster MPPT response to further enhance performance.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project successfully showed how a solar charge controller can be designed, simulated, tested and function using an Arduino Nano Microcontroller, a DC-DC Buck converter, Proteus electronic CAD software for the design and an Arduino C/C++ code.

The development of this single-input MPPT charge controller has successfully demonstrated an efficient method for maximizing solar energy utilization while ensuring stable and safe battery charging. This project aimed to create a cost-effective, high-performance charge controller capable of handling high current loads and providing a well-regulated output voltage suitable for battery charging applications and external load. The controller effectively extracts maximum power from the solar panel by continuously adjusting the duty cycle of the buck converter circuit, which steps down the voltage while maintaining a high current output.

The charge controller is designed to deliver up to 15A of current, making it suitable for high-capacity battery systems. It provides a stable output voltage slightly below the system lnput source due to internal component voltage drops, and charges batteries and power banks commonly used in solar energy storage systems. To achieve this, the system incorporates an IR2104 MOSFET driver, which controls the switching of the MOSFETs to regulate power flow efficiently. Additionally, an ACS712 current sensor is used to accurately measure the current flowing to the battery, and a 9k/1k voltage divider serves as a voltage sensor for monitoring battery and solar panel voltages.

5.2 Key Features and Performance

One of the major strengths of this charge controller while utilizing MPPT algorithm is its real-time monitoring and user-friendly interface. The system features a 20x4 LCD display, which provides critical information about the charging process, including:

To enhance usability, a toggle button allows the user to switch between two LCD screens, displaying different sets of data for a more comprehensive overview of the system's performance. This ensures that all essential information is readily accessible without overwhelming the display with excessive details at once.

The MPPT algorithm implemented in this charge controller dynamically adjusts the duty cycle to ensure maximum power extraction under varying solar conditions. Unlike traditional PWM-based charge controllers, which do not fully utilize available solar power, the MPPT technique ensures higher energy efficiency by continuously tracking the optimal operating point of the solar panel. This leads to increased energy harvesting efficiency and faster battery charging.

Challenges and Potential Improvements

Although the charge controller performs well in extracting maximum power and regulating battery charging, there are some areas where improvements can be made:

Efficiency Optimization:

While the MPPT algorithm enhances energy conversion efficiency, further optimizations in the MOSFET switching techniques and inductor selection could improve overall system efficiency.

Reducing switching losses and improving heat dissipation mechanisms would enhance long-term reliability.

Enhanced Protection Features:

The current design could be improved by adding overcurrent, overvoltage, and over-temperature protection to prevent damage to the battery and other components.

Implementing a TVS diode (450-500W capacity) for surge protection would enhance system robustness against unexpected voltage spikes.

Temperature Compensation and Battery Health Monitoring:

Incorporating a temperature sensor would allow for temperature compensation in battery charging, ensuring safer and more efficient charging under varying environmental conditions.

Advanced state-of-charge (SoC) estimation algorithms could be implemented to provide more accurate battery health monitoring and prevent overcharging or deep discharging.

Remote Monitoring and Data Logging:

Adding wireless communication features (such as Wi-Fi or Bluetooth) would allow users to monitor the charge controller remotely via a smartphone app or web interface.

Data logging capabilities could be integrated to track long-term performance and optimize energy usage based on historical trends.

Final Thoughts

In conclusion, this charge controller provides a reliable, efficient, and user-friendly solution for solar-powered battery charging applications. The system successfully implements maximum power point tracking (MPPT), real-time monitoring, and effective power regulation, ensuring that the battery receives optimal charging under varying solar conditions. The ability to handle high currents (up to 15A) and maintain a stable output voltage makes it well-suited for off-grid solar energy systems.

While the charge controller performs efficiently, future improvements can enhance its efficiency, protection mechanisms, and usability. The integration of remote monitoring, data logging, and support for additional battery types would make it even more versatile. Nonetheless, this project serves as a strong foundation for future developments in solar energy harvesting and battery management, contributing to the broader goal of sustainable and renewable energy utilization.

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CODE USED

```
#include <Wire.h>

#include <LiquidCrystal_I2C.h>

// Define pin assignments

#define pwm1 11 // PWM output for MPPT control

 #define i1Pin A0 // Solar panel current sensor input

#define BiPin A1 // Battery current sensor input

#define v1Pin A2 // Solar panel voltage sensor input

#define BvPin A3 // Battery voltage sensor input

#define buttonPin 10 // Button to toggle LCD display

#define relayControlPin 5 // Relay control for load

#define loadButtonPin 2 // Button to toggle load relay

// Initialize LCD with I2C address 0x20, 20 columns, 4 rowS

LiquidCrystal_I2C lcd(0x20, 20, 4);

// Voltage and current measurements

float V1, I1, BatteryVoltage, BatteryCurrent;

const float R1 = 9000.0; // Resistor value for voltage divider

const float R2 = 1000.0;

const float Vref = 5.0; // Reference voltage for ADC

const float sensitivity = 185.0; // ACS712 sensor sensitivity (mV/A)

const float zeroOffset = 2.5; // Offset voltage for ACS712 sensor

// Battery charge state thresholds
```

```
const float BULK_THRESHOLD = 48.5;
const float ABSORPTION_THRESHOLD = 53.5;
const float FLOAT_THRESHOLD = 53.5;
// Button handling variables
bool screenFlag = false;
bool lastButtonState = LOW;
unsigned long lastDebounceTime = 0;
const unsigned long debounceDelay = 50;
const unsigned long updateInterval = 500;
unsigned long lastUpdate = 0;
bool loadState = false;
bool lastLoadButtonState = LOW;
// Battery status strings
String batteryMode = "";
String chargingStatus = "Charging: No";
// MPPT (Maximum Power Point Tracking)
Variables float previousPower = 0;
float previousVoltage = 0;
float dutyCycle = 128; // Initial PWM duty cycle (range: 0-255)
const float dutyStep = 5; // Step size for MPPT adjustment
// Determine battery charge mode based on voltage
String getBatteryMode(float voltage) {
```

```
if (voltage >= FLOAT_THRESHOLD) return "Float";

else if (voltage >= ABSORPTION_THRESHOLD) return "Absorp";

else return "Bulk";

}

//Update charging status based on solar input

void updateChargingStatus() {

chargingStatus = (V1 > 0 && I1 > 0) ? "Charging: Yes" : "Charging: No";

}

// MPPT Algorithm: Perturb & Observe method

void updateMPPT() {

float power = V1 * I1;

// Calculate power (P = V * I)

if (power > previousPower) {

if (V1 > previousVoltage) dutyCycle += dutyStep; // Increase duty cycle if voltage increased

else dutyCycle -= dutyStep; // Decrease otherwise}

else {

if (V1 > previousVoltage) dutyCycle -= dutyStep;

else dutyCycle += dutyStep;

}

dutyCycle = constrain(dutyCycle, 0, 255); // Ensure duty cycle stays within valid range

analogWrite(pwm1, dutyCycle); // Apply new duty cycle

previousPower = power;
```

```
previousVoltage = V1;

}

void setup() {

// Set pin modes pinMode(pwm1, OUTPUT);

pinMode(buttonPin, INPUT_PULLUP);

pinMode(loadButtonPin, INPUT_PULLUP);

pinMode(relayControlPin, OUTPUT);

digitalWrite(relayControlPin, LOW);

// Initialize LCD lcd.init(); lcd.backlight();

displayScreen1();

// Show initial screen

// Set initial PWM duty cycle analogWrite(pwm1, dutyCycle);

}

void loop() {

// Handle LCD toggle button with debounce int reading = digitalRead(buttonPin);

if (reading != lastButtonState) lastDebounceTime = millis();

if ((millis() - lastDebounceTime) > debounceDelay && reading == LOW) screenFlag = !screenFlag;

lastButtonState = reading;

// Handle load relay toggle button int loadButtonReading = digitalRead(loadButtonPin);

if (loadButtonReading != lastLoadButtonState && loadButtonReading == LOW) { loadState = !loadState;

digitalWrite(relayControlPin, loadState ? HIGH : LOW);
```

delay(50); } lastLoadButtonState = loadButtonReading;

// Periodic updates every updateInterval milliseconds if (millis() - lastUpdate >= updateInterval) { lastUpdate = millis();

V1 = readVoltage(v1Pin, R1, R2, Vref);

BatteryVoltage = readVoltage(BvPin, R1, R2, Vref);

I1 = readCurrent(i1Pin, sensitivity, Vref, zeroOffset);

BatteryCurrent = readCurrent(BiPin, sensitivity, Vref, zeroOffset);

batteryMode = getBatteryMode(BatteryVoltage);

updateChargingStatus();

updateMPPT(); // Update MPPT algorithm

// Switch between display screens

screenFlag ? displayScreen2() : displayScreen1();

}

}

// Display solar and battery data on LCD void displayScreen1() {

lcd.clear();

lcd.setCursor(0, 0);

lcd.print("SOL-VOLT: " + String(V1, 1) + "V");

lcd.setCursor(0, 1);

lcd.print("SOL-AMPS: " + String(I1, 1) + "A");

lcd.setCursor(0, 2);

lcd.print("BAT-VOLT: " + String(BatteryVoltage, 1) + "V");

lcd.setCursor(0, 3);

```
lcd.print("BAT-AMPS: " + String(BatteryCurrent, 1) + "A"); }

// Display battery mode and load status on LCD void displayScreen2() {

lcd.clear();

lcd.setCursor(0, 0);

lcd.print("BAT-MODE: " + batteryMode);

lcd.setCursor(0, 1); lcd.print(chargingStatus);

lcd.setCursor(0, 2);

lcd.print("LOAD: " + String(loadState ? "ON" : "OFF"));

}

// Read voltage from an analog pin using a voltage divider

float readVoltage(int pin, float R1, float R2, float Vref) {

return analogRead(pin) * (Vref / 1023.0) * ((R1 + R2) / R2);

}

// Read current from an ACS712 sensor

float readCurrent(int pin, float sensitivity,

float Vref, float zeroOffset) {

return (analogRead(pin) * (Vref / 1023.0) - zeroOffset) / (sensitivity / 1000.0);

}
```