Building an Efficient Maximum Power Point Tracking (MPPT) Solar Charge Controller

ECE 499: Design Project II

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Table of Contents

I - Objectives

- Gain a thorough understanding of solar charge methods, including the various types (“direct-to-battery", “simple PWM” and “MPPT”), their basic designs and subsystems, and be able to explain why the ideal type of Solar Charge Controller uses a Maximum Power Point Tracking algorithm, or “MPPT” due to the nature of solar panel behavior.
- Analyze MPPT theory with respect to I-V and P-V curve of a solar panel.
- Explain and explore the basic design of an MPPT controller including various subsystems (synchronous buck converter, current sensor, microcontroller, etc.).
- Give a brief overview of the range of open-source MPPT designs currently available and explain various advantages/disadvantages of each and why we chose to build this design (with reference to “1kW Arduino MPPT Solar Charge Controller” by ASCAS on instructables.com).
- Explain the algorithm of the open-source firmware with analysis of firmware code section (with reference to FUGU MPPT open-source firmware and any modifications).
- Explain component selection for major components (current sensor, microcontroller, MOSFETs, test setup, etc.)
- Build a working prototype so we can try installing the open-source firmware and get a test setup working with a panel and battery before July ending.
- Design a custom PCB for the MPPT controller.
- Design an enclosure for the MPPT controller.

II - Introduction

Problem Definition

Solar energy systems are crucial for sustainable energy solutions and off-grid living. To maximize the efficiency of solar panels, it's essential to operate them at their maximum power point, which varies with sunlight conditions [1]. Maximum Power Point Tracking, or "MPPT" solar charge controller designs are by far the most efficient type and significantly improve solar energy conversion efficiency by 30-40% over other designs, providing a solution for efficient battery charging under varying sunlight conditions [2]. This project aims to contribute to sustainable energy technologies with practical applications for off-grid living, such as a cabin with low power needs.

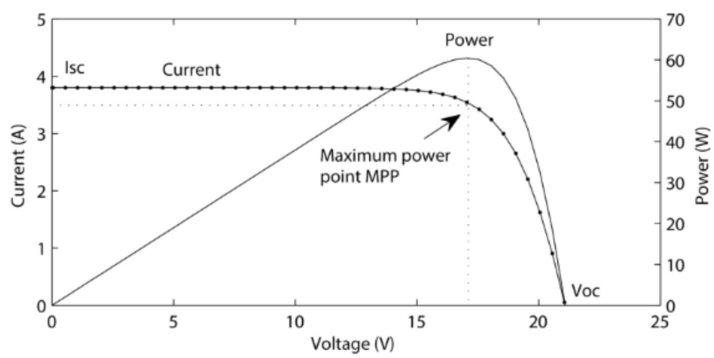

Figure 1: I-V and P-V curves of a photovoltaic (PV) panel showing Maximum Power Point for a single sunlight intensity [5].

By continuously tracking the maximum power point of the solar panels and adjusting the PWM (Pulse Width Modulation) duty cycle of the synchronous buck converter, the MPPT controller ensures that the panels operate at their optimal voltage, regardless of varying sunlight conditions. This leads to maximum energy extraction from the panels and efficient charging of the battery.

Scope of Work

The goal of this project is to build an MPPT solar charge controller that works with a solar panel or array of panels to charge a battery. All MPPT controllers rely on a microcontroller to run the MPPT algorithm and continually adjust the PWM frequency of the buck converter (which uses MOSFETs and a MOSFET driver) at high-speed using feedback from a current sensor to estimate the instantaneous power being extracted, while sweeping and keeping track across a range to find the current maximum power point. This must be done very quickly to be effective. So, some firmware development is necessary, along with some power electronics knowledge and understanding of photovoltaic (PV) cell behavior.

A very common battery voltage is 12V, as all cars and many off-grid setups use 12VDC electrical systems (usually lead-acid battery, but increasingly lithium at higher voltages as well). Solar panel output voltage varies between models and of course many are installed in series, but typically a single 100W panel has a maximum output voltage of 17-18V. These are often installed in series with a resulting array voltage greater than the battery voltage. This is why we use a buck converter which steps this voltage down to the desired battery charging voltage or inverter operating voltage. This buck converter, when controlled using an MPPT algorithm, also allows us to independently control the battery charging voltage separately from the panel voltage (which is ideally kept as close to the maximum power point as possible).

Typical MPPT designs are very flexible and support a range of input voltages up to 80-100VDC, and multiple battery chemistries from 12V lead-acid to 48V or more lithium cell arrays. Also, during low-light conditions like dawn/dusk, panel voltage is often below battery charging voltage. MPPT designs allow the controller to also work in boost mode (stepping up voltage vs. buck mode stepping down), extracting energy even in marginal conditions. We are targeting a 12V charging voltage for a single lead-acid battery and 1-2 100W panels, as this is a very common entry-level setup and already owned by a group member. MPPT controllers, being all about efficiency and extracting maximum energy, typically rely on a synchronous buck converter rather than the much more common asynchronous type. This is because a synchronous buck converter has a much higher efficiency of ~98% than a comparable asynchronous version of ~80%.

Synchronous designs achieve this by replacing the blocking diode with another MOSFET. Simple in concept, but difficult to implement – if both are accidentally switched on at the same time, a short circuit occurs, and proper synchronous operation must be maintained at all times with no interruption. The microcontroller must be able to keep up with all tasks without stalling, freezing, or getting bogged down to keep this going.

The difficulties with implementing an MPPT charge controller (getting the synchronous buck design working and developing the firmware, and much more) have been solved by the instructables.com project creator ASCAS throughout his project "1KW ARDUINO MPPT Solar Charge Controller (esp32 + WIFI)" [2]. We have chosen to build our design based on this project, as it is a phenomenal learning resource and helps us greatly in reducing the scope of what we need to do. The project creator wrote and released an open-source MPPT firmware for the ESP32 microcontroller (FUGU Open-Source MPPT Firmware), which we can use to run our controller, greatly reducing the amount of time needed to get up and running [2]. He also provides board schematics and component lists. The project article provides a complete overview of MPPT theory, operational understanding, and typical design, with a step-by-step guide that walks the reader through each design difficulty encountered, discussion on each component (what it does and why it was selected), and rationale behind almost every nuance you could possibly think of in building one of these devices.

Summary of Project Goals

- Fully understand the operating concept of an MPPT solar charge controller and its subsystems.
- Build a prototype – use an existing design to order a test PCB, use recommendations for initial component selection, assemble test board and panel setup. Get to installing/testing the open-source firmware as soon as possible.
- Design custom PCB based on knowledge from the prototype.
- Design enclosure to be 3D-printed.

Ethical Considerations

There are several guidelines in the Engineers and Geoscientists BC (EGBC) Code of Ethics that are specifically relevant to this project. The first principle emphasizes holding paramount the safety, health, and welfare of the public. The goal of our project is to create a solar charge controller that is dependable and safe, supporting renewable energy sources and advancing public welfare in the process. Principle 2 involves undertaking and accepting responsibility for professional assignments only when qualified by training or experience. Our team comprises individuals with the necessary expertise in hardware design, software development, and power electronics, ensuring that we are qualified to undertake this project. Principle 3 states that one should provide an opinion on a professional subject only when it is founded upon adequate knowledge and honest conviction. We will base our design and implementation decisions on thorough research and testing, ensuring they are well-founded and reliable. Principle 7 advocates conducting oneself with fairness, courtesy, and good faith towards clients, colleagues, and others. Our team will work collaboratively, maintain open communication, and share responsibilities fairly.

III - Literature Survey & Specifications

Types of Solar Charge Controllers

The simplest way to charge a battery with a solar panel is to just connect it directly to a battery. The battery will charge in an uncontrolled manner to its full voltage and needs to be disconnected manually once charged. Next, you have PWM charge controllers. These can control the charging current using pulse-width modulation. A limitation of a simple PWM charge controller is that the battery charging voltage is always the same as the operating panel voltage. A further enhancement on this concept is to use a buck converter to step down the panel voltage to whatever battery voltage is needed, allowing for higher-voltage panel arrays. There is still a deficit here in that the panel voltage will still change with light intensity and cannot be optimized to the panel's operating maximum power point independently. If you could be constantly optimizing that buck converter's PWM frequency while tracking the power output, you could do a lot better, by some 30-40%. This is what an MPPT solar charge controller does.

Table 1: Decision Matrix-Style Comparison of Solar Charge Controller Types

Criterion	Direct Connection	PWM Charge Controllers	PWM with Buck Converter	MPPT Charge Controller
Overview	Simplest method, direct connection of solar panel to battery.	Uses pulse-width modulation to control charging current.	Enhances PWM by stepping down panel voltage to match battery voltage.	Optimizes charging by continuously tracking the maximum power point of solar panels.
Capability	Basic	Prevents overcharging, better control over charging.	Allows higher-voltage panels, better voltage regulation.	Maximizes power extraction, accommodates wide range of configurations, adapts to light conditions.
Efficiency	Risk of overcharging and battery damage.	Moderate, tied to panel voltage.	Improved over basic PWM, still not fully optimal.	30-40% improvement over PWM
Cost	Very low	Moderate, affordable.	Higher initial cost.	Higher initial cost.
Ease of Use	Simple, requires manual monitoring.	Easy to install and use with basic knowledge.	More complex but manageable	More complex, often comes with user-friendly interfaces.
Suitability	Not suitable for long-term use or efficiency.	Good balance for cost vs. performance.	Better than basic PWM, but still not optimal.	Best choice for efficiency and performance despite higher cost.

After reviewing the different types of solar charge controllers, it is obvious that MPPT charge controllers offer the best solution for maximizing the efficiency and longevity of solar power systems. While they are more expensive and complex than PWM controllers, their ability to continuously optimize the power output from solar panels provides substantial efficiency gains. This makes MPPT controllers the preferred choice for both residential and commercial solar power installations aiming for high performance and reliability.

A Simple Explanation of How an MPPT Solar Charge Controller Works

Say you have a knob that adjusts the PWM duty cycle of a buck converter, connected between a solar panel and a battery with a wattmeter inline to measure power going into the battery. You are outside and the sunlight intensity changes from moment to moment. You sweep the knob, adjusting duty cycle from 0-100% and notice that the wattmeter shows a maximum output at a certain PWM frequency. The sunlight changes and then you sweep again, turning the knob back and forth to find the new PWM frequency that gives maximum output. This is the essence of an MPPT charge controller. Similarly, a microcontroller runs the MPPT algorithm by sweeping the PWM duty cycle, using feedback from the current sensor to calculate the maximum power point and adjust accordingly.

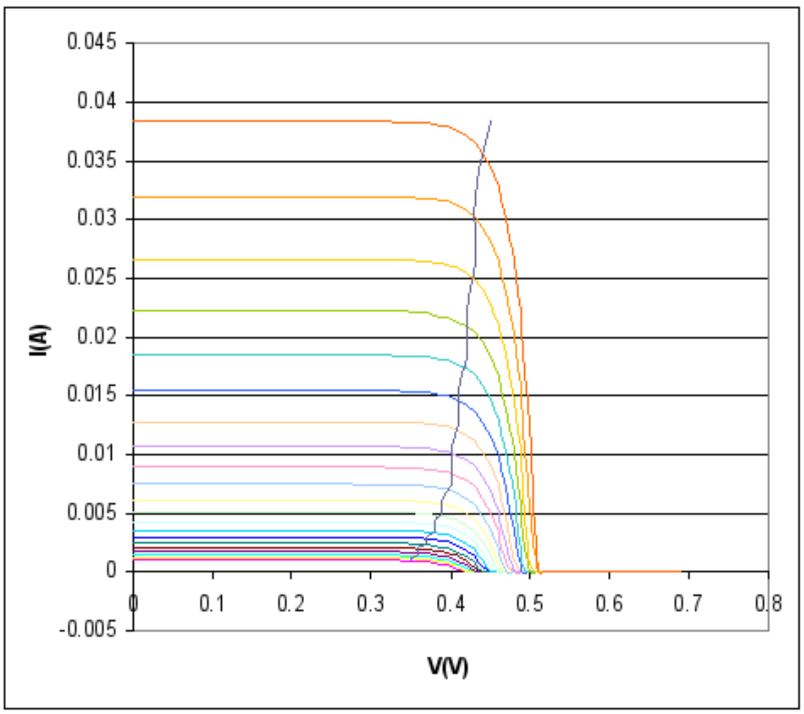

Figure 2: I-V curve of a solar cell shown from Wikipedia MPPT article with line through curve knees tracing maximum power point [3].

The MPPT controller will use a microcontroller to manage the pulse width modulation (PWM) required for optimal performance. By decoupling the panel voltage from the battery voltage, the controller can adjust the duty cycle of the PWM signal to maintain the panels at their maximum power point while regulating the charging voltage and current to the battery.

Discussion on Maximum Power Point Tracking Algorithm

"Steady Output and Fast Tracking MPPT (SOFT-MPPT) for P&O and InC Algorithms" [1] discusses three algorithms. The P&O algorithm calculates PV output power and adjusts the voltage periodically. If power increases, the adjustment direction is maintained; otherwise, it is reversed.

$$P = VI$$

$$\Delta P = P(n) - P(n-1)$$

$$\Delta V = V(n) - V(n-1)$$

$$\text{If } \Delta P > 0 \text{ then } V(n+1) = V(n) + \Delta V$$

$$\text{Else } V(n+1) = V(n) - \Delta V$$

The InC algorithm finds the maximum power point (MPP) when the incremental conductance is equal to the negative of the instantaneous conductance.

$$\frac{dI}{dV} + \frac{I}{V} = 0 \qquad \text{at MPP}$$

$$\text{If } \frac{dI}{dV} > -\frac{I}{V} \qquad \text{then increase V}$$

$$\text{If } \frac{dI}{dV} < -\frac{I}{V} \qquad \text{then decrease V}$$

The SOFT-MPPT algorithm dynamically adjusts the voltage and current. This algorithm introduces a modulating factor (M) related to the current that changes the size of the perturbation (D). It also adds steady state detection that stops artificial perturbation to minimize unnecessary oscillations in power, when it is close enough to the MPP.

$$\Delta D(k) = \Delta D_{min} + M\frac{dP}{dV}$$

$$M(k) = \frac{1 - 2.5\%}{I(k)}$$

What is a Buck Converter?

To extract the maximum amount of power, the voltage is adjusted to the proper value using a buck step-down converter. Its main job is to maximize power extraction from the solar panel by converting a higher voltage from the panel to a lower, more appropriate voltage for charging the battery [5]. The buck converter is essential to improving the overall efficiency and performance of the solar power system because it effectively reduces the panel voltage to the necessary voltage for battery charging and continuously adjusts to the MPP [5].

The basic idea behind a buck convertor is as follows: by using a really fast switch to rapidly connect/disconnect the input from a circuit with an inductor, you cause a current flow in the inductor when the switch is ON (storing energy in that inductor's magnetic field, and inducing a voltage across the inductor opposite to current flow) and then, when the switch turns OFF, the energy in the inductor keeps the current flowing (with a diode forcing the inductor current to flow in the desired direction), with a higher average current output from the circuit (at a lower voltage) than the average current through the switch [6].

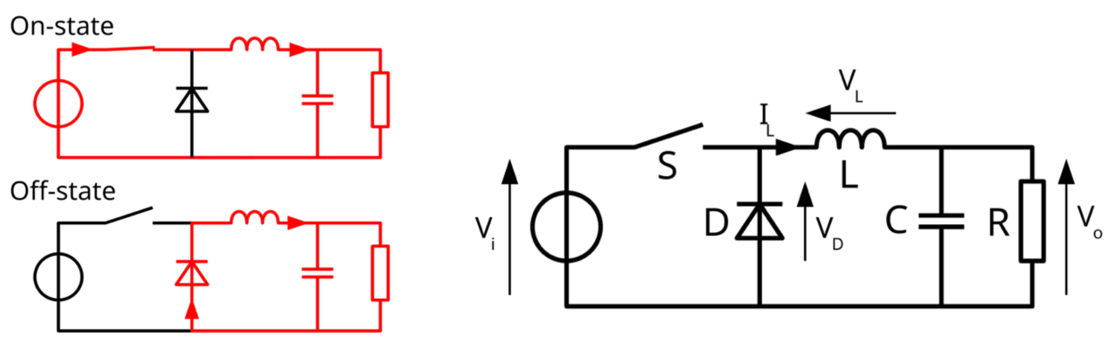

Figure 3: Basic topology of a buck converter from Wikipedia article showing ON and OFF state. S is typically a MOSFET for fast switching and the diode can be replaced by a second MOSFET actively controlled in a synchronous design [6].

Asynchronous vs. Synchronous Buck Converters

ASCAS posted a tutorial an on Autodesk Instructables on how to build a 1kW Arduino MPPT Solar Charge Controller [2]. He explains the pros and cons of Asynchronous and Synchronous Buck Converters. Asynchronous Buck Converters are simple and widely used, they are typically 75%-87% efficient. It often involves the use of a diode and a MOSFET or BJT. Synchronous Buck Converters more complex but significantly more efficient than the asynchronous variety ranging from 88%-98%. They remove the diode forward voltage drop from the asynchronous buck converter by using another MOSFET on the low side instead of the diode. This must be switched at exactly the right time in sync with the other MOSFET to act as a functional replacement of the diode. By doing so, we eliminate the large power loss from the diode forward voltage drop in the asynchronous buck converter and raise the efficiency from ~80% to ~98%. This is especially important for a charge controller, as the buck converter here is central to the role of efficiently charging the battery and capturing maximum energy from the panels, and not simply just stepping down a DC voltage and acting as a power supply for some minor subsystem as is more common for a buck converter. Safeguards must be implemented to prevent overvoltage and short-circuiting on the chip when using a synchronous buck converter.

What Microcontroller Should We Use?

According to ASCAS in his article at instructables.com "1KW ARDUINO MPPT Solar Charge Controller (esp32 + WIFI)", running a synchronous buck converter necessitates using a fast, multicore microcontroller [2]. This is because there are tasks that must run at high speeds that cannot be stopped for any reason while the device is in operation, like the control of the synchronous buck converter through feedback from the external current sensor, external high-resolution ADC and MPPT tracking algorithm [2]. This has to occur simultaneously and seamlessly while the device still responds to user inputs, outputs to the display, and outputs any telemetry. As mentioned previously, that project creator wrote and released an open-source MPPT firmware called FUGU for the ESP32 microcontroller, which uses a fast, dual-core design. We intend to use this firmware with an ESP32 MCU to great effect in our project, as it will allow us to start testing with much less overhead than developing a proprietary closed-source firmware of our own. Better to learn from the best and try to understand what has been already done/figured out and why.

Current Sensing

All MPPT SCCs use one or more current sensors to accurately measure the current coming in from the panels and sometimes out to the battery as well. Since *power in = power out (-losses)*, and $P = VI$, less current at a higher voltage is input to the controller when stepping down with the buck converter, and more current at a lower voltage is output to the battery. So if we want to use the current measurement to estimate watts or coulombs or charge current for a user display, and our current sensor is on the input, it will be slightly off [2]. This is simple to account for in the software calculation for the display output parameters. A common current sensor is the ACS712 series by Allegro. It has some limitations but is cheap, easy to acquire, and will work for this project. It is unshielded and less stable than more sensitive designs, as it relies on an external 5V reference [2]. This needs to be a strong 5V reference so that we can be sure the reading is accurate and not drifting with a fluctuating reference voltage. We do our best here and power the ACS712 current sensor with a 5V linear regulator.

Analog-to-Digital Conversion (ADC): Built-in ESP32 ADC vs. External ADCs

The ADC translates analog signals from the current sensor into digital data that can be used by the microcontroller. There are two options we are considering for the ADC. The first option is to use the built in ADC in the ESP32 microcontroller, it has 12-bit resolution and multiple input channels. The built in ADC is the most convenient cost-effective option; however, the ADC on the ESP32 is known to be non-linear, noisy and to contain dead zones at both ends of the 0 to 1V operating range. A dedicated ADC would offer more precise, reliable measurements compared to the expected measurements of the internal ADC. The external ADCs are compared in Table 2. ADCs. The I2C interface integrates easily with the ESP32 micro controller. We will choose the ADS1015 because the sample rate is higher than the ADS1115 and a 12-bit resolution will high enough precision for your MPPT controller.

Table 2: ADC Comparisons [7]

ADC	Resolution	Channels	Sampling Rate	Interface	Power
MCP0008	10-bit	8	< 200ksps	SPI	Low
MCP3208	12-bit	8	< 100ksps	SPI	Low
ADS1015	12-bit	4	< 3300sps	I2C	Very low
ADS1115	16-bit	4	< 860sps	I2C	Very low

IV - Team Duties & Project Planning

Our team consists of three members: Angel, Ben, and Jenna. Each person will have specific roles and deliverables that contribute to the success of our project.

- Angel's responsibilities include creating a thorough project plan, managing the spending plan, and ensuring that the team members communicate and work together efficiently. Following recommendations, she will also oversee the procurement of the test PCB and beginning parts. Angel needs to get input from Ben and Jenna to understand their needs, hold regular meetings to track progress and ensure that all necessary components are ordered to be delivered on time. In addition, Angel is going to design and produce a 3D-printed case for the charge controller. Without a well-defined project plan and timely material acquisition, the project may experience mismanagement and delays.

- Ben's focus will be on assembling and testing boards using the ordered components. He will make sure the electrical system is operating correctly by checking it. If the prototype functions as intended, Ben will work with each member of the team to design a special PCB and make the final component selections. For the charge controller to function properly, the electrical system must be designed and tested, and any issues or delays in this area will have a direct impact on the project.

- Jenna is working towards installing and testing open-source firmware on the prototype, making necessary modifications based on test results, and working with Ben to test and integrate the hardware and software are among Jenna's responsibilities. In order for Jenna to succeed, hardware-software compatibility needs to be ensured, and Ben's thorough input on the system design is required. Angel will require information on a frequent basis in order to stay on course. The firmware and enclosure design are critical to the charge controller's operation and user interface, therefore any delays in these areas could affect the project.

The project is expected to be completed before August. Hence, it is important to identify potential setbacks that could delay the project. The late arrival of components, due to shipping or supply chain issues, could postpone the arrival of necessary parts, while malfunctioning components could disrupt the assembly and functioning of the MPPT solar charge controller. Additionally, team members may face time limitations due to other academic or professional commitments, impacting their availability for the project.

To mitigate these risks, we will break the project into smaller parts, this will allow us to make progress even if certain parts are delayed or require rework, as each section can be developed, tested, and completed independently. We will also provide cross-training for team members to ensure that everyone has a basic understanding of each other's roles. This will allow us to cover for one another if someone is unavailable or if an area encounters issues. Additionally, we will maintain backup suppliers by identifying multiple sources for critical components used in the project. This will help us avoid delays due to supply chain issues, as we can quickly turn to an alternative source if one supplier is delayed. These measures will help ensure that the project remains on track and is completed before the August deadline, despite any potential setbacks.

V - Milestones & Progress Made

To help us stay on track to finish the solar charge controller prototype by August, we have included significant checkpoints in our project timeline.

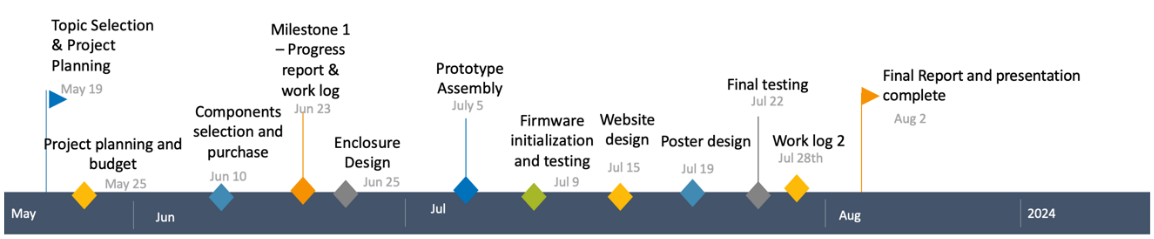

Figure 4: Project timeline

This early progress tracking creates a strong basis for the later stages, which are scheduled for July and August and include custom PCB design, enclosure development, firmware customisation, and extensive system integration and testing. Our group is still dedicated to reaching these targets, making sure every stage is carried out painstakingly to complete our project. Holding regular team meetings has made it easier to coordinate and communicate effectively, resulting in agreement on duties and responsibilities. To successfully complete the project on schedule, we will keep track of and accurately record our progress going forward.

VI - Summary & Future Work

Our project focuses on developing a solar charge controller utilizing Maximum Power Point Tracking (MPPT) technology, chosen for its superior efficiency in optimizing energy extraction from solar panels. By dynamically adjusting the operating point to the Maximum Power Point (MPP), MPPT controllers maximize energy yield under varying environmental conditions, surpassing traditional methods like "direct-to-battery" and simple PWM. Our project plan includes rigorous research into solar charge methods and MPPT theory, followed by the design, assembly, and testing of a prototype. Currently, we have successfully looked into initial tests with promising results, and will be moving on to validating the functionality of our MPPT controller in a practical setup with solar panels and batteries. Our focus will be on implementing MPPT algorithms, exploring integration with energy storage systems, and assessing scalability and commercial practicality. Additionally, we plan to enhance user interface features and ensure compliance with environmental standards. This project not only advances our understanding of renewable energy technologies but also sets the stage for future innovations in sustainable energy solutions.

VII - References

[1] S. Bhattacharyya, D. S. Kumar P, S. Samanta, and S. Mishra, "Steady Output and Fast Tracking MPPT (SOFT-MPPT) for P&O and InC Algorithms," IEEE transactions on sustainable energy, vol. 12, no. 1, pp. 293–302, 2021, doi: 10.1109/TSTE.2020.2991768.

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