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DESIGN AND CONSTRUCTION OF A SMART DC-DC CHARGE CONTROLLER FOR SOLAR CHARGE STATIONS

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Abstract: Efficient solar energy conversion necessitates advanced charge controllers. This paper presents the design and construction of a smart DC-DC charge controller for solar charge stations. The controller, employing Maximum Power Point Tracking (MPPT), efficiently charges 12V-48V batteries up to 20A, maximizing power extraction from solar panels. This paper details the design and experimental performance validation of a smart solar charge controller based on the Perturb and Observe (P&O) MPPT algorithm for charging 12V to 48V batteries with a maximum charging current of 20A.

Keywords: Solar Charge Controller, DC-DC Converter, MPPT (Maximum Power Point Tracking), Battery Charging.

I. INTRODUCTION

Electricity is an essential part of life in modern civilization. It is practically indispensable in all the different socio-political sectors and at every scale of society. There are many methods of electricity generation from burning fossil fuels to using radioactive fuel in nuclear power plants [1]. However these methods of generation are not all created equally. Whilst there exists long standing infrastructure for the use of fossil fuels, they are not only a very limited resource, but their use is also damaging to the environment [2]. Therefore it is of the utmost importance we explore alternatives such as solar power.

Whilst solar power is the most abundant and accessible form of power, it must be noted that it is imperfect [3]. With the biggest drawback and the focus of this project being the inconsistency in power generated by solar panels over the course of a day [3]. This necessitates the use of batteries for energy storage and resupply during periods of downtime. However, when using batteries it is essential that their charging voltage be regulated as the fluctuating (and often times too high) voltage produced by the panels throughout the day may damage the batteries. For these reasons it is necessary that all solar systems come installed with a charge controller to regulate the output of the system.

A solar charge controller is an electronic device used in off-grid and hybrid off-grid applications to regulate current and voltage input from PV arrays to batteries and electrical loads (lights, fans, monitors, surveillance cameras, process control equipment, etc.) [4]. The charge controller ensures that the deep cycle batteries are not overcharged during the day, and that the power doesn't run backwards to the solar panels overnight and drain the batteries. Some charge controllers are available with additional capabilities, like lighting and load control, but managing the power is its primary job [5].

The scope of this paper is to the design and construct a smart DC-DC charge controller for solar charge stations capable of charging a battery bank from a PV array. It must be capable of automatically detecting the total voltage of the connected batteries and adjust the output voltage accordingly.

II. TYPES OF CHARGE CONTROLLERS

I. Pulse Width Modulation (PWM)

For a PWM solar charge controller, during bulk charging, when there is a continuous connection from the array to the battery bank, the array output voltage is 'pulled down' to the battery voltage. As the battery charges, the voltage of the battery rises, so the voltage output of the solar panel rises as well, using more of the solar power as it charges. As a result, it is necessary to match the nominal voltage of the solar array with the voltage of the battery bank [5, 6].

II. Maximum Power Point Tracking (MPPT)

An MPPT solar charge controller will measure the voltage of the panel and down-convert the PV voltage to the battery voltage. Because power into the charge controller equals power out of the charge controller, when the voltage is dropped

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to match the battery bank, the current is raised, so more of the available power from the panel is used. A higher voltage solar array than the battery can be used, like the 60 cell nominal 20V grid-tie solar panels that are more readily available [5, 6].

III. TYPES OF MPPT ALGORITHMS

I. Perturb and Observe(P&O)

The P&O algorithm is one of the most commonly used MPPT algorithms. It periodically perturbs the operating point of the solar panels and observes the resulting change in power output. Based on this observation, it adjusts the operating point to maximize power. [7].

The draw backs of using this conventional technique are its failure to track Maximum Power Point when there is a big change in the insolation level as well as the fact that it continues oscillation around MPP. However, this method is featured by its simple structure, simple implementation, and its lower cost [8]. The P&O algorithm flowchart is demonstrated in the figure below [9].

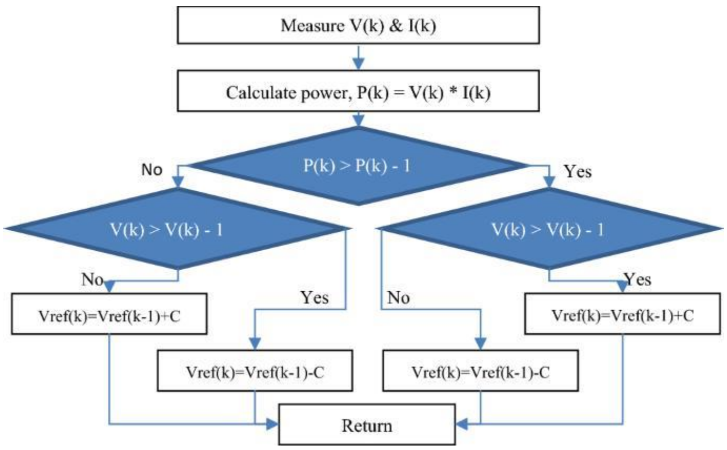

Figure 1: Flowchart of P&O MPPT technique[9].

II. Incremental Conductance (INC)

The INC algorithm achieves Maximum Power Point Tracking (MPPT) by iteratively adjusting the PV panel voltage [10]. It calculates the derivative of the power-voltage (P-V) curve and aims to maintain this derivative at zero (dP/dV = 0). This zero derivative indicates the MPP, which is achieved by comparing instantaneous and incremental conductance to determine the slope of the P-V curve and guide voltage adjustments [10].

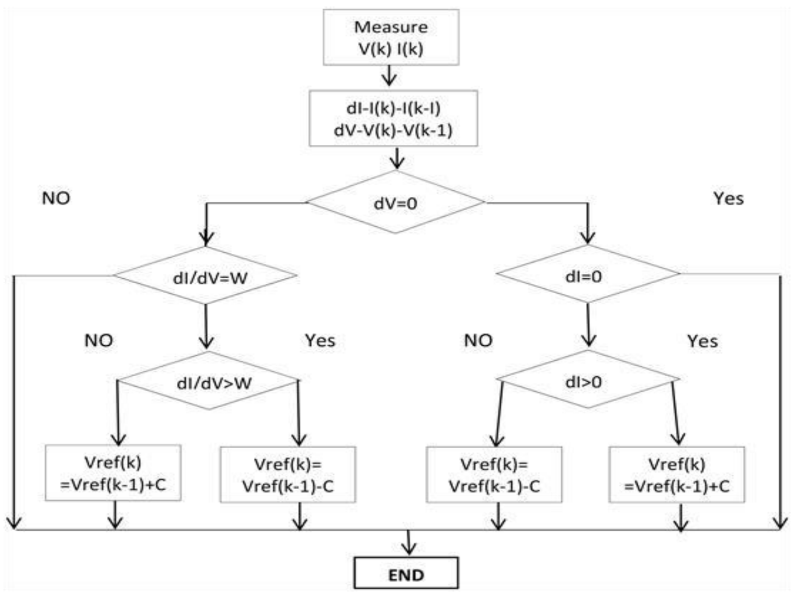

Figure 2: Flowchart of Incremental Conductance Algorithm [10].

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III. Fractional Open Circuit Voltage (FOCV)

The Fractional Open Circuit Voltage (FOCV) algorithm uses the approximate proportionality between a photovoltaic (PV) array's open-circuit voltage (V_{oc}) and its maximum power point voltage (V_{mpp}) [10].

It periodically interrupts the power delivery to measure V_{oc} and then V_{mpp} is estimated by multiplying V_{oc} with a predetermined empirical constant, 'k'. The MPPT controller then regulates the DC-DC converter to operate the PV array at this calculated V_{mpp} [9, 10].

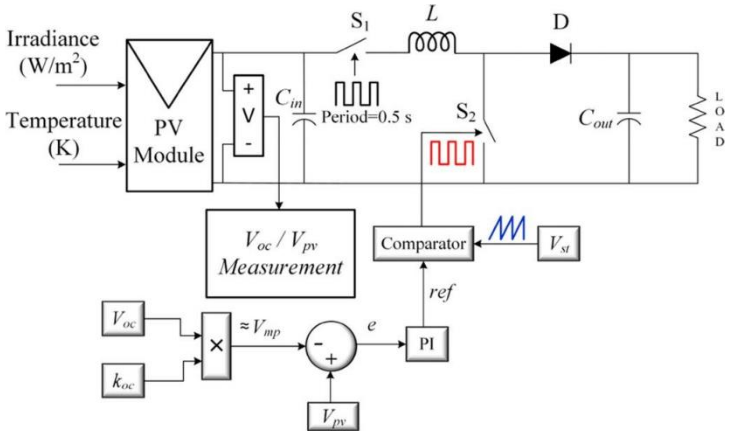

Figure 3: Diagram of FOCV MPPT algorithm [10].

IV. DESIGN PARAMETERS FOR THE SMART DC-DC SOLAR CHARGE CONTROLLER

This section presents the steps taken in designing a smart DC-DC charge controller to meet the following specifications:

- MPPT Algorithm: Perturb and Observe (P&O)
- Battery Voltage Range: 12V, 24V, 36V, 48V (selectable)
- Maximum Charging Current: 20A
- Microcontroller-Based (ESP32 microcontroller)
- DC-DC Converter Type: Buck (Step-down)
- Display: LCD for status display
- Protections: Over-voltage, under-voltage, over-current, temperature

I. Input Voltage/Current

The current sensing mechanism in the MPPT system utilizes the **ACS712-30A** bidirectional current sensor IC, configured to function as a unidirectional sensor to optimize ADC resolution. The sensor's **-IP** and **+IP** pins are connected in reverse, allowing the output voltage (V_{out}) to remain at 2.5V when no current flows. The relationship for current measurement is expressed as:

$$V_{out} = 2.5 + (\text{current sensed x } 0.066) \qquad (1)$$

TABLE 1: ACS712-30A (CURRENT & OUTPUT VOLTAGE RELATIONSHIP) [11]

Current (A)	Analog Output Voltage (V)
-35	0.19
-30	0.52
-25	0.85
-20	1.18
-15	1.51
-10	1.84
-5	2.17

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0	2.5
5	2.83
10	3.16
15	3.49
20	3.82
25	4.15
30	4.48
35	4.81

This configuration establishes a voltage floor and ceiling that can be scaled to match the ADC's voltage reference, preventing clipping.

A voltage divider is implemented to scale down the input voltage to a level suitable for the analogue-to-digital converter (ADC) within the controller. The voltage divider equation is:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2} \quad (2)$$

Where V_{out} is the output voltage (voltage across R_2), V_{in} is the input voltage (voltage from the solar panel) and R_1 And R_2 are the resistor values for the voltage divider. By carefully selecting the values of R_1 and R_2, the output voltage can be scaled down to a range that is compatible with the ADC's input voltage range.

II. Inductor specifications:

In selecting an appropriate inductor value for the design, to handle the maximum output voltage, the following formula is used:

$$L = \frac{V_{mp} - V_{bat}}{V_{mp} \times \%eff} f_{sw} P_{solar} \% I_{ripple} \quad (3)$$

And to enable it handle the peak current given by:

$$I_{peak} = \frac{2P_{solar} + V_{mp} I_{mp} \times \% I_{ripple}}{2V_{bat}} \quad (4)$$

An inductor with a saturation current of at least the peak current is chosen according to the formula:

$$I_{sat} = \frac{B_{sat} A_e}{\sqrt{A_L L}} \quad (5)$$

Where, L = Inductance, V_{mp} = Solar panel maximum power point voltage, V_{bat} = Maximum battery voltage, %eff = MPPT buck conversion efficiency, f_{sw} = MPPT buck converter PWM switching frequency, P_{soloar} = The maximum solar panel power output, $\% I_{ripple}$ = Percentage ripple of output current, I_{peak} = Maximum current rating for inductor, I_{mp} = Solar panel maximum power point current, I_{sat} = Inductor Saturation Current, B_{sat} = Toroid's Magnetic Saturation Flux Density, A_e = Toroid's Effective Cross Sectional Area, A_L = Toroid's Inductance Factor [11]

III. Connecting Wires/Traces:

The thickness of these especially along the high power sections of the circuit depends on the maximum current flowing through that section. This is because the heat produced by electricity passing through a wire is given by:

$$\text{Heat} = I^2 R \quad (6)$$

Where I is the current flowing through the wire/trace and R is the resistance of the wire/trace. And the resistance is dependant on the cross-sectional area of the wire/trace as given by:

$$\text{Resistance} = pLA \quad (7)$$

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Where p is the resistivity of the conducting material, L is the length of the wire/trace and A is the cross-sectional area. Therefore shorter connecting wires/traces are preferred, and the cross-sectional area of these should be chosen to accommodate the specified current.

Lastly all other circuit components including all capacitors, MOSFETs and Diodes, are chosen such that their maximum current/voltage ratings are above the desired specifications of the circuit.

IV. PWM Floor Value

In the design of the MPPT system, it is crucial to establish a specific floor value for the PWM duty cycle. The PWM floor duty cycle can be calculated using the formula:

$$PWMFloorDutyCycle = \frac{V_{out}}{V_{input}} \times 100 \ (8)$$

Where V_{out} = Output Voltage and V_{in} = Input Voltage.
The minimum permissible duty cycle establishes the ideal unloaded PWM duty cycle for achieving the desired battery voltage with the buck converter.

The PWM resolution and frequency are vital for MPPT buck converter performance. Higher PWM resolution enhances regulation accuracy by providing finer voltage and current control, while lower resolution results in coarser control. Increasing PWM frequency improves power handling and reduces output ripple; however, it also increases switching losses, thus requiring a balanced and judicious frequency selection [11].

The relationship between PWM resolution and frequency is defined by the following formula:

$$MaxPWMFrequency = \frac{MCUClock}{PWMResolution} \ (9)$$

TABLE 2: ESP32: PWM RESOLUTION & PWM FREQUENCY TABLE [20]

Resolution (Bits)	Resolution (decimal)	Max PWM Frequency (kHz)
1	2	40000
2	4	20000
3	8	10000
4	16	5000
5	32	2500
6	64	1250
7	128	625
8	256	312.5
9	512	156.25
10	1024	78.125
11	2048	39.0625
12	4096	19.53125

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V. CIRCUIT DESIGN FOR THE SMART DC-DC CHARGE CONTROLLER

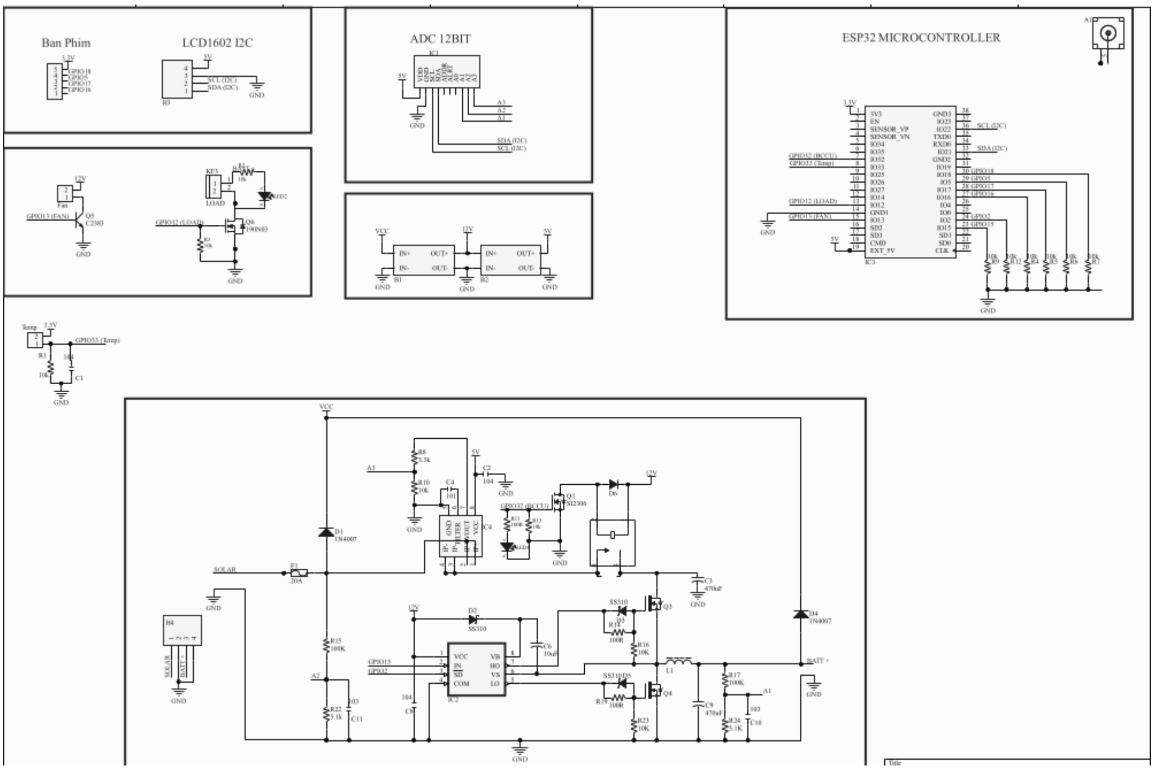

Figure 4: The circuit diagram for the smart DC-DC converter [12].

The design incorporates a buck DC-DC converter topology and uses the P&O MPPT algorithm. This ensures effective regulation of output voltage and current levels.
Controlled by an ESP32 microcontroller, the smart charge controller utilizes a PWM technique for precise control over the duty cycle.

The circuit also includes components for measuring voltage and current, managing protection mechanisms, and ensuring stability and reliability throughout the operation.

Two linear buck regulators are included to provide supply 12V and 5V power to the electronic components like the relay and micro-controller.

The design uses a synchronous buck converter which addresses the inefficiency inherent in the traditional asynchronous buck converter by making a slight but critical modification: replacing the diode with a MOSFET. This diode introduces a significant voltage drop, reducing overall efficiency. A MOSFET, on the other hand, does not experience the same voltage drop when activated, enhancing performance. N-channel MOSFETs are preferred over P-channel MOSFETs for this application due to their considerably lower on-resistance (Rds(on)), which further minimizes the voltage drop during conduction [11].

The inductor in the circuit serves as a crucial energy storage component, storing energy during one phase of the switching cycle and releasing it during the next, ensuring a continuous current flow to the load.

The central microcontroller in the MPPT system is responsible for managing control, processing, and communication tasks. The ESP32 (WROOM32 module) was selected for this due to its cost-effectiveness and versatility. Moreover, the ESP32 comes equipped with built-in Wi-Fi and Bluetooth, eliminating the need for additional wireless communication modules [11].

To address the limitations of the ESP32's internal ADC, the system incorporates an external precision ADC, specifically the ADS1015 from Texas Instruments. It offers superior accuracy, allowing for much finer sensing capabilities. Moreover,

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the external ADC's built-in voltage reference ensures consistent analogue readings that are immune to fluctuations in the power supply [11].

To prevent overcharging, a MOSFET (Q6) is employed as a switch to control the charging process. Once the battery voltage reaches its maximum safe threshold, the ESP32 disables the MOSFET, effectively halting the charging operation and safeguarding the battery against overcharge damage. Furthermore, Schottky diodes (D1 and D4) are integrated to provide reverse current protection. These diodes prevent current from flowing back from the battery to the solar panel during periods of insufficient sunlight, ensuring that no energy is wasted and that the battery is protected from unnecessary discharge [11].

A temperature sensor is incorporated into the system to monitor the temperature of the main synchronous converter MOSFETs. The ESP32 utilizes this information to regulate the speed of the included fan and ensure the MOSFETs do not overheat at high current draw.

Perturb and Observe(P&O) MPPT Algorithm Implementation

- Initially, the system measures the voltage and current output of the solar panel. From these values, the power is calculated using the formula:

$$P\text{Power}, \mathrm{P} = \mathrm{V} \times \mathrm{I} \qquad (10)$$

Where, V = Voltage and I = Current.

- Subsequently, the ESP32 makes slight adjustments, or perturbations, to the duty cycle of the buck converter's PWM signal and monitors any resulting changes in power output.
- If an increase in power is observed, the perturbation continues in the same direction
- Conversely, if power decreases, the perturbation direction is reversed.
- This iterative process allows the controller to continuously track the maximum power point (MPP) of the solar panel, adapting to changing sunlight conditions [13].

VI. SYSTEM IMPLEMENTATION AND RESULT ANALYSIS

To evaluate the performance and reliability of the charge controller, varying input voltages were applied and the controller's output was monitored. Its ability to operate effectively in different sunlight conditions was determined. Efficiency was measured by comparing the input and output power.

The controller's battery charging performance was tested with different battery types to ensure compatibility and safe charging. Temperature stability was assessed by subjecting the controller to varying temperatures and monitoring its performance.

TABLE 3:STANDARD INPUT AND OUTPUT READINGS FOR THE SMART STATION

Input Power	PWM	PPWM	Input Voltage	Input Current	Output Current	Output Current
413	1390	1315	39.8	10.37	25.7	16.06
413	1391	1316	39.8	10.38	25.7	16.07
413	1392	1317	39.8	10.37	25.7	16.06
412	1393	1319	39.7	10.37	25.7	16.02
412	1394	1319	39.7	10.37	25.7	16.02
412	1395	1319	39.7	10.38	25.7	16.03
411	1396	1321	39.6	10.37	25.7	15.98
411	1397	1322	39.6	10.37	25.7	15.98
411	1398	1324	39.6	10.37	25.7	15.98
411	1399	1324	39.6	10.38	25.7	15.99

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411	1400	1325	39.5	10.40	25.7	15.98
411	1401	1327	39.5	10.41	25.7	16.00
411	1402	1327	39.5	10.41	25.7	16.00
410	1403	1328	39.4	10.41	25.7	15.96
411	1404	1329	39.4	10.42	25.7	15.98
410	1405	1330	39.4	10.41	25.7	15.96
411	1406	1331	39.4	10.42	25.7	15.98
410	1407	1332	39.4	10.41	25.7	15.96
410	1408	1333	39.3	10.42	25.7	15.93
409	1409	1335	39.3	10.41	25.7	15.92
410	1410	1336	39.3	10.42	25.7	15.93
409	1411	1337	39.3	10.41	25.7	15.92

TABLE 4: DUTY CYCLE VARIATIONS OF THE MAIN DC-DC BUCK CONVERTER FOR DIFFERENT OUTPUTS

Duty Cycle (%)	Output Voltage (V) (22V Input)	Output Voltage (V) (17V Input)
10	4	3.5
20	8	6.5
30	11	9
40	13.5	10.8
50	15	12
60	16.5	13
70	17.5	13.8
80	18.5	14.5
90	19.5	15.5
95	21	16.5

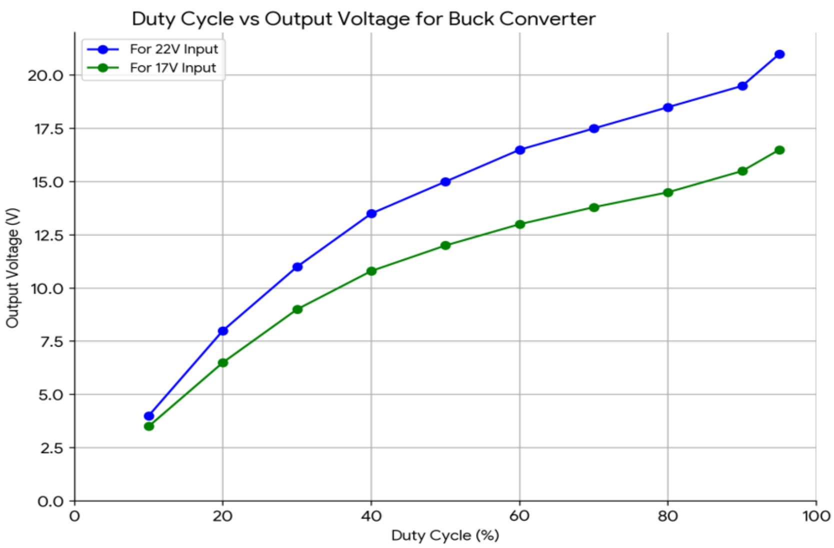

Figure 5: Duty cycle variations of the main DC-DC buck converter for different outputs

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In construction, A bulk capacitor designed to filter out ripple voltages caused by the fast-switching nature of the buck converter is connected across the output terminals of the converter circuit.

Pull-down resistors are included to prevent the synchronous MOSFETs from floating before start-up, ensuring that they remain in the off state until properly triggered. Gate resistors are also included to limit transient currents provided by the IR2014 (IC2), protecting the gate pins of the synchronous MOSFETs from potentially damaging surges during switching. And lastly a fan is used reduce the temperature of the MOSFETs during periods of prolonged usage at high currents.

VII. CONCLUSION

In summary, this paper has showcased the important factors to be considered in the design and construction of a smart DC-DC charge controller for solar charge stations. This controller, is capable of automatically detecting the battery voltage and adapting its algorithm accordingly, and also uses a synchrounous DC-DC converter setup with an external ADC for improved efficiency and finer control.

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