Abstract

With renewable energy based households becoming more energy efficient to maximise the output of renewable energy systems, a maximum power point tracker (MPPT) may be a recommended addition to the household's battery management system. The purpose of this document is to explore the feasibility of an MPPT by creating an MPPT prototype using an incremental conductance algorithm and comparing the effectiveness of a photovoltaic system using an MPPT versus a photovoltaic system not using an MPPT.

Author: Hau Shian Chin
Student ID: 300493343

1. Introduction

To improve the power efficiency of any household renewable energy system, a maximum power point tracker (MPPT) should be incorporated into the battery management system (BMS), perhaps even coupled with an inverter. An MPPT dynamically alters the impedance of the photovoltaic (PV) panels to achieve maximum power output. MPPTs are incredibly beneficial in cloudy weather or if the load changes regularly.

To assess the efficacy of an MPPT inside the renewable energy system. A controlled PV system and an uncontrolled PV system be provided with the same step input solar irradiance. Both PV systems encompass two polycrystalline panels which will provide an output that can be used to compare the systems.

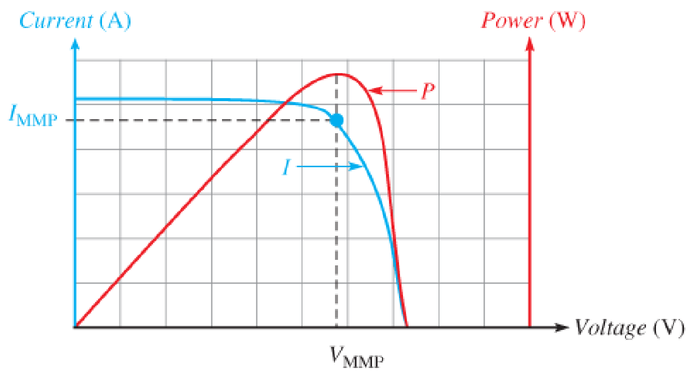

Figure 1: MPPT example [1]

An example can be observed in Figure 1, the impedance of the PV was manipulated to achieve the maximum power point (MPP), it increases or decreases the voltage and current accordingly so that it maintains the maximum power output from the PV system .

2. Background

2.1. Topology of the PV system

The configuration of the PV system which encompasses two polycrystalline panels is set to parallel so that in the event of a cloudy forecast, power may still be produced by the unshaded PV; as shown in Figure 2.1. As a result, the components selected for the MPPT must be able to tolerate higher current instead of voltages. This PV system will then be connected into an MPPT circuit to allow for maximum power output.

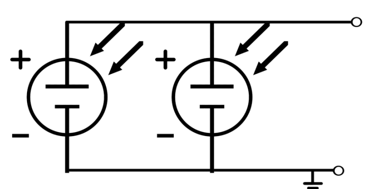

Figure 2.1: Example of parallel PV configuration

2.2. MPPT Algorithm

The complexity of an MPPT algorithm is limited to the processing capabilities of the microcontroller (MCU). Complex algorithms (genetic algorithms, fuzzy logic algorithms) tend to be more computationally intensive, thus more expensive MCUs are required to run these algorithms. Therefore, it can be justified that the MPPT uses a less computationally intensive algorithm such as “Perturb and Observe (P & O)” or “Incremental Conductance (InC)” to reduce the cost spent on the MCU.

Although the P & O algorithm is less complex, the InC algorithm allows for more dynamic performance during turbulent weather. Moreover, InC accurately finds the MPP in changing atmospheric conditions while P & O requires more stable weather conditions [2]. In the event that the renewable energy system household is located in a location with a turbulent climate, an InC algorithm-based algorithm will make the MPPT more globally viable. Additionally, P&O comes with higher oscillations at the MPP, which could prove to be hazardous and add to the wear and tear of the inverters / BMS.

2.3. Component parameters

2.3.1. Sensors

As both the P & O and InC algorithms require voltage and current inputs of the PV system. Voltage / current sensors are required. However, due to the budget constraints of this project, it is recommended to build a current sensor with a shunt resistor and a differential amplifier to detect the current supplied by the PV. Moreover, a voltage sensor can be built with a negative feedback operational amplifier (opAmp) to detect the voltage across the PV, this is more favourable than a voltage divider as there is less power being drawn from the PV. Resistors selected for these sensors must be of high value to prevent unnecessary current drain. The output of these amplifiers must fit within the resolution of the MCU’s analogue to digital converter (ADC). Additionally, the output of these opAmp cannot be greater than 5V as it would damage the MCUs.

2.3.2. Microcontroller (MCU)

Controlling the MPPT circuit to achieve MPP, a MCU is required as it can process the current and voltage observed by sensors to produce a duty cycle pulse associated with these sets of input. This duty cycle can then be accepted by the gate driver to control the MOSFET of the buck-boost converter that regulates the power input to the load, in a practical setting this load may be a BMS.

2.3.3. DC to DC converter

When connecting the PV power output to the power input of the BMS, DC to DC power conversion is required. Buck-boost converters such as the one shown in Figure 2.3.3, should be utilised when regulating the charging of the BMS. Using the output of an MCU, a gate driver can output a PWM that controls the switching frequency of a MOSFET of a buck-boost converter, thus regulating the required voltage input of the BMS. Using a buck-boost converter is recommended for an MPPT as it reduces power conversion loss on a wide voltage variation of the battery compared to using a variable voltage divider; which results in low power efficiency, or a buck / boost converter which can only decrease / increase the voltage respectively [3]. Furthermore, this is beneficial for resource dependent projects such as a renewable energy household due to its energy efficiency.

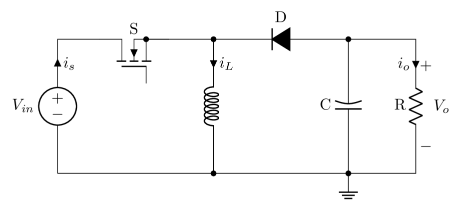

Figure 2.3.3: Buck-boost converter schematic [4]

2.4. MPPT arrangement

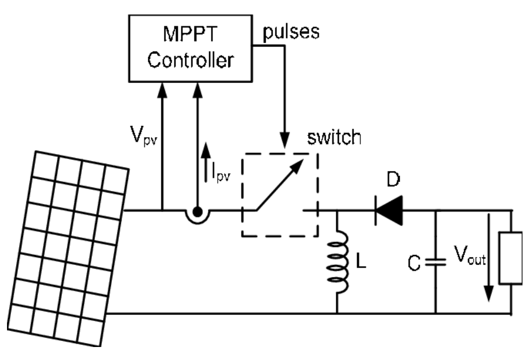

Figure 2.4: MPPT diagram [5]

Figure 2.4 shows how the MPPT will be arranged with the current PV system and the BMS. The BMS can be represented by the load resistors. The inductor, capacitor and the diode configuration along with the load resistor represented the buck-boost section of the MPPT whereas the switch, pulse and MPPT controller represented the MOSFET, gate driver output and the MCU respectively. Additionally, the Vpv and Ipv represent the current sensors that observe the voltage and current output of the PV system.

Voltage and current combinations that are inefficient can be detected by the sensors and corrected by the MPPT controller before power is applied to the BMS. The MPPT system is designed in such a way that the imperfections can be corrected to regulate power properly through the system by adjusting switching frequency.

3. Design

3.1. Component selection

Components selected for the MPPT considers the budget constraints ($50) and the component parameters mentioned in 2.3. Moreover, following Figure 2.4 provides the guidelines as to the required components. Additionally, components selected must tolerate a higher current due to the parallel arrangement of the PV system; A maximum voltage of 17.4 V and maximum current 1.22 A. Although the voltage is not the PV's short circuit value, it can be made negligible as it is only relevant for the MOSFET rated voltage range.

Due to the time constraints of this project, the Arduino Uno was selected as the MCU which comes with a 10 bit ADC for the voltage and current sensors, thus a 4.9mV minimum input voltage. The load resistor of the MPPT which represents the BMS (in a practical scenario) will be 1Ω, 10Ω and 100Ω to determine the MPPT's feasibility.

The gate driver and MOSFET selected for this project may be unideal, IR2117 and FPQ50N06 (gate driver and MOSFET respectively) was selected as it has been used in a previous buck-boost converter project. 4 and 2 pin terminals were selected for a way to connect the PV system, the MCU while simultaneously providing power to the sensors and gate driver.

3.1.1. Component value calculations

3.1.1.1. Sensors

Voltage sensors can be made with a negative feedback opAmp circuit. Calculating the gain of this opAmp while considering the maximum voltage of 17 V and the maximum input voltage of the Arduino MCU to be 5 V; will result in a gain of 0.29 as shown in Equation 3.1.1.1a. This means that at maximum output from the voltage sensor will be less than 5V to prevent hardware damage. Furthermore, high resistor values must be selected making R_i 10 kΩ and R_f 2.9kΩ; an example can be shown in Figure 3.1.1.1a. Due to the 10 bit ADC nature of the Arduino the minimum detectable voltage from the PV system would be 1.6mV.

$$\frac{17}{5}^{-1} = 0.29 \therefore G = 0.29,\ G = -\frac{R_f}{R_1} = \frac{2.9k\Omega}{10\ k\Omega}$$

Equation 3.1.1.1a: Voltage sensor gain calculations

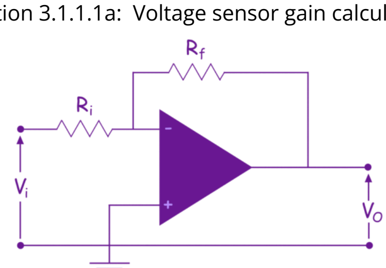

Figure 3.1.1.1a: Negative feedback opAmp example [6]

The shunt resistor provides an ease of current flow which can be used to calculate the current provided by the PV system via a differential opAmp. This will result in a voltage output that would reflect the current provided by the PV system. As the voltage applied onto the shunt resistor is small, the gain of the current sensor must be high to meet the minimum resolution of the 10 bit ADC.

$$Vo_{max} = 5V,\ Vo_{min} = \frac{5}{2^{10}}V,\ Ii_{min} = 0,\ Vi_{max} = 50mV,\ Ii_{max} = 0.61 * 2\ A$$

$$R_{shunt} = \frac{Vi_{max}}{Ii_{max}} = \frac{0.05}{1.22} = 0.041\Omega,\ G = \frac{Vo_{max} - Vo_{min}}{(Ii_{max} - Ii_{min}) * R_{shunt}} = 99.9023$$

Equation 3.1.1.1b: Shunt resistor and differential opAmp gain calculations

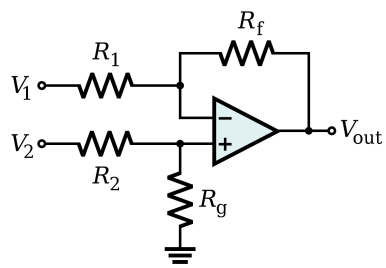

Figure 3.1.1.1b: Example of a differential opAmp [7]

The resistor values selected for differential opAmp can provided as $R_1 = R_2$, $R_f = R_g$; as shown in Figure 3.1.1.1b, thus to meet the provided gain parameters of the differential amp $R_1 = R_2 = 1k\Omega$, $R_f = R_g = 99.9k\Omega$ as calculated in Equation 3.1.1.1b.

3.1.1.2. Buck-boost converter

To calculate the capacitor and inductor values of the buck-boost converter, current output from the PV system with the respective $1\Omega, 10\Omega, 100\Omega$ load resistors must be considered. This will provide voltage values for the buck-boost converter equations, thus the capacitor and inductor values for the buck-boost. Furthermore, as the current value varies depending on the load resistor, this will result in varying capacitor and inductor values for the varying load resistor. Rated voltage of the PV can be given as 17.4V and 0.61A. Additionally, the frequency output of MCU is clocked at 30kHz.

$$R = 1\Omega, 10\Omega, 100\Omega,\ V_{pp} = 17.4V,\ f = 30kHz$$

$$I_{out} = \sqrt{\frac{P_{out}}{R}} = \sqrt{\frac{21.228}{R}} = 4.6074A,\ 1.457A,\ 0.4607A \therefore V = \frac{P_{out}}{I_{out}} = 4.61V,\ 14.6V,\ 46.1V$$

$$\Delta L = 0.2 * I_{out} * \frac{V_{out}}{V_{pp}} = 0.244,\ L = abs\left(\frac{V_{pp} * (V_{out} - V_{pp})}{30 * 10^3 * (\Delta L * V_{out})}\right) = 6.60mH,\ 0.462mH,\ 1.50mH$$

$$D = \frac{V_{out}}{V_{out} + V_{pp}} = 0.2094, 0.4557, 0.7259,\ C = \frac{I_{out} * D}{30 * 10^3 * 0.05 * V_{out}} = 0.14mF,\ 0.03mF,\ 4.84\mu F$$

Equation 3.1.1.2: Calculating the capacitor and inductor values for the buck-boost converter

As shown in Equation 3.1.1.2, the capacitor and inductor value varies for different load resistor values. As only one inductor and capacitor value may be selected, it may be feasible to select the capacitor and inductor values for the 100Ω resistor. This will allow for greater resolution when observing the efficacy of the MPPT due to higher power draw.

3.1.2. Bill of Materials (BOM)

supplier	Manu. No.	Quantity	Description
Element14	12FR040E	1	0.04Ω shunt resistor
Element14	CGS553U030W4C	1	55000uF smoothing cap
Element14	ECA2AHG100	2	10uF capacitor
Element14	FQP50N06	1	N gate MOSFET
Element14	UG1B-E3/54	2	diode
Element14	MCAP115018077-561LU	1	560μH inductor,
Element14	ECA1HHG221	1	220μF capacitor
Element14	CTBP3051/2	1	2 pin terminal
Element14	IR2117	1	Gate driver
RS-pro	897-1339	1	4 pin terminal

Table 3.1.2: Purchased BOM

As observed in table final BOM deviated from the calculated values of the buck-boost converter in Section 3.1.1.2 due to miscalculations that occured when designing the original buck-boost converter for the MPPT. This resulted in an incorrect inductor and capacitor values in the purchased BOM. Although the combination of the inductor and capacitor values may work, the MPPT may not be as efficient compared to the values calculated in Section 3.1.1.2.

Resistor values and gate driver capacitors used for the MPPT can be selected from the array of resistors and capacitors inside the lab, thus does not need to be addressed in the BOM. Approximate values can be used as the error can be negligible.

3.2. Schematic

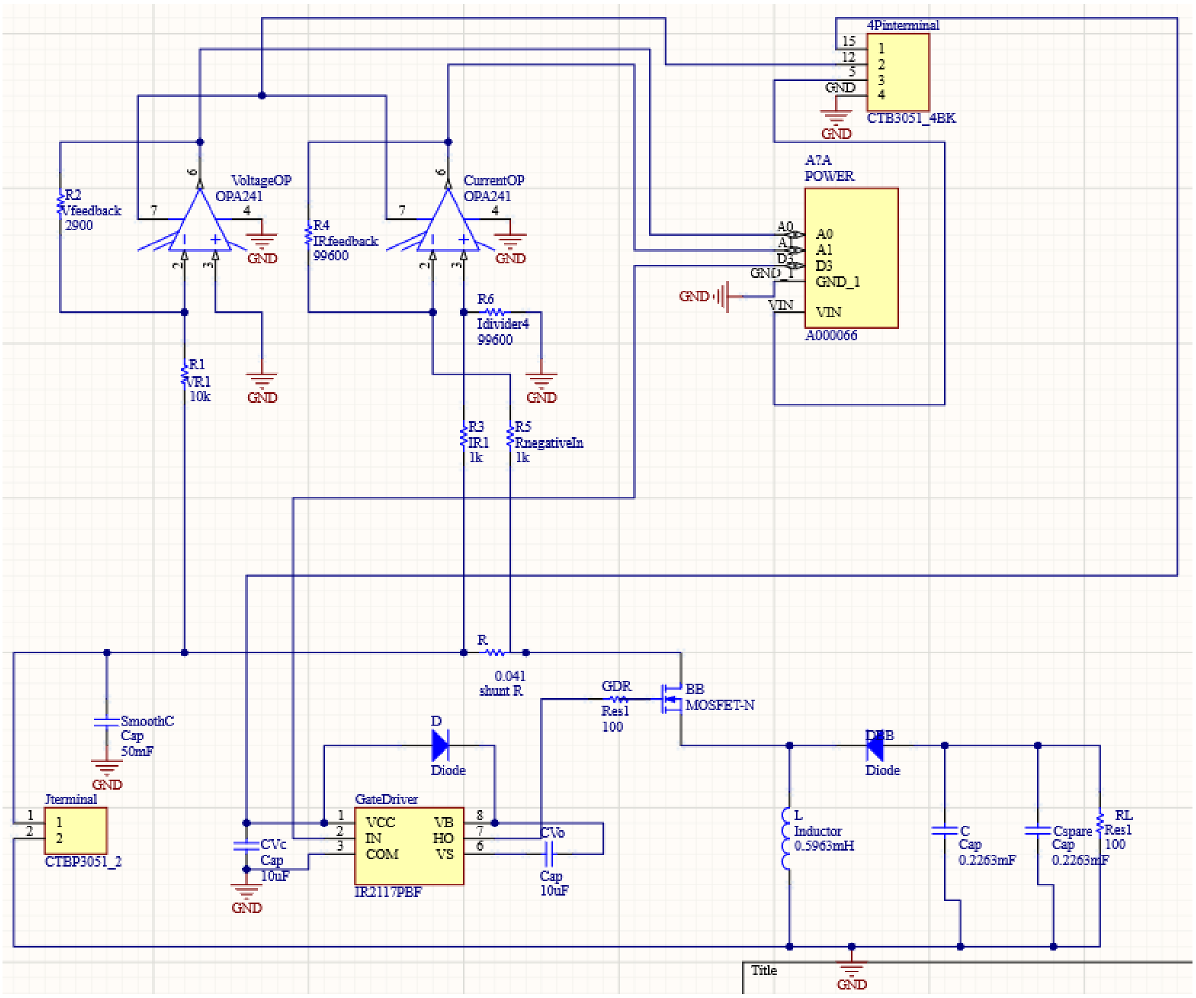

Figure 3.2: Schematic of the MPPT system

Using the incorrect values provided in the BOM, the MPPT schematic in Figure 3.2 was created using Altium Designer which encompasses 2 opAmps for the sensors along with a current shunt resistor, gate driver for the MCU generated pulse, 1 x 2 pin terminal, 1 x 4 pin terminal, a smoothing capacitor and a buck-boost converter. This schematic will then be turned into a PCB using Altium Designer so that the MPPT can be wired up to the PV system, the MCU and the load resistors / simulated BMS. The incorrect values can later be altered as the schematic is arranged in a way to allow for easy replacement of components.

3.3. Board layout

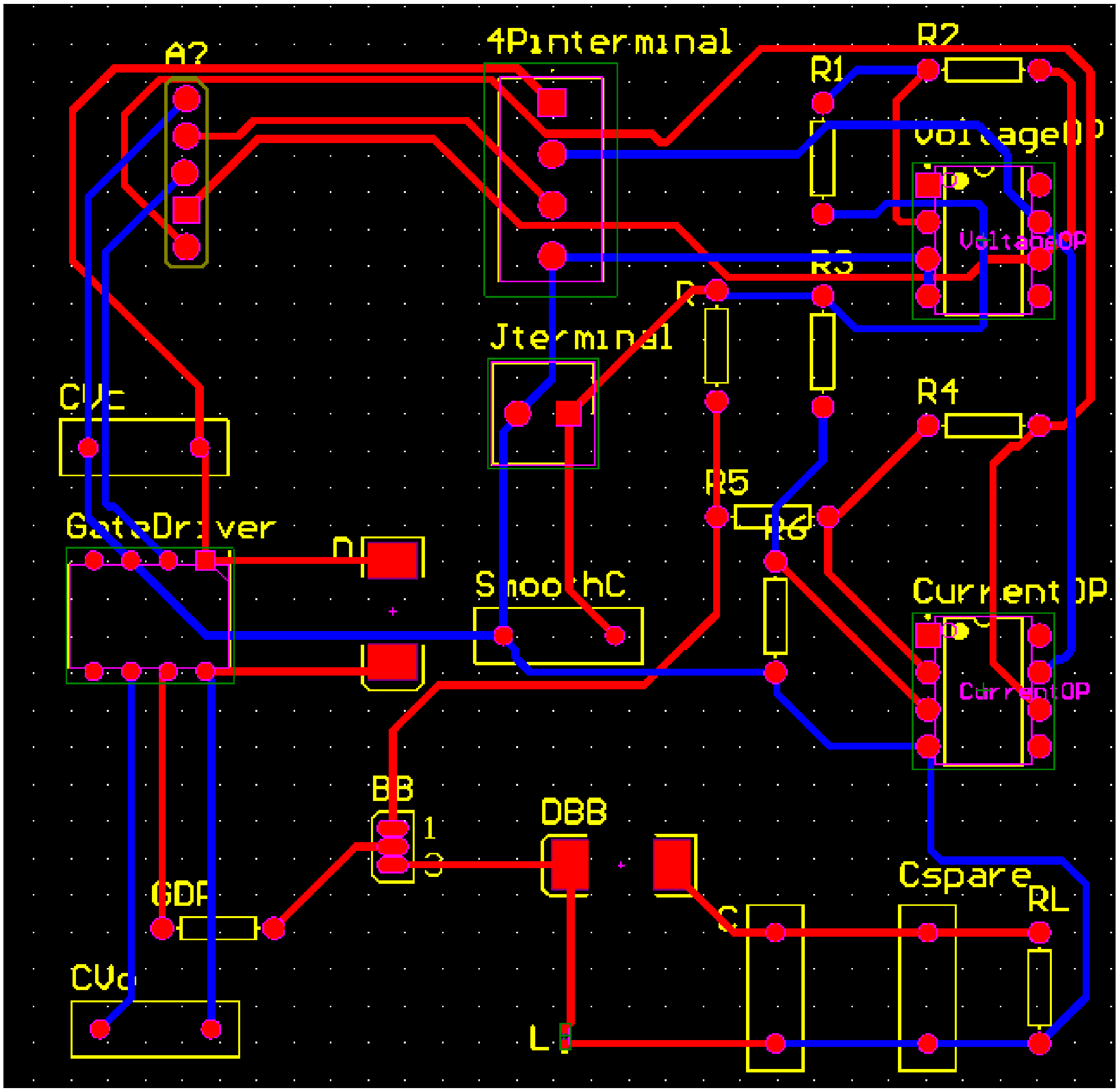

Figure 3.3: PCB designed in Altium Designer

As observed in Figure 3.3, the PCB was designed in Altium Designer which will later be outsourced to create the final PCB. This PCB was arranged so that connections of different components would not interfere with one another.

3.4. Algorithm Design

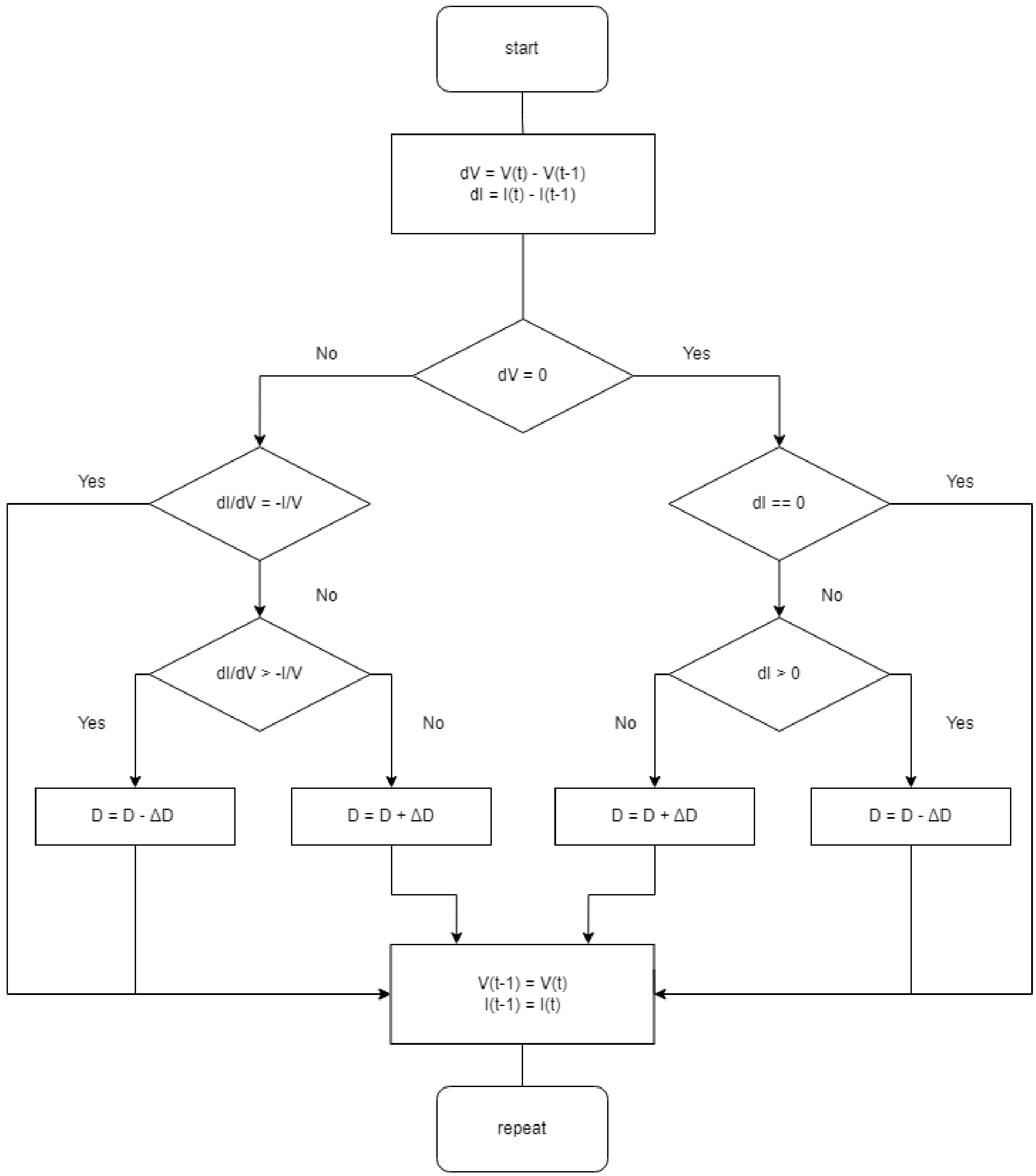

Figure 3.4: InC MPPT algorithm

As observed in Figure 3.4 the InC algorithm will be implemented on the MCU so that MPP can be achieved when power is applied on the load resistor. The voltage and current sensor will act as inputs and thus, follow the given flow diagram. Using the MCU to generate a PWM output, operating voltage manipulation can be achieved by altering the gate driver's PWM, which alters the switching frequency of the buck-boost converter's MOSFET, consequently achieving MPP.

4. Implementation

4.1. Hardware implementation

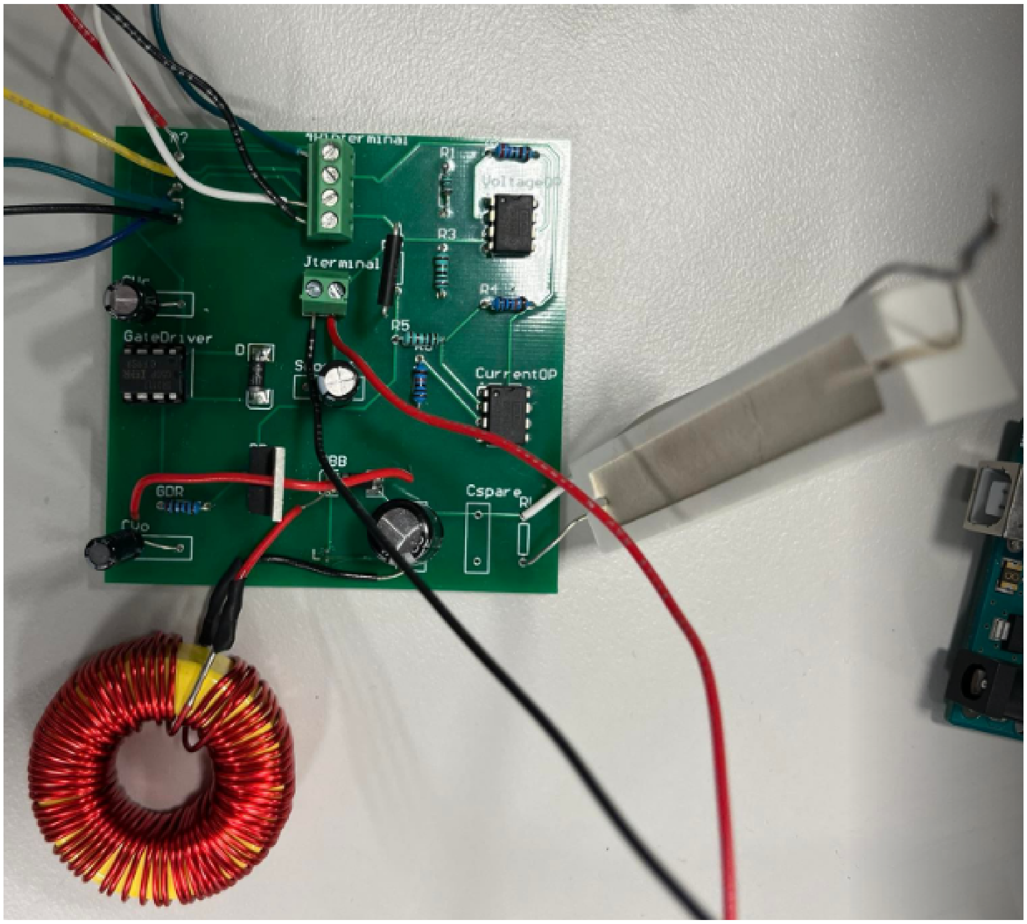

Figure 4.1: Failed hardware implementation of the MPPT

Figure 3.2 schematic shows that the current sensor uses 1kΩ resistors R3 and R5, however, the hardware implementation in Figure 4.1 used a 10kΩ resistor to reduce the consumption of the sensor. The feedback and ground resistor increased by an order of magnitude in an attempt to match the desired gain calculated in Equation 3.1.1.1b. In addition, the smoothing capacitor was changed to 68μF since this was the largest available capacitor. Because of the lack of an exact resistor to match Equations 3.1.1.1a and 3.1.1.1b, there was deviation of values calculated for resistors. A slight deviation of this magnitude is negligible so long as the output voltage does not exceed 5V; however, calibration may be necessary for the sensors.

In Figure 4.1, the MPPT PCB circuit without the MCU and PV system is shown along with the schematic in Figure 3.2 and Altium Designer PCB in Figure 3.3. Nonetheless, due to a missing line connection of this PCB design, the hardware implementation was discontinued to prevent potential hazards caused by faulty power electronics.

4.2. Software simulation

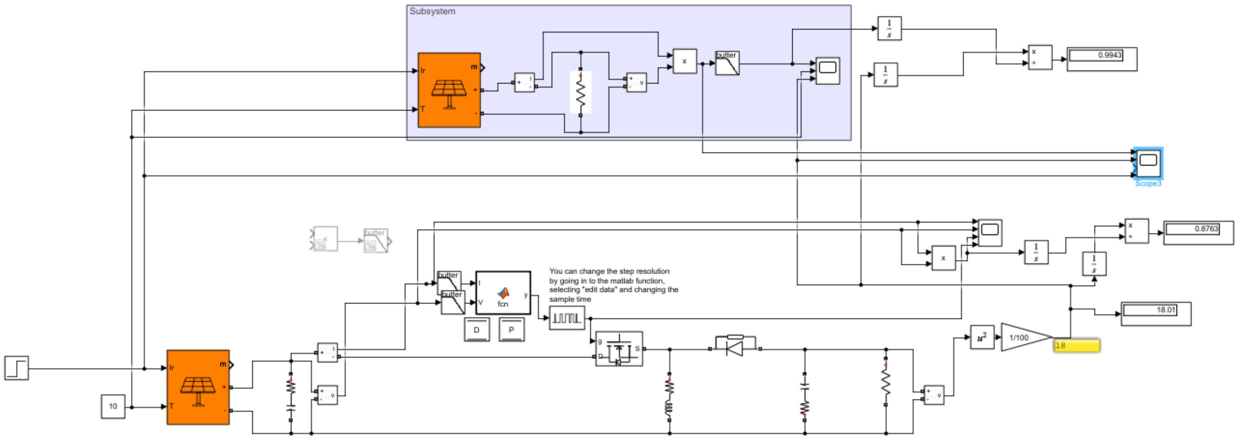

Figure 4.2: Simulated MPPT system with PV and load resistor

The MPPT simulator is highlighted in Figure 4.2.1 due to a hardware failure caused by a misconstruction of the MPPT PCB in Section 3.2. However, this simulation will provide sufficient parameters for determining the feasibility of an MPPT using the InC algorithm. In a subsection, the uncontrolled system is displayed, while the controlled system is shown outside the subsection.

The simulated voltage and current sensor can be represented by the voltage and current measurement block, the gate driver can be represented by the PWM block, the MOSFET of the buck-boost converter can be represented by the MOSFET block and the 2 polycrystalline panels can be presented by the PV block. Furthermore, the buck-boost converter can be represented by the arrangement of diode, inductor, capacitor and finally, the BMS/load resistor can be represented by the resistor block. As shown in Figure 3.2, the simulation is designed in a similar manner. Additionally

The buck-boost converter capacitor and inductor values of the simulated MPPT deviated from the BOM component values to compensate for the misculations that occur prior to this report mentioned in Section 3.1.2. Consequently, the simulated buck-boost capacitor and inductor will follow the values of Equation 3.1.1.2, thus C = 4.84μF and L = 1.5mH.

4.2.1. Algorithm

```
function y  = fcn(I, V)

%declare global variables (presistent) and assign values
persistent Dprev Vprev Iprev;
if isempty(Dprev)
    %duty cycle value calculated in section 3.1.1.2
    Dinit = 0.7259;
    Vprev = 0;
    Iprev = 0;
    Dprev = Dinit;
end
%small change duty cycle
%observe the sensor values
inc = 0.0025;
dV = V - Vprev;
dI = I - Iprev;
if dV == 0
    if dI == 0
        D = Dprev;
    else
        if dI > 0
            D = Dprev - (inc); %parameter met for decreasing duty cycle
        else
            D = Dprev + (inc); %parameter met for increasing duty cycle
        end
    end
else
    if dI/dV == -I/V
        D = Dprev;
    else
        if dI/dV > -I/V
            D = Dprev - (inc); %parameter met for decreasing duty cycle
        else
            D = Dprev + (inc); %parameter met for increasing duty cycle
        end
    end
end
%reassign previous values to current values
Dprev = D;
Vprev = V;
Iprev = I;
%output to the simulated gate drive
y = D;
```

Figure 4.1: Implemented InC MPPT algorithm as shown in Figure 3.4

Figure 4.1 highlights the InC algorithm designed in Section 3.4 that was coded in the Matlab simulation of the MPPT. The InC algorithm processes the voltage and current detected by the simulated sensors (which intended to work as the sensors designed in Section 3.1.1) to output a PWM for the simulated gate driver. Although changing the duty cycle of a MCU's output to suit a specific load resistor value may result in greater efficiency, it wouldn't be practical in a real world scenario as consumers will generally not be able take apart an MPPT. Therefore, the duty cycle was initialised at 0.7259 as calculated in Equation 3.1.1.2.

5. Evaluation

To compare the efficacy of the MPPT in different weather conditions it may be advised to create 2 step input from $0\ to\ 1000W/m^2$ and $0\ to\ 400W/m^2$ to gauge the it's performance under high and low solar irradiance. These parameters will be conducted on the 1Ω, 10Ω, 100Ω load resistors to assess the feasibility of a controlled system versus an uncontrolled system. Figures 5.1-3 show the uncontrolled system in pink and the controlled system in blue.

5.1. 1Ω Resistor

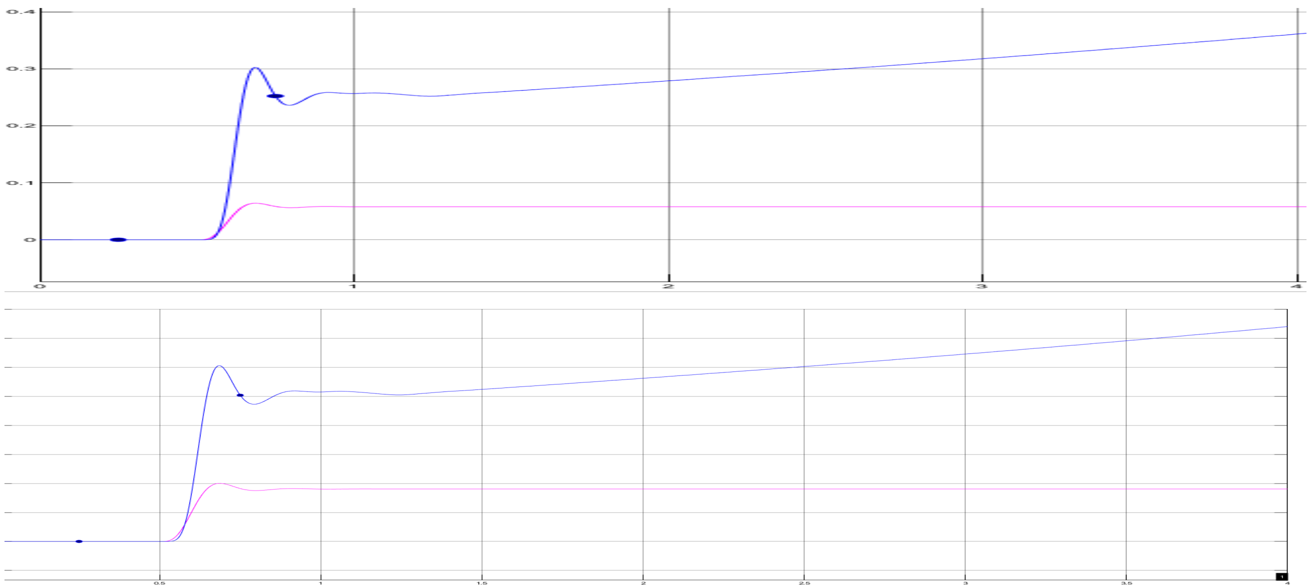

Figure 5.1: $0\ to\ 400W/m^2$(top) and $0\ to\ 1000W/m^2$(bottom)

Step input	Uncontrolled Steady state	Controlled Steady state
$0\ to\ 400W/m^2$	0.057 W	N/A
$0\ to\ 1000W/m^2$	0.36 W	N/A

Table 5.1: 1Ω resistor MPPT results

The results from the simulation as shown in Figure 5.1 illustrates that an MPPT (controlled system) may not be feasible for a load resistor of 1Ω as it converges instead of reaching a steady state compared to an uncontrolled system which achieves steady state in both step inputs as shown in Table 5.1. This may be a result of an unchanged duty cycle as it doesn't follow the same duty cycle suggested in Equation 3.1.1.2 or an error in the Simulink model. Additionally, the algorithm could have some errors. These findings suggest that if a 1Ω was the impedance of a BMS, it may be recommended to use an uncontrolled system.

5.2. 10Ω Resistor

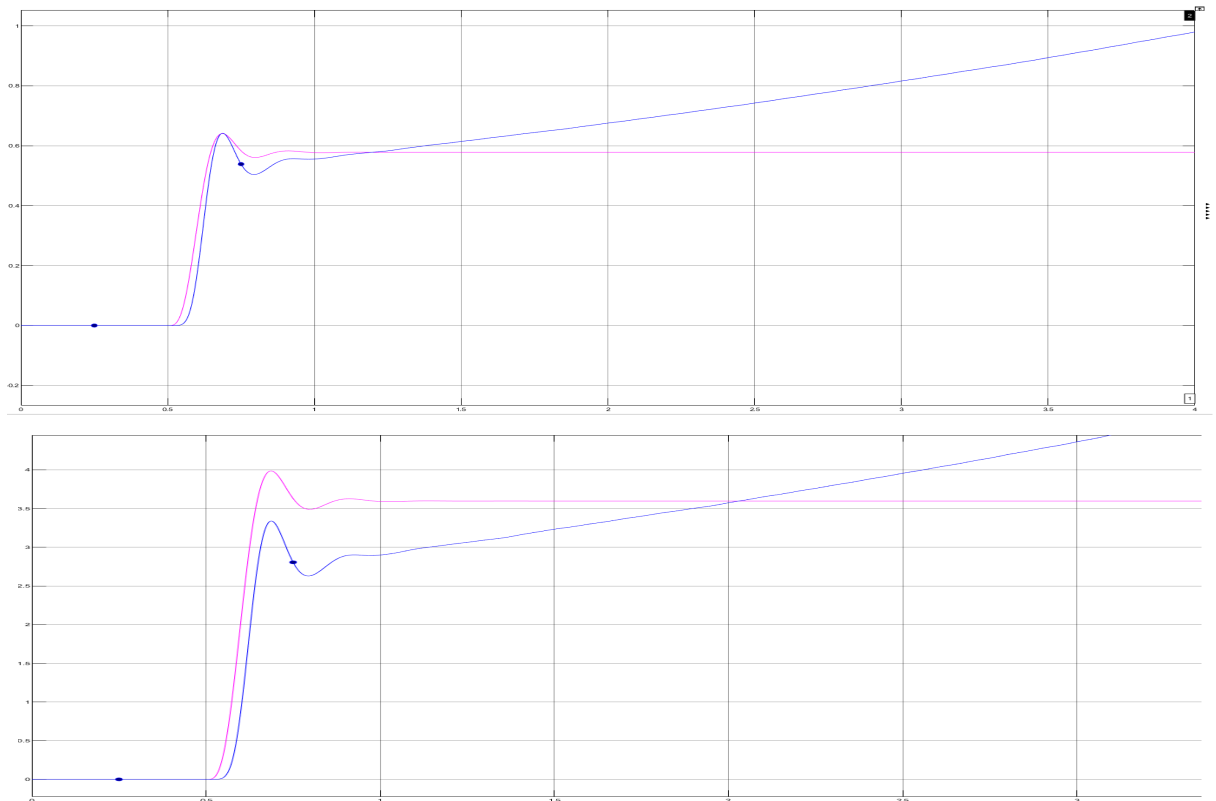

Figure 5.2: $0\ to\ 400W/m^2$(top) and $0\ to\ 1000W/m^2$(bottom)

Step input	Uncontrolled Steady state	Controlled Steady state
$0\ to\ 400W/m^2$	0.57 W	N/A
$0\ to\ 1000W/m^2$	3.584 W	N/A

Table 5.2: 10Ω resistor MPPT results

The results from the simulation as shown in Figure 5.2 illustrates that an MPPT (controlled system) may not be feasible for a load resistor of 10Ω as it converges instead of reaching a steady state compared to an uncontrolled system which achieves steady state in both step inputs as shown in Table 5.2.

It can also be shown that a 10Ω resistor underperforms compared to a 1Ω resistive load. This may be a result of an unchanged duty cycle as it doesn't follow the same duty cycle suggested in

Equation 3.1.1.2 or an error in the Simulink model. Additionally, the algorithm may have some errors. These findings suggest that if a 10Ω was the impedance of a BMS, it may be recommended to use an uncontrolled system.

5.3. 100Ω Resistor

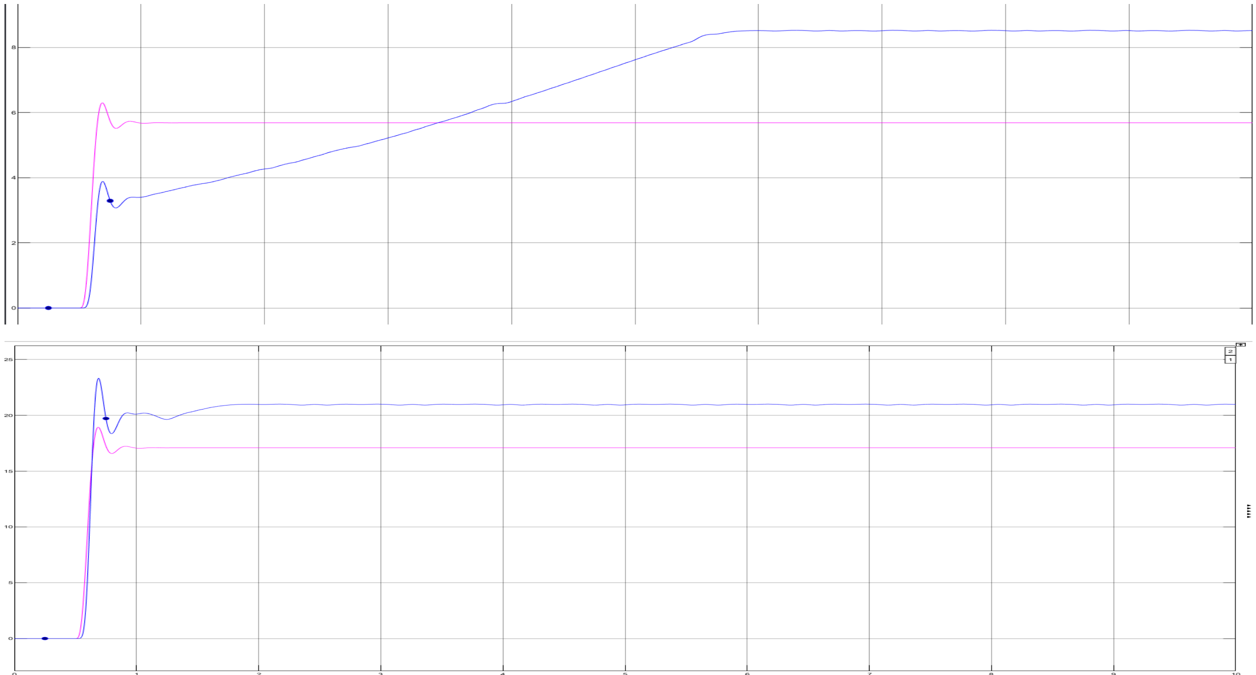

Figure 5.3: $0\ to\ 400W/m^2$(top) and $0\ to\ 1000W/m^2$(bottom)

Step input	Uncontrolled Steady state	Controlled Steady state
$0\ to\ 400W/m^2$	5.7 W	8.5 W
$0\ to\ 1000W/m^2$	17 W	21 W

Table 5.3: 100Ω resistor MPPT results

The results from the simulation as shown in Figure 5.3 illustrates that an MPPT (controlled system) is feasible with a resistive load of 100Ω so long at there is $1000W/m^2$ of solar irradiance available. Compared to the $0\ to\ 400W/m^2$ step function, the $0\ to\ 1000W/m^2$ achieves steady state at a faster rate. Additionally, the $0\ to\ 1000W/m^2$ step input has shown to achieve a steady state of 21 W with an oscillation of 0.7%. Whereas the step input of $0\ to\ 400W/m^2$ achieved a steady state of 8.5 W with 0.03% oscillation.

The 100Ω provides the best MPPT outcome when compared to other load resistors. Therefore, in order for an MPPT to function effectively in this simulation, the load resistor must be 100Ω. It is possible to use an MPPT if the right parameters are provided, such as a 100Ω impedance

BMS. Even so, the rate at which steady state is achieved could raise questions about the MPPT's overall performance due to the constantly changing weather.

6. Conclusion

In retrospect, the hardware implementation of MPPT could benefit from additional safety features, such as a diode connected in series with the PV system, to allow current to follow the desired direction, thereby preventing polarity hazards. Future MPPT versions might include safety measures such as an LED light to indicate the wiring of the system is not faulty. Additionally, more cost-effective microcontrollers might be used as the InC algorithm is computationally inexpensive.

According to section 5, the feasibility of MPPTs can vary with the load impedance and solar irradiance within a simulated renewable energy system. Depending on the load impedance and/or the solar irradiance, an MPPT may underperform. Furthermore, the rate at which the controlled system achieves a steady state may also vary depending on the availability of solar irradiance.

Although the simulation deviated from what is expected from an MPPT, the converging characteristics shown in the controlled output (1Ω, 10Ω, 100Ω $[0\ to\ 400W/m^2]$) may indicate that the controlled system does eventually reach its MPP. A steady state can be reached within a 10 second time frame as shown in Figure 5.3 suggests that the rate at which the system achieves steady state after convergence may be negligible in a practical sense.

Reference

[1] “Maximum Power Point Tracking (MPPT) charge controller working principle,” *Electrical Academia*. [Online]. Available: https://electricalacademia.com/renewable-energy/maximum-power-point-tracking-mppt-charge-controller-working-principle/. [Accessed: 15-Jun-2022].

[2] I. W. Christopher and R. Ramesh, “Comparative study of p&o and inc mppt algorithms,” *American Journal of Engineering Research (AJER)*, vol. 2, no. 12, pp. 402–408, 2013. 12

[3] F. Kano, Y. Kasai, H. Kimura, K. Sagawa, J. Haruna and H. Funato, "Buck-Boost Type MPPT Circuit Suitable for Photovoltaic Generation of Vehicle Installation," *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, 2018, pp. 2036-2041, doi: 10.23919/IPEC.2018.8507955.

[4] Admin, “Buck-boost converter in CircuiTikZ,” *TikZBlog*, 10-Feb-2021. [Online]. Available: https://latexdraw.com/buck-boost-converter-in-circuitikz/. [Accessed: 15-Jun-2022].

[5] Admin, “Buck-boost converter in CircuiTikZ,” *TikZBlog*, 10-Feb-2021. [Online]. Available: https://latexdraw.com/buck-boost-converter-in-circuitikz/. [Accessed: 15-Jun-2022].

[6]“Opamp output voltage in negative feedback,” *Electrical Engineering Stack Exchange*, 02-Dec-2020. [Online]. Available: https://electronics.stackexchange.com/questions/535215/opamp-output-voltage-in-negative-feedback. [Accessed: 15-Jun-2022].

[7] “File:op-amp differential Amplifier.svg,” *Wikipedia*, 26-Jan-2009. [Online]. Available: https://en.wikipedia.org/wiki/File:Op-Amp_Differential_Amplifier.svg. [Accessed: 15-Jun-2022].