An Inexpensive Maximum Power Point Tracking System for an Insulated Solar Electric Cooker using an Off-the-Shelf Buck Converter

Senior Project

Andrew A. Perez

Advisor Dr. Peter Schwartz

Department of Physics, California Polytechnic State University

September 2022
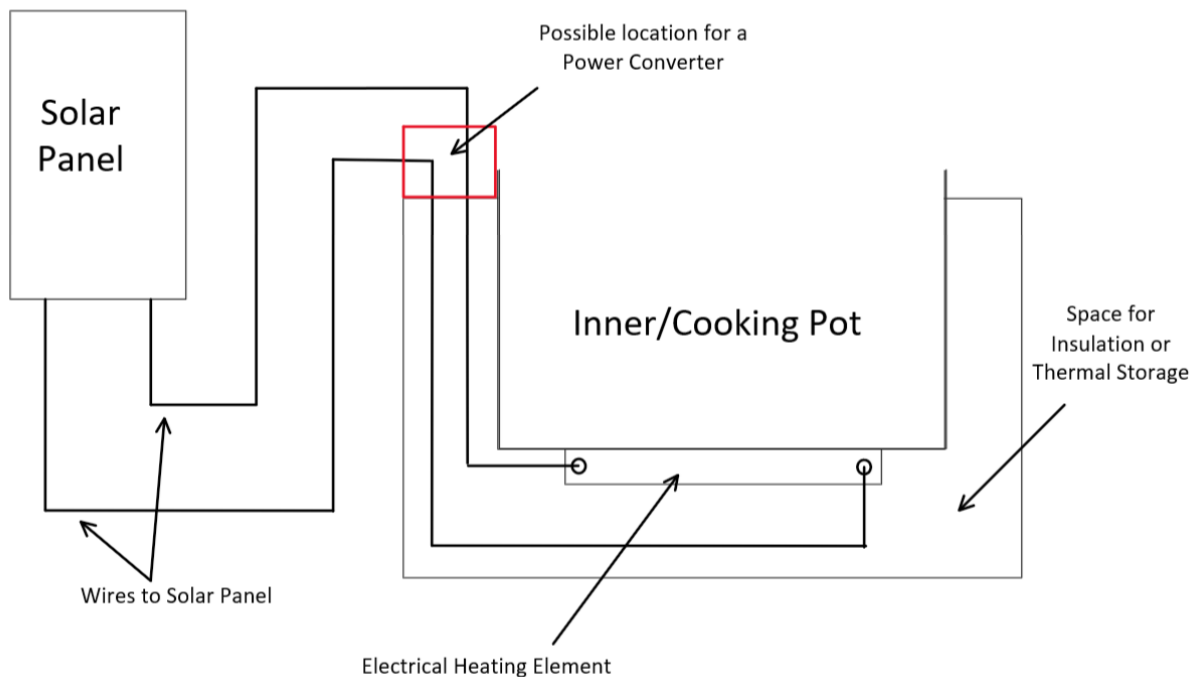
Contents

1 Introduction

Figure 1: Schematic of a basic Insulated Solar Electric Cooker (ISEC) with a red box showing a possible power converter location to be used as part of the Maximum Power Point Tracking (MPPT) circuit.

Not every person throughout the world can afford and utilize safer cooking technologies like electric or gas-based cooking. Instead as many as 2.4 billion people cook with kerosene, biomass, and coal,[1] which causes not only a slew of negative health conditions[2,3] but environmental issues such as deforestation and CO_2 emissions.[4,5] These side effects can be reduced and removed with an Insulated Solar Electric Cooker (ISEC), found in Figure 1. ISECs use a solar panel-powered electric heating element and insulation to build up the temperatures required to cook over time.[6] This electric heating element can be a resistive heating element like Nickel Chromium (NiCr) wire,[7] a chain of diodes,[8] or any other material that dissipates power as heat when current is passed through it. ISECs may also employ thermal storage, allowing stored energy to be used when conditions do not allow the solar panel to supply power, all without the cost and complexity of a battery.[6–8] An important part of the ISEC is its global learning community, which leverages the ISECs inexpensive costs and open manufacturing schematic[7] to act as an intermediate technology that communities can manufacture and claim as their own.[9]

One big issue exists with the current ISEC design: the power delivery system to the heating element. An ISEC using a resistive heating element does not always perform well enough to be viable as a consistent cooker in variable weather conditions. The Maximum Power Point (MPP), or point where the maximum power possible is delivered from the solar

panel to the load, changes with the intensity of light and temperature. Maximum Power Point Tracking (MPPT) is an often costly method that ensures a solar panel's load, like the resistive heating element, always stays at that MPP, which would increase the consistency of ISECs. MPPT techniques can be either analog or digital, with digital more often being closer to the MPP. All digital MPPT techniques utilize a power converter, a microcontroller, and sensor(s) to locate and set the optimal voltage and current draw to the load at any given instant. These power converters come in many forms, but in the case of an ISEC with a 100-watt solar panel, a step-down DC-DC, or buck, power converter is sufficient for MPPT. Since buck converters are available online at a low price, they may be the heart of inexpensive MPPT. This project looks at the implementation of off-the-shelf buck converters in conjunction with a microcontroller as a cheap modified perturb and observe (P&O) MPPT circuit for ISECs.

2 Solar Panel Basics and ISEC Limitations

Given a sunlight incident on a photovoltaic solar panel, the current and voltage will follow the equation

$$I_{\mathrm{pv}} = I_{\mathrm{L}} - I_0(e^{\frac{qV_{\mathrm{pv}}}{nkT}} - 1) \tag{1}$$

derived from the diode law, where q is the elementary charge constant, k is the Boltzmann constant, n is the ideality factor referring to how close the solar panel follows the ideal diode equation, T is the temperature, I_0 is the current leakage in the absence of light proportional to temperature, I_{L} is the current generated by the light proportional linearly to the incident light's intensity, and V_{pv} and I_{pv} refer to the photovoltaic voltage and current, or the voltage and current coming out of the solar panel, respectively. Note that n, I_{L}, and I_0 all are properties of the solar panel. Because $P = IV$, it follows that

$$P_{\mathrm{pv}} = (I_{\mathrm{L}} - I_0(e^{\frac{qV_{\mathrm{pv}}}{nkT}} - 1)) * V_{\mathrm{pv}} \tag{2}$$

where P_{pv} is the photovoltaic power, or all the power coming from the solar cell. Graphing Equations 1 and 2 gives what are called solar output curves. These solar output curves generated in Figure 2, with the black curve simulating a 100-watt solar panel, like the one ISECs use, near ideal conditions. The other graphs change either the intensity or temperature relative to the black curve. The MPP can be found as the maximum value of power in the solar output P-V curve on the right graph of Figure 2. Once located, the optimal voltage V_{MPP} and solar output I-V curve can be used to find the complete MPP. Importantly, the MPP can be seen moving 2.5 V down for a 10% change in temperature and 3 A down for a 50% change in intensity. Focusing on the magenta curve, halving the intensity almost halves the possible current and similarly almost halves the available power.[8]

We can also graph the 3.3Ω resistive heating elements I-V curve with ease due to the simple relation for a resistor, $V = IR$. The 3.3Ω resistance value is typical for an ISEC. The intersection of this resistor graph with a solar output graph indicates the system operating point, or the values of V, I, and P the entire system will operate at when the solar panel is connected to the resistor. Due to the linearity of the resistor I-V curve and the large range of possible solar output curves, the system operating point for a single-valued resistor is rarely
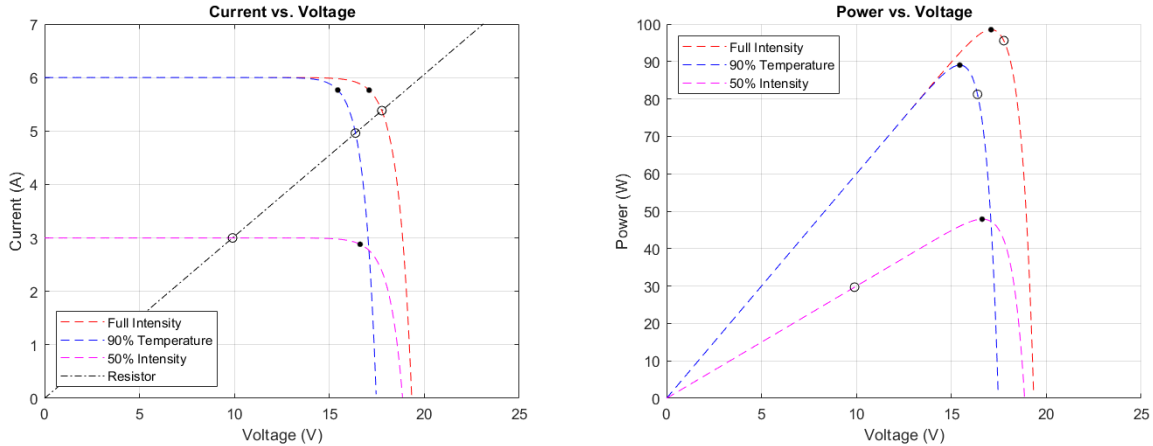
Figure 2: Current (left) or power (right) versus voltage solar output graphs generated from generated from Equations 1 and 2, respectively. The red dotted line models near ideal conditions for the 100-watt solar panel, the blue dotted line is set to 90% the temperature compared to ideal, and the magenta dotted line is set to 50% of the solar intensity compared to ideal. The MPP for each state can be found as a black dot. The black line on the left graph models the 3.3Ω resistor, with the operating points for each weather condition being found as black circles on the intersections. Note how only the red curve has its operating point very close to the MPP.

near the MPP. This can be seen in Figure 2, where the ideal case is modeled as drawing 97% of possible power or modeled as near the MPP. This drops to 91% of possible power with the solar panel experiencing a 10% drop in temperature and drops to 62% of possible power with the solar panel experiencing a 50% drop in intensity. As resistive heating elements like NiCr wire are convenient for ISECs, this under-performance in non-ideal conditions becomes more prominent.[8]

Without the implementation of MPPT, using a resistive heating element means the system operating point will only be near the MPP under very few specific combinations of intensity and temperature. In any other case, the operating point will be away from the MPP, losing potential power. This loss of power could make it impossible to build up enough energy to cook, an issue of reliability that makes the ISEC less compelling to learn and use. MPPT fixes this reliability issue. However, off-the-shelf MPPT systems can be expensive,[10] which does not fit the goal of an ISEC as an appropriate intermediate technology.

3 Maximum Power Point Tracking

3.1 MPPT Basics and Switch-based DC-DC Power Converters

MPPT holds much significance in increasing the efficiency of solar panels in varying weather conditions. It comes as no surprise then that there are many different techniques and approaches to MPPT. These include but are not limited to analog techniques like Constant Voltage (CV) and Open Voltage (OV) techniques, simpler digital techniques like Perturb and Observe (P&O) and its close cousin Incremental Conductance (InCond), and even more

sophisticated techniques like neural networks. Analog techniques require no input and instead approximate and work near the MPP: CV uses a previously found MPP and assumes that voltage is close enough to the actual MPP while OV uses a fixed percentage of the voltage of the solar panel when it is disconnected. Simple digital techniques utilize sensors and seek to use the knowledge of the circuit to hunt down the MPP: P&O has one vary the voltage out and see how output power changes while InCond utilizes the sensor reading of the solar panel output to locate where one is on the P-V graph and move towards the MPP. An extensive digital technique like a neural network allows one to build a model for specific areas by including more inputs like weather data and pressure to both find and predict the MPP, but requires a lot more data and can be quite computationally heavy.[10] Due to both constraints in knowledge and what was hoped to be achieved with the ISEC, an InCond grounded P&O was selected.

It is inherent to the digital MPPT that P_{pv} must be controllable, as MPPT becomes impossible otherwise. Hence, DC-DC power converters are fundamental to the MPPT. In the case of a resistive load, the equations a converter follows can be simplified significantly. We are utilizing a buck converter, a switch-based DC-DC converter, that operates on a cycle depending on which MOSFET, found in Figure 3 in the green boxes, is on. A MOSFET, or metal-oxide-semiconductor field-effect transistor, is a device where a voltage inputted determines its conductivity. This allows it to act similar to an ideal switch near instantly, which is utilized to switch between 2 states of the cycle by turning one MOSFET on when the other turns off. We shall refer to MOSFET $M1$ being on as the top part of the cycle, while MOSFET $M2$ is referred to as the bottom part of the cycle.

In the top part of the cycle the output capacitor C_{OUT}, found Figure 3 in a blue box, is charged. This capacitor is used both as energy storage and to set how high the output voltage is, depending on the degree of charging. Switching to the bottom cycle, or turning off $M1$ and turning on $M2$, sees the capacitor releasing its stored energy. The inductor $L1$ in the red box and the diodes in the yellow boxes are both necessary components to ensure the circuit runs during the MOSFET switch and make sure nothing breaks. This cycle is then repeated rapidly to maintain the output voltage and sustain current flow.[11]
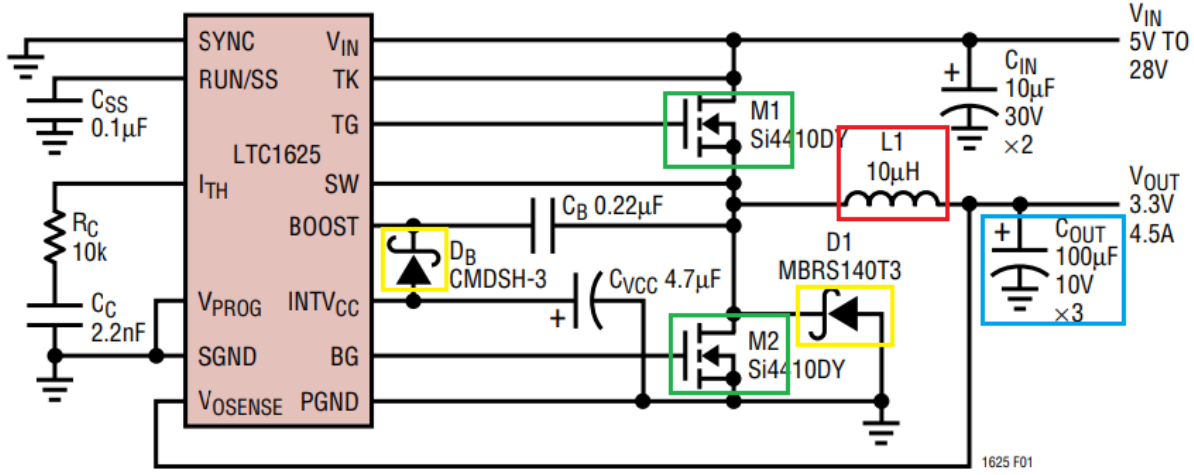
Figure 3: Typical high-efficiency step-down converter using the microprocessor chip on the chosen buck converter. This application is to take a variable input voltage and output a constant voltage and current. Of note are the MOSFETs $M1$ and $M2$ in green, the energy storage capacitor C_{OUT} in blue, the inductor $L1$ in red, and the diodes in yellow.[12]

DC-DC power converters can be characterized by two values: static gain G and duty cycle D. G relates input and output variables with the equation

$$G = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{3}$$

and because $P = IV$ and conservation of energy says $P_{\text{in}} = P_{\text{out}}$, it follows that

$$G = \frac{I_{\text{in}}}{I_{\text{out}}} \tag{4}$$

.[13] The duty cycle is the ratio of time for the MOSFETs to be open in a cycle, represented as a percentage. As a percentage, a duty cycle naturally has a range of $[0, 1]$. Note since only one MOSFET is on at a time and a MOSFET is always on, $D_{M1} + D_{M2} = 1$. For the top cycle of a buck converter, $D = G$ which consequentially means

$$D_{M1} = \frac{V_{\text{out}}}{\eta V_{\text{in}}} \tag{5}$$

where η is equal to the efficiency of the buck converter.[11] Simple resistors also follow the relationship

$$I_{\text{R}} = \frac{V_{\text{R}}}{R} \tag{6}$$

with V_{R} being the voltage across the resistor, I_{R} being the current through the resistor, and R being the resistance of the resistor. Taking the input as the solar panel and output as the resistor and combining Equations 6 with 3, 4, and $G = D$ leads to

$$V_{\text{pv}} = \frac{R}{D_{M1}^2} I_{\text{pv}} \tag{7}$$

6

.[13] Equation 7 is a straight line with slope $\frac{D_{M1}^2}{R}$ when graphed on the I-V plane. A straight line centered at the origin can also be described by the angle θ it forms with the x-axis, or the voltage axis. Trigonometric identities can be used to show angle θ follows the equation

$$\theta = \tan^{-1}(\frac{D_{M1}^2}{R}) \tag{8}$$

.[13] However, D_{M1} has a defined possible range. This means θ also has a defined range of $[\tan^{-1}(\frac{0}{R}), \tan^{-1}(\frac{1}{R})] = [0, \tan^{-1}(\frac{1}{R})]$.[13] Testing has shown that the chosen buck converter can access the highest MPP expected of an ISEC, implying all MPPs pertinent to this paper will fall within the range of θ. This means for the specific implementation of MPPT to ISEC, buck DC-DC power converters are the most cost-effective to use.[11]

3.2 InCond MPPT

InCond works by establishing a model based on the solar cell output curves in Figure 2.[10] A mathematical model of this process can be developed by looking at Figure 2's Power vs. Voltage graph and noticing the power maximizes when the curve levels out, or the derivative of the curve is equal to zero. This can be represented by the equation

$$\frac{\mathrm{d}P_{\mathrm{pv}}}{\mathrm{d}V_{\mathrm{pv}}} = 0. \tag{9}$$

When Equation 9 is true, $V_{\mathrm{pv}} = V_{\mathrm{MPP}}$ and $P_{\mathrm{pv}} = P_{\mathrm{MPP}}$. Hence, reaching Equation 9 or any of its equivalents is the goal.[14] Equation 9 can be rewritten using $P = IV$ to get an equivalent

$$\frac{\mathrm{d}I_{\mathrm{pv}}}{\mathrm{d}V_{\mathrm{pv}}} = -\frac{I_{\mathrm{pv}}}{V_{\mathrm{pv}}}. \tag{10}$$

For InCond, each time step corresponds to a measurement of V_{pv} and I_{pv}. By comparing the value of $\frac{\mathrm{d}I_{\mathrm{pv}}}{\mathrm{d}V_{\mathrm{pv}}}$ to $\frac{I_{\mathrm{pv}}}{V_{\mathrm{pv}}}$, the location on the Power vs. Voltage graph is established, with $\frac{\mathrm{d}I_{\mathrm{pv}}}{\mathrm{d}V_{\mathrm{pv}}} > -\frac{I_{\mathrm{pv}}}{V_{\mathrm{pv}}}$ being to the left of the MPP and $\frac{\mathrm{d}I_{\mathrm{pv}}}{\mathrm{d}V_{\mathrm{pv}}} < -\frac{I_{\mathrm{pv}}}{V_{\mathrm{pv}}}$ to the right of MPP. It follows to either raise or lower the value of V_{pv} to get closer to the MPP. This entire process is summarized in Figure 4 found below.[14]
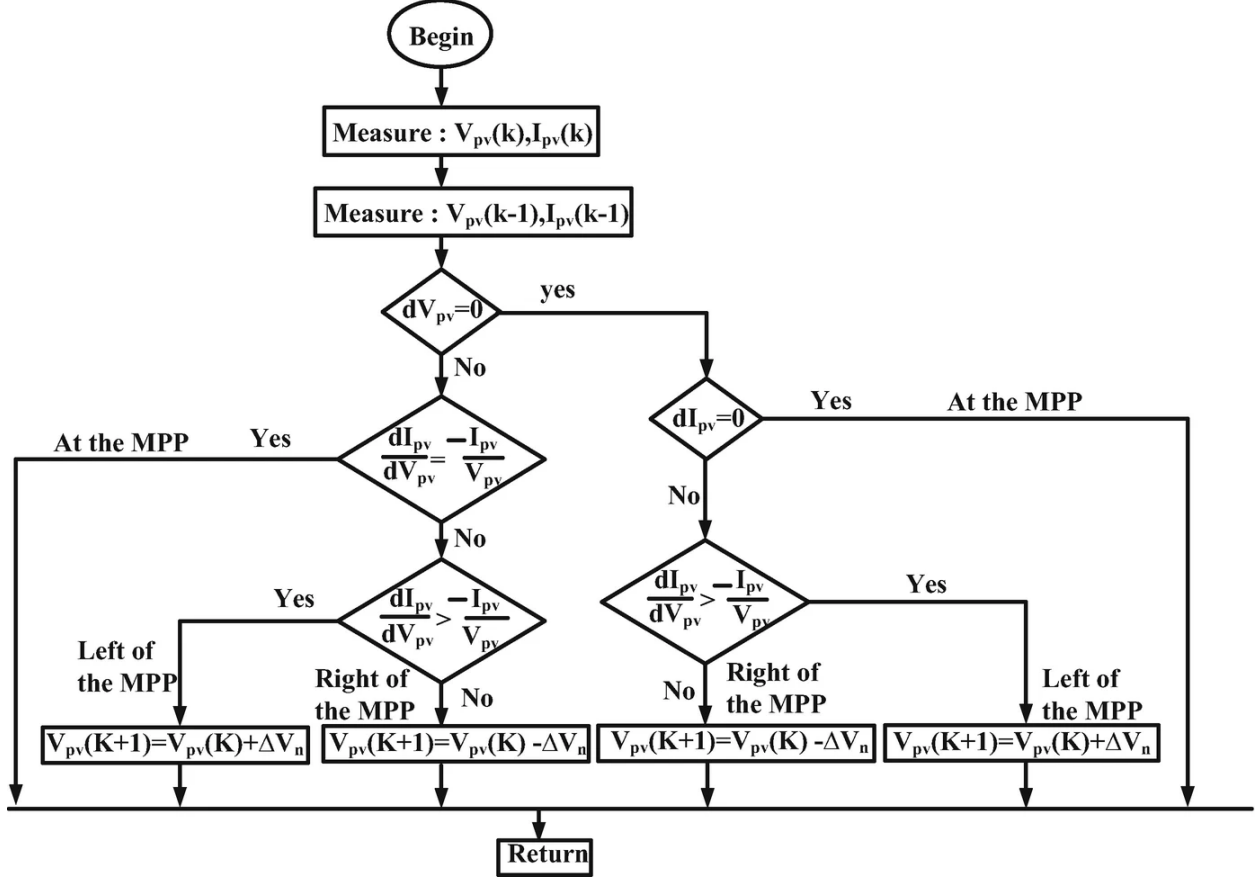
Figure 4: A decision tree of the logic of the incremental conductance MPPT technique.[14]

3.3 InCond-grounded P&O MPPT

Here a modified P&O method of MPPT specific to ISEC is discussed, due to the narrow scope of this paper. The ISEC is in a better position to take advantage of P&O than most other technologies because its goal is not a battery but a resistive heating element. As discussed above, it simplifies many of the equations governing the system. One more equation is necessary to complete the picture established: the other simple resistor equation found with $P = IV$ and Equation 6.

$$P_{\mathrm{R}} = \frac{V_{\mathrm{R}}^2}{R} \tag{11}$$

Equations 5, 11, and the conservation of energy equation $P_{\mathrm{in}} = P_{\mathrm{out}}$ can be used to convert Equation 9 into an equivalent, more applicable MPP equation

$$\frac{\mathrm{d}V_{\mathrm{R}}}{D_{M1}\mathrm{d}V_{\mathrm{R}} - V_{\mathrm{R}}\mathrm{d}D_{M1}} = 0. \tag{12}$$

Note that η and R are both treated as constants and consequentially multiplied into the zero and removed. In actuality both depend on temperature which itself changes with time, but the dependence is small enough that it is phased out.

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While Equation 12 seems more complicated than Equation 10, it is notable that dD_{M1} and D_{M1} are variables we decide through the change of the gain. This means only one reading of V_R is necessary for each iteration of the loop, unlike the InCond. By observing the sign of both the top and bottom of Equation 12, a new comparison can be made similar to the one found above, being situated around $\frac{dD_{M1}}{dV_R} = \frac{D_{M1}}{V_R}$ after taking into account the values of dD_{M1} and dV_R.
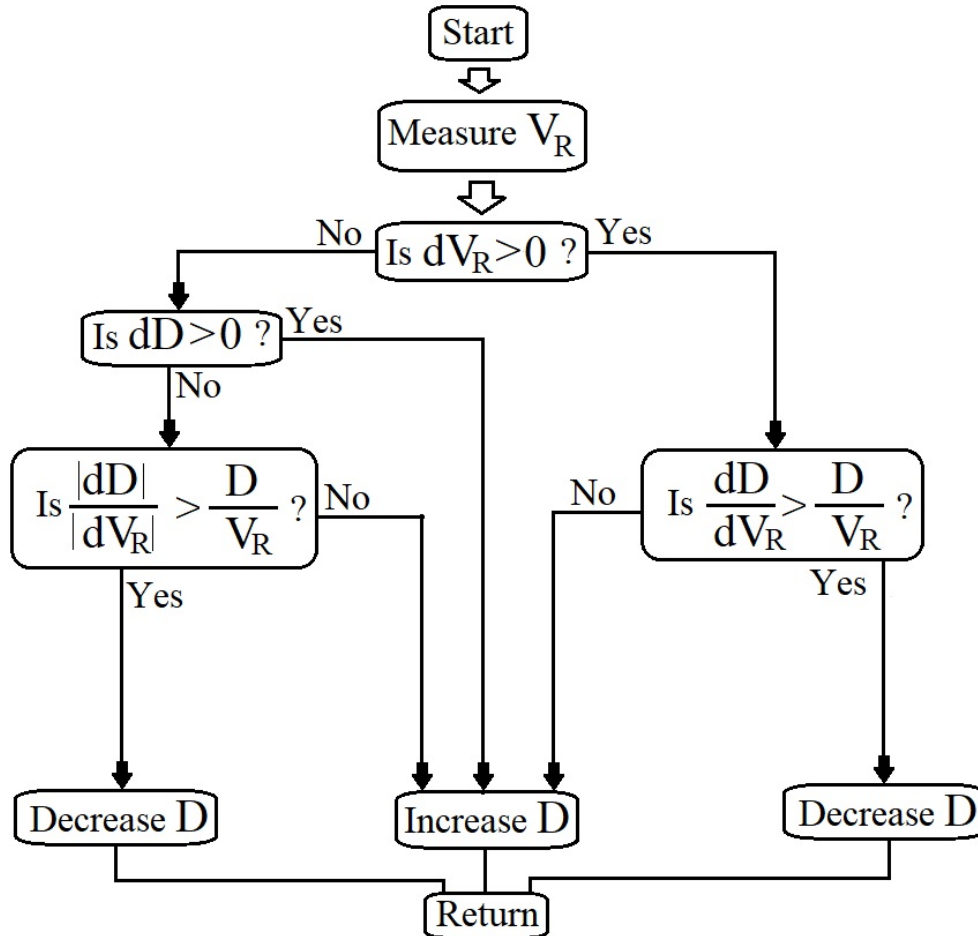

Figure 5: A decision tree of the logic behind a possible InCond theory-based P&O MPPT. Note the D mentioned refers to D_{M1}.

Another similar method may consider how the voltage out is going to be affected solely by a change in D_{M1}. Any code may just focus on changing the gain and seeing its effect on V_R to track the maximum power point, leading to a simpler logic chain than Figure 5.

Both methods are theoretically sound and are not exactly the original P&O method, while the second method of directly changing the gain and seeing its effects was chosen due to time constraints. The specifics shall be elaborated more in the Code Explanation section.

4 Parts List

Below are the parts chosen for the circuit. Table 1 shows the costs and total for each major electronic component. Note that for the production of the circuit, soldering and several connection wires are required, increasing costs. The logic microcontroller and its sensors are significantly more powerful and are hence more expensive than necessary. All parts are prominently displayed in Figure 10, found in the next section.

Table 1: Costs of electronics chosen for the MPPT.

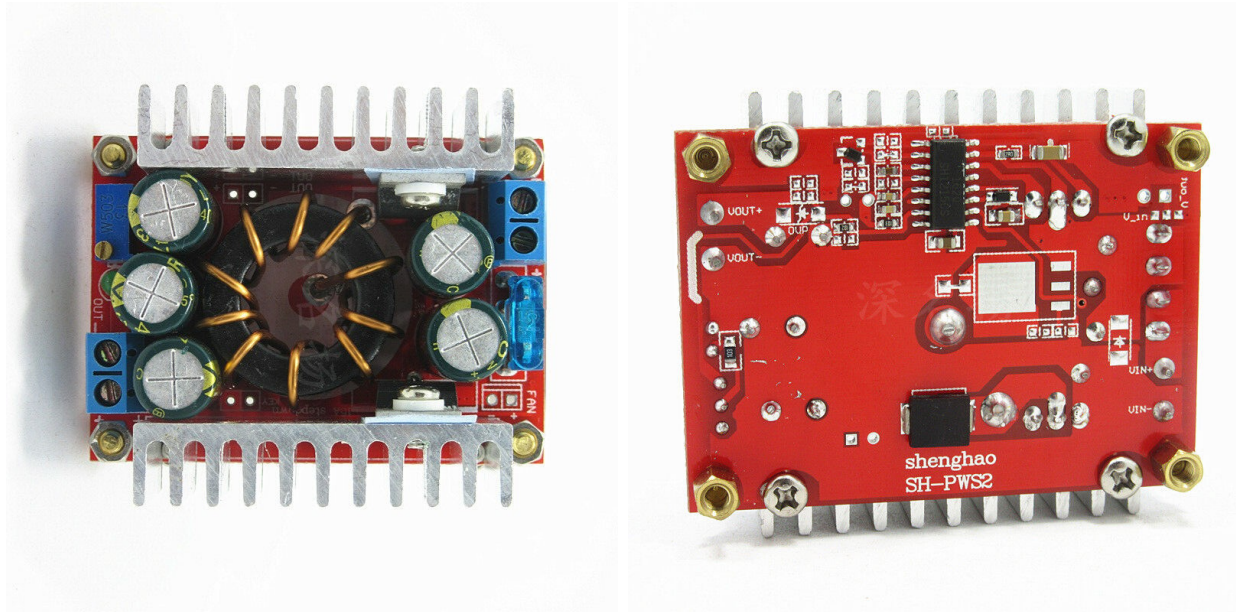| Product	Cost in USD for 1
DC/DC Buck Adjustable 4-32V to 1.2-32V Converter Step Down Module	10.45
Elegoo Uno R3 Board ATmega328P	29.99
MCP4725 Breakout Module I2C DAC 12Bit Development Board	5.50
Adafruit INA260 High or Low Side Voltage, Current, Power Sensor	9.95
Total	55.89

4.1 Buck Converter

Figure 6: Two images of the chosen buck converter seen from an overhead (left) and bottom (right) view. Of particular importance to applications is the potentiometer and its pins, found on the left either as a blue box with a screw (left) or as three soldering sites in a straight line (right).[15]

We choose a simple buck converter found on eBay that can be seen in Figure 6. The main influence for this particular model was the ease of access to the circuit diagram, displayed in Figure 7. This ease of access facilitated the wiring and planning of the circuit. Since ISECs

most often use a 100-watt solar panel, $V_{\text{MPP,max}} = 18.2\text{V}$ and $I_{\text{MPP,max}} = 5.6\text{A}$ when using a $R = 3.3\Omega$. These values for MPP fall comfortably inside the operating range of the specific buck converter, which works within a 4 V to 32 V input, a 1.2 V to 32 V output, and up to 15 A. Like most inexpensive adjustable buck converters found online, the adjustment mechanism is a manual potentiometer, shorted to act as a single variable resistor. Of particular note in the specifications is an efficiency up to 98%, allowing the use of $\eta \approx 0.98$.[15]

Similar to most available buck converters, all logic falls to a microprocessor, seen as the black chip on top of the right image of Figure 6. These microprocessors all have a feedback loop constantly making reading and adjustments not dissimilar to Figure 5's feedback loop. The main goal of this feedback loop is to maintain the present output voltage and current, which can be manually changed by the potentiometer. It should be clear as to why a current buck converter would only require some adjustments to act as a MPPT device, as it already deals with a similar logic that can be co-opted for our use. Looking at the specific feedback microprocessor for the chosen buck converter, the model can be determined. LTC1625 operates with the aforementioned cycle, where the duty cycle can be found by the equation

$$D_{M1} = \frac{V_{\text{out}}}{V_{\text{in}}}. \tag{13}$$

Equation 13 can be found in the manual for the LTC1625, noting that the manual assumes $\eta \approx 1$.[12]

Focus on Pin # 7, labeled V_{OSENSE}. It takes a feedback input from the output voltage, either from a voltage divider or from remote sensing. When V_{PROG} is open, the output voltage can be set by changing what is being fed back into V_{OSENSE}. V_{OSENSE} is intended to be set in the middle of a voltage divider with an input from V_{Out} to ground, as seen in Figure 8. This would lead to

$$V_{\text{Out}} = 1.19V(1 + \frac{R2}{R1}) \tag{14}$$

with $R1$ and $R2$ being the intended resistances of the voltage divider.[12] Figure 7 does display a voltage divider into V_{OSENSE}, with a shorted potentiometer to act as a variable resistor for $R1$ and a $R2 = 1800\Omega$. A voltage divider has $V_{\text{output}} \propto V_{\text{input}}$ which can be written as $V_{\text{OSENSE}} \propto V_{\text{R}}$ in relevant variables. If the input into V_{OSENSE} is labeled as V_{control}, Equations 13, 14, and the voltage divider proportionality combine into $D_{M1} \propto V_{\text{control}}$. This proportionality means V_{control} can be used for the decided MPPT technique.

Figure 7 also shows how V_{OSENSE} is connected to the rest of the circuit. It is connected to the output voltage adjustment potentiometer. By removing the potentiometer and inserting a wire, V_{OSENSE} can be accessed directly, allowing for external control of the gain.
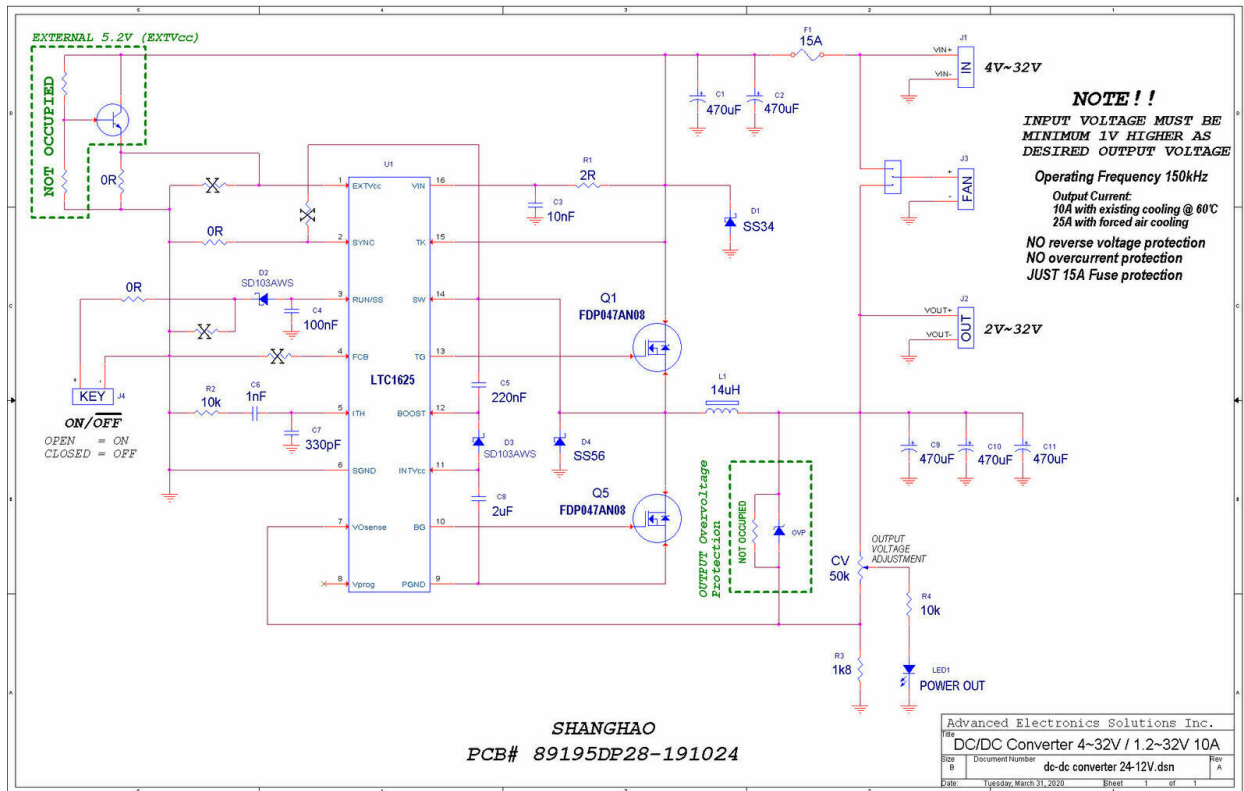
Figure 7: Circuit diagram for the chosen buck converter. Of particular importance to applications is pin #7, the feedback pin labeled VO$_{\text{SENSE}}$, and its connection to the OUTPUT VOLTAGE ADJUSTMENT potentiometer. Note the resistor directly under the potentiometer, which is intended to be the bottom half of the voltage divider.[15]
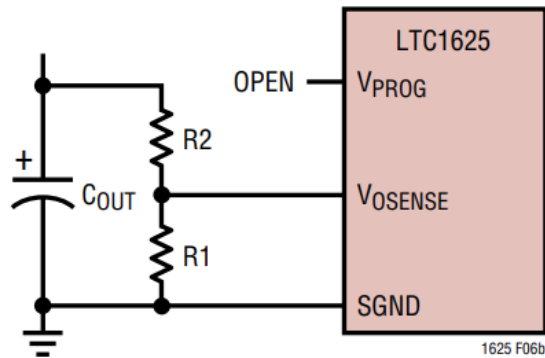

Figure 8: Circuit diagram of one of the intended inputs for V_{OSENSE}, using a voltage divider.[12]

4.2   Logic Microcontroller and other Digital Devices

The chosen microcontroller was an Elegoo Uno R3 because of the sharp similarity to an Arduino and familiarity with the Arduino IDE. It utilizes the ATmega328, the same microprocessor chip found on Arduino Uno boards, and has similar ports including a USB connection, 14 digital pins, and 6 analog pins.[16] By connecting the Elegoo Uno R3 to a computer, code can be uploaded which will then run whenever power is connected. Able to be powered by a USB connection or a battery, it has many more features, pins, and computational power than necessary for this particular application. This choice of microprocessor influenced the chosen sensor and input for compatibility.

Chosen to sense V_{out} was the INA260 Precision Digital Current and Power Monitor. It is a high sensitivity monitor that utilizes an integrated precision shunt resistor to detect current, voltage, and power with high accuracy. It importantly outputs a digital signal that can be connected directly to the SCL and SDA pins on an Arduino-like device, facilitating easy connections.[17] It is overkill for this current application due to the lack of current or power sensing. When correctly hooked up to the Elegoo Uno, it will send the voltage in millivolts with an accuracy of one-fourth of a millivolt.

Chosen to input a variable voltage as V_{control} into V_{OSENSE} was the MCP4725 Digital-to-Analog Converter. It is a low-power, high-accuracy voltage output Digital-to-Analog converter which allows the Elegoo Uno to transmit out non-PWM analog signals, reducing noise.[18] When correctly hooked up to the Elegoo Uno, this will send out a voltage from 0-5 V. The variable deciding the output comes from the Arduino IDE and takes a number from 0-4095, corresponding to 0-5 V. The MCP4725 is specifically intended for the Arduino IDE-based microprocessors and may be phased out if a more traditional use of the buck converter like a digital potentiometer is applied.

5   Full Circuit

Figure 9 showcases how to connect the P&O MPPT circuit. Note that for this circuit, the potentiometer is assumed to be removed. The real picture in Figure 10 shows each component is small enough to fit in a enclosure, to be attached outside an ISEC.
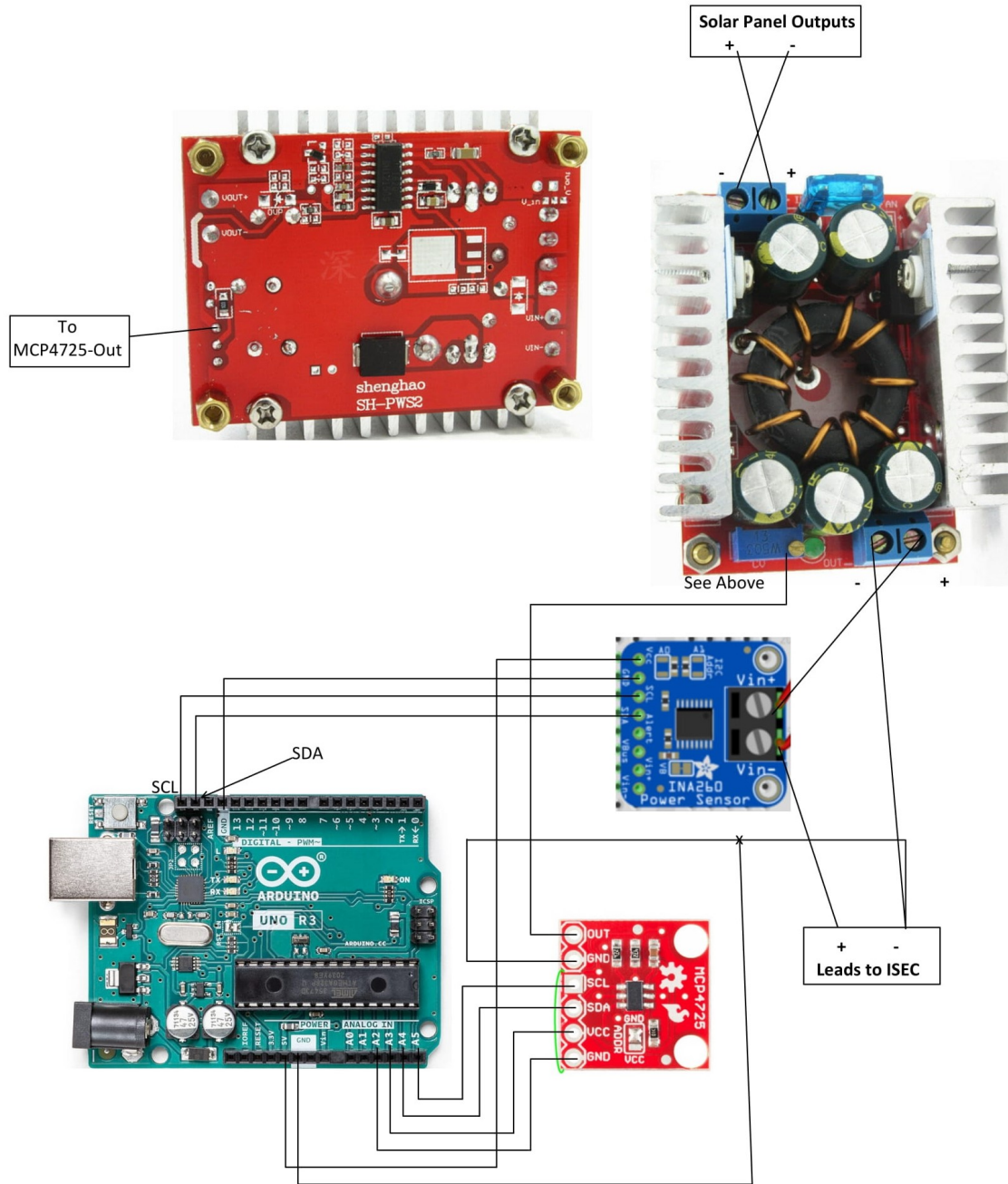
Figure 9: Circuit diagram showing how to connect all components for the self-made P&O MPPT. The two images at the top are the front and back of the buck converter, only one of which is shown connected. The INA260 (blue, right), the MCP4725 (red, bottom right), and Elgloo Uno (blue-green, left) all form a circuit centered around the buck converter.
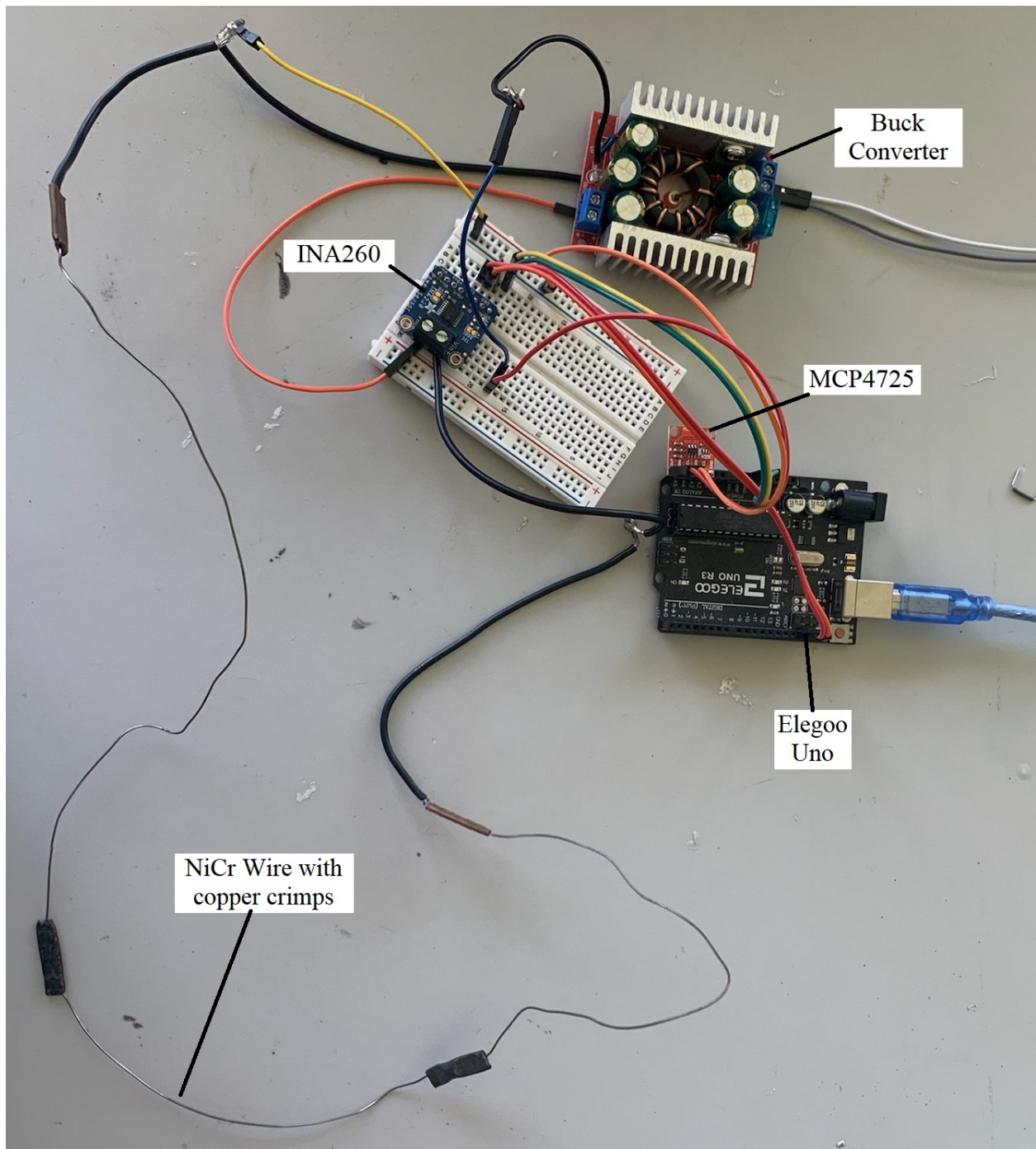
Figure 10: An actual picture of the circuit diagram from Figure 9 connected. Note that the circuit is not on and should sit in an enclosure when powered. Note that a NiCr resisive heating element is shown in place of an ISEC.

6 Code Explanation

Not displayed here is the setup, which checks for both devices to be connected, establishes the pins for those devices, and does an initial reading of $V_{\text{R}} = V_{\text{out}}$. Also not displayed are the other parts of the loop, including the reading of $V_{\text{R}} = V_{\text{out}}$, the updating of the MCP4725, and the checks to ensure V_{control} stays within the expected values.

The code establishes its feedback loop, found in Figure 11, by making 2 comparisons. The variables used are the voltage across the resistor $V_{\text{R}} = V_{\text{out}}$ labeled as x, the voltage from the previous loop labeled V_{outprev}, and dir. dir is a variable telling what direction V_{control}, and hence the gain, moved the last step. $dir = 2$ means V_{control} was increased in the previous step and $dir = 1$ means V_{control} was decreased in the previous step. Since Equation 11 tells us $P_{\text{R}} \propto V_{\text{R}}^2$, comparing the voltages between steps translates to a comparison of powers and as such detects if the position on the P-V graph has moved towards the MPP. The value of dir tells the sign of the change in gain. Combining these two tells whether the change in gain from the previous step is moving towards the MPP. If so, the code continues that gain change and if not, the code reverses the gain change. The current gain change per step is set for the current iteration of the code, at 2 out of the 4096 for V_{control}, corresponding to 2 mV to V_{OSENSE}. Lastly, the variable n is a variable used elsewhere in the code as a check to ensure everything is done in the right order.

Figure 11: Modified P&O Feedback loop coded in Arduino IDE.

```
while (n==0) // Feedback loop
{
  if (dir == 2 && x > VoutPrev)
  {
     Vcontrol = Vcontrol+2;
    n = 1;

  }
  else if (dir == 2 && x < VoutPrev)
  {
     Vcontrol = Vcontrol-2;
    dir = 1;
    n = 1;
  }
  else if (dir == 1 && x > VoutPrev)
  {
     Vcontrol = Vcontrol-2;
    n = 1;
  }
  else if (dir == 1 && x < VoutPrev)
  {
     Vcontrol = Vcontrol+2;
    dir = 2;
    n = 1;
  }
  else
  {
    dir = 2;
    n = 1;
  }
}
```

7 Testing Methods and Results

7.1 V_{OSENSE} as a Voltage input

The testing shown in Figure 12 led to the results in Figure 13. The testing method had the Elgloo Uno connected to the MCP4725, which itself was connected to V_{OSENSE}. The Elegoo Uno was connected to a computer, which increased the voltage provided by the MCP4725 every 5 seconds. The buck converter was connected to a wall outlet power supply for the input and a resistive load for the output. The data was taken by hand using a multimeter. The results show a clear relationship of an increasing V_{OSENSE} meaning an increasing V_{out}. However, the results are unexpectedly nonlinear for low V_{OSENSE}, with a repeatable dip being found on the 3.3 Ω resistor graph. The unexpected behavior could come from the way the LTC1625 interacts with the output of the MCP4725, as the current from the MCP4725 will not be the same as what is expected from a voltage divider connected to V_{out}. The relationship does become linear after $V_{\text{OSENSE}} = 0.16$ V for both graphs. This does still confirm the viability of controlling the buck converter with an input to V_{OSENSE}, as there is some proportionality relationship between V_{OSENSE} and V_{out}.
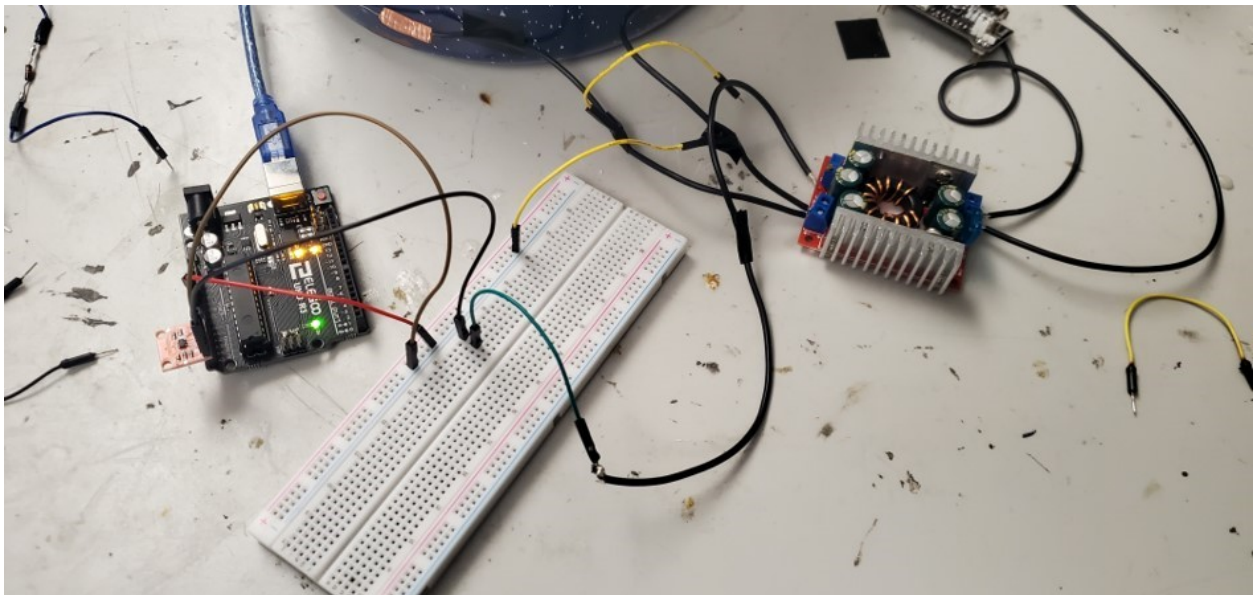

Figure 12: A picture showing the test to confirm the use of V_{OSENSE} as a measure to change the gain.
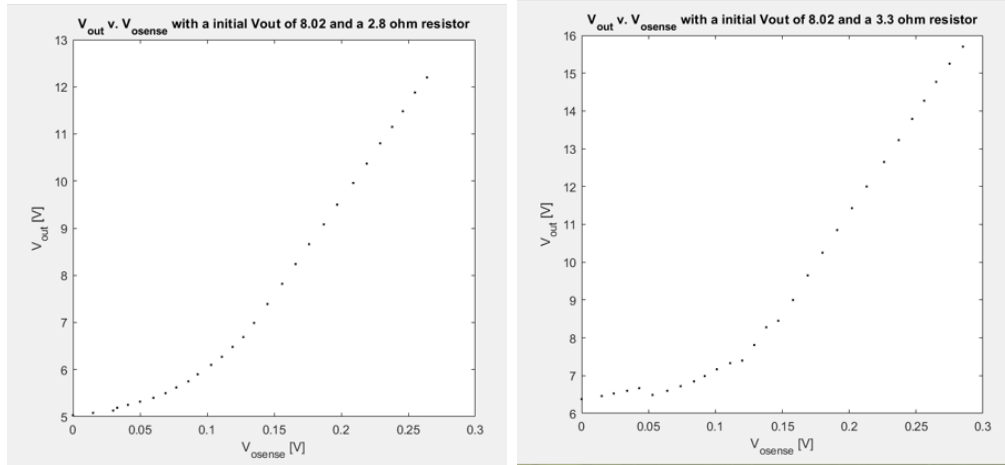
Figure 13: V_{out} versus $V_{\text{OSENSE}} = V_{\text{control}}$ confirming the viability of using V_{OSENSE} as a feedback point for a standalone voltage. Note the unexpected nonlinearity for low V_{OSENSE}. Note the unexpected lack of smoothness at a low V_{OSENSE} in the 3.3 Ω graph.

7.2   MPPT Circuit

This complete circuit was tested with 2 separate power sources: in the lab with a power supply and in the field with a 100-watt solar panel. Special care must be taken while setting up the circuit. If the MCP4725 is either connected to V_{OSENSE} before power is being supplied to the buck converter or connected when turning on or updating code to the Elegoo Uno, the LTC1625 microprocessor will break. Before completing the circuit by connecting the MCP4725 to the buck converter, the buck converter must be connected to its power source and the Elegoo Uno must be running the correct code.

7.2.1   In-Lab

Tests were done in lab with a power supply as the input. This power supply offered the ability to set a maximum possible draw of voltage and current, which shall be referred to as the capped voltage and current, respectively. These are set beforehand, and the actual voltage and current were displayed on a screen. The output of the buck converter was connected to a resistive load equivalent to an ISEC.
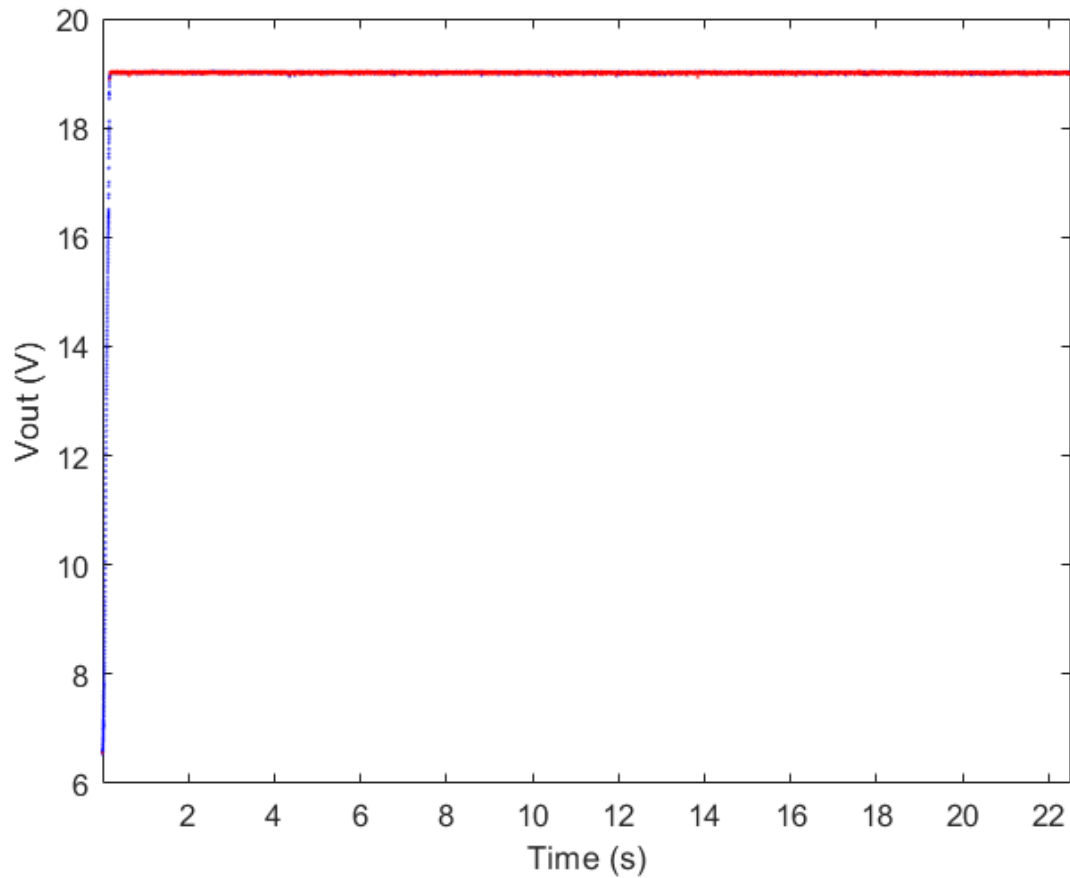
19

Figure 14: V_{out} versus time graph showcasing the circuit reaching and maintaining the MPP with a constant input. Each red point refers to a decision to go down, each blue a decision to go up. Note the rapid initial rise then level off.

The test shown in Figure 14 was to connect the circuit with a capped voltage of 19 V, start at 0 V, and see if the circuit could optimize and rise to the maximum power possible. As seen in Figure 14, the circuit did just that, rising and staying stably at the maximum possible voltage, and hence at P_{MPP}. This confirms the circuit can act as a MPPT circuit given a constant input.

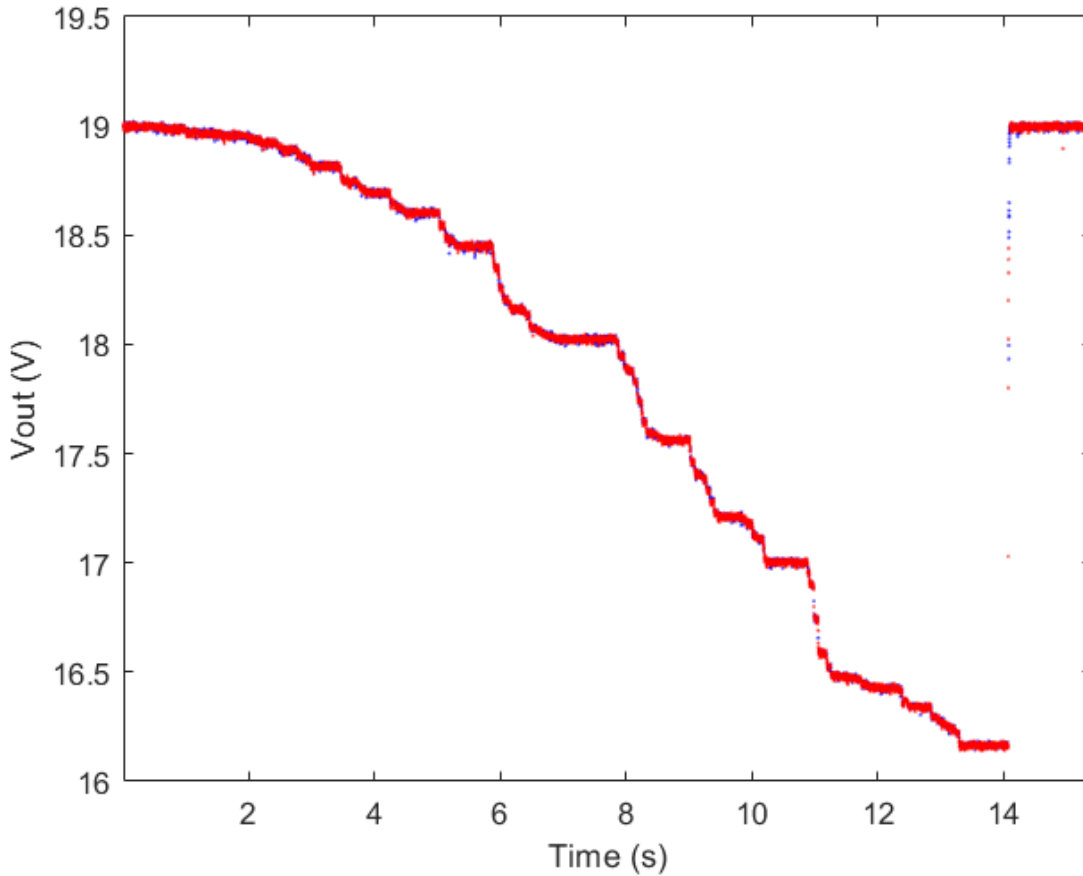**Figure 15:** V_{out} versus time graph showcasing how the circuit follows the MPP with a controlled change of voltage. The change is a slow decline from the initial 19 V down to 16.25 V, then a sharp increase back to 19 V. Note how similar the graph is to the actual explained test. Each red point refers to a decision to go down, each blue a decision to go up.

The test shown in Figure 15 was to start at an already established MPP with a capped voltage of 19 V, slowly lower the capped voltage down to almost 16 V, then abruptly raise it back to the initial capped voltage of 19 V. This checks if the circuit can follow the MPP as the available voltage and power are changing, similar to a cloud moving over the solar panel. As seen in Figure 15, it did just that, moving with the changing voltage and never dropping below the maximum power. This confirms the circuit can act as an MPPT circuit in a lab environment.

7.2.2 Solar Panel

The important field test is to connect the circuit to a resistive load such as an ISEC using a solar panel as the power supply. However, as seen in Figure 16, the circuit did not work as a MPPT. It failed spectacularly. Looking at the graphs show how each walks up and down, but none of them ever get above 6 V, meaning not even a third of P_{MPP} was achieved. Speculating on the failure leads to the noise of the system and the inherent inconsistency of a

solar panel's provided power. This has to be fixed if so, as the point of MPPT is following the MPP, especially in rapidly changing conditions. Alternatively, it could be because some of the variables of the code are not ideal. These could be the delay time between measurement and changing V_{control} not allowing enough time for a noticeable change, the step size of each change being small enough that it gets lost in the noise, or more.
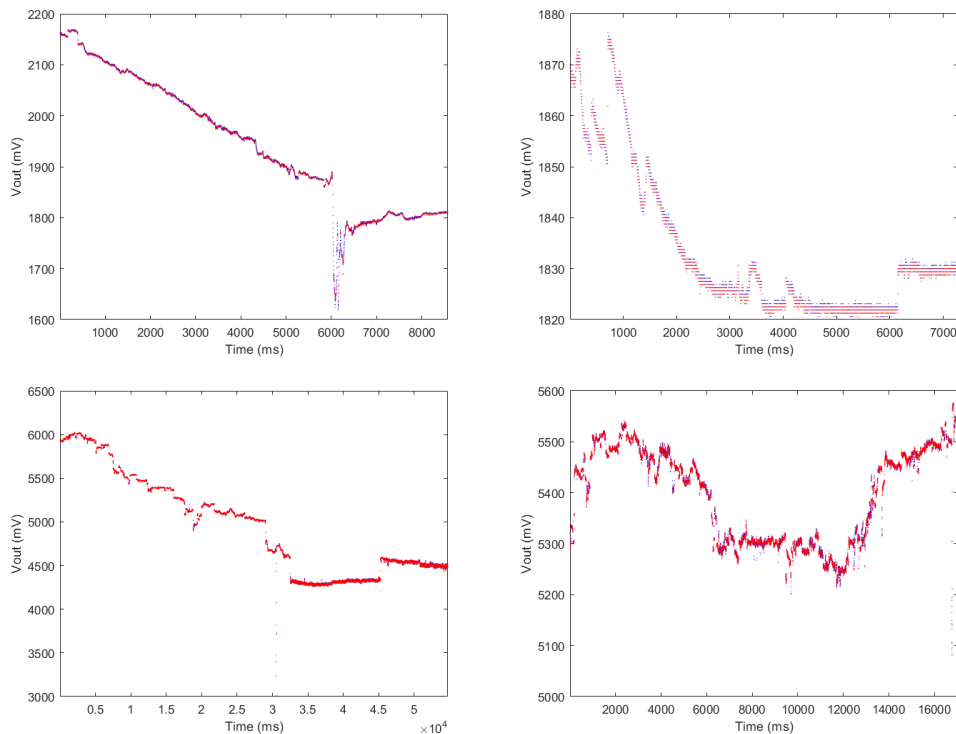

Figure 16: 4 V_{out} versus time graphs, not showing the optimization or consistency sought. Each red point refers to a decision to go down, each blue a decision to go up. This is in near-optimal weather conditions, with up to 90 watts of power available, meaning a $V_{\text{MPP}} > 17$V is expected. However, none of the graphs can rise above 6500 mV, or 6.5 V.

8 Future Scope

Due to a combination of poor timekeeping, material constraints, and shipping times, this project remains unfinished.

The most glaring flaw is the lack of testing and confirmation of the circuit using a solar panel. The adjustment of code to fix the issue found in the results is necessary for further study. The next issue is the high price, as cost is an important feature of the ISEC. It simply is not feasible to use this circuit if the extra power comes at the cost of another solar panel. This issue can be addressed in multiple ways, possibly by researching the exact specifications required out of every component and not leaving resources unutilized. Thirdly, the circuit is difficult to set up and prone to breaking. It is problematic if a single misplaced wire breaks a vital and costly component, so making the circuit less susceptible to breaking is a must.

Areas for further study are plentiful regarding this circuit. The other method of changing V_{OSENSE}, using a digital potentiometer, is the manufacturer's intended use for the buck converter. That may be where the circuit should be headed, regardless of the increased expense of a digital potentiometer rated to handle 20 V and 4 A. Improving the MPPT logic and code would be another avenue, to further study and combine MPPT techniques so it may be optimized for ISECs. Combining and creating a new full ISEC circuit may also be a project, incorporating and cataloging all components, including any from a MPPT circuit.

9   Conclusion

In conclusion, cheap MPPT using a microcontroller and an off-the-shelf buck converter is entirely possible, as the theory is sound. However, there are still many hurdles and roadblocks before it becomes a viable installation.

10 References

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11 Code

```
#include "Wire.h"
#include  "MCP4725.h"
#include  <Adafruit_INA260.h>


Adafruit_INA260 ina260 = Adafruit_INA260();
MCP4725 MCP(0x60);   // 0x62, 0x60 or 0x63


int Vcontrol; // define the control voltage on a 0-4095 scale
int n;
int s;
int dir;
float x;
float  VoutPrev;

void setup() {
    Serial.begin(115200);
  // Wait until serial port is opened
  while (!Serial) { delay(50); }

  pinMode(A2, OUTPUT); //Set up DAC Ground
  pinMode(A3, OUTPUT); //Set up DAC Voltage in
  digitalWrite(A2, LOW);//Set A2 as GND
  digitalWrite(A3, HIGH);//Set A3 as Vcc

  if (MCP.begin() == false) //check for both devices
  {
    Serial.println("Could not find DAC-MCP4725");
    while (1);
  }

  if (!ina260.begin()) {
    Serial.println("Couldn't find INA260 chip");
    while (1);
  }

  Vcontrol = 0; // From 0-4095
```

```
   x=0;
   n=0;
   s=0;
   dir = 1;

   x=ina260.readBusVoltage()+x;  //Initial  voltage  reading
   VoutPrev = x;
   Vcontrol = Vcontrol+10;
   dir = 2;
    MCP.setValue(Vcontrol);

    Serial.println("Setup  Done");
}

void loop() {

   while (s<1)  //Loop  to  read  voltage
   {
      delay(10);
       x=ina260.readBusVoltage()+x;
      s=s+1;
   }
   x=x/1;

   while (n==0) // Feedback loop
   {
      if (dir == 2 && x > VoutPrev)
      {
         Vcontrol = Vcontrol+2;
        n = 1;

      }
      else if (dir == 2 && x < VoutPrev)
      {
         Vcontrol = Vcontrol-2;
         dir = 1;
```

```
    n = 1;
  }
  else if (dir == 1 && x > VoutPrev)
  {
    Vcontrol = Vcontrol-2;
    n = 1;
  }
  else if (dir == 1 && x < VoutPrev)
  {
    Vcontrol = Vcontrol+2;
    dir = 2;
    n = 1;
  }
  else
  {
    dir = 2;
    n = 1;
  }
}

if (Vcontrol < 1)
{
  Vcontrol = 1;
  dir = 2;
}
else if (Vcontrol >1500)
{
  Serial.println("Vcontrol too big");
  while(1){}
}
 MCP.setValue(Vcontrol);



 Serial.print(x);
 Serial.print("   ");
```

```
 Serial.print(dir);
 Serial.print("   ");
 Serial.print(Vcontrol);
 Serial.print("   ");
 Serial.println(n);



if (n == 1)
{

  VoutPrev = x;
  x=0;
  n=0;
  s=0;
}
}
```