Source Independent Power Converter for Cell Phone Charging

A Major Qualifying Project
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Abstract

As part of an initiative to educate middle school students about electrical energy, the country of Switzerland has sponsored several STEM programs encouraging teachers to integrate hands-on experiences in their classrooms. This paper highlights the design and development of a versatile cell phone charger capable of accommodating various power inputs (hand generator, solar panel, AC, etc.), charging a cell phone and displaying the flow of electrical energy for educational purposes. A working prototype utilizing a SEPIC DC-DC converter was built and tested based on specifications provided by the project sponsor. Real-time power monitoring was accomplished by using voltage and current sensors providing signals to a Raspberry Pi microcontroller, and outputs were presented on an LCD touchscreen display. System testing shows further refinements are recommended including the implementation of an additional charging mode as well as slight modification to the custom PCB design.

Acknowledgments

We would like to thank the following individuals for their guidance and support throughout the course of this project. From supplying hardware to technical advice their contributions are greatly appreciated.

- Professor Stephen Bitar
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- Dr. Stefan Bertsch
- Dr. Emine Cagin
- William Appleyard

Executive Summary

In the modern age electrical energy serves as the foundation for almost everything we do. Most commonplace activities such as driving a car, preparing food, or writing a paper like this one require the use of electrical energy. However, for today's youth, the concept of electrical energy and its generation remains abstract. In order to promote an energy conscious future, it is essential that future generations are taught about the intricacies of electrical power generation and the importance of maintaining efficient and renewable sources of energy.

In order to support the future development of a better, more efficient power infrastructure, the country of Switzerland issued an initiative to promote hands-on STEM education in the classroom. In support of this initiative, our sponsor Daniel Oplinger, with the support of Ostschweizer Fachhochschule Buchs, developed a series of energy sources to be used to illustrate the process of electrical power generation to students. These include: a steam generator, a hydroelectric generator, a solar panel array, and a mechanical hand-crank.

The goal of this project was to develop a power converter capable of charging a cellular device using these energy sources as well as a power monitoring system to analyze output power over time. Since most students have and are familiar with a variety of cellular devices, cell phone charging provides a very accessible and easy to visualize application of electrical power. The team strived to create a functional prototype that would give students the opportunity to both charge their cellular devices using Daniel Oppliger's energy sources, and visualize how electrical energy can be manipulated. The varying input power parameters of each energy source was taken into consideration, and features were integrated into the prototype to allow for input power fluctuation.

Several primary objectives were identified for the final design. The device being developed needed to accept several voltage inputs, both AC and DC, and output sufficient power to charge a cellular device from any manufacturer. In addition to this, to support the educational objective of the system, the device needed to be able to display output power in real time in a graphical format. In order to best illustrate the concept of electrical power generation and use, it was essential that the output power measurement had a high level of accuracy and that the displayed output power graph responded quickly to changes in input power parameters.

There were also several considerations regarding operating conditions and component power use that were identified for the design of the prototype. Since the energy sources were designed for use outdoors, it was determined that a protective enclosure would be required to ensure that the electrical components of the design are not damaged during operation. Due to the importance of the accuracy of output power measurements, it was determined that the power monitoring portion of the design needed an independent power source. After analysis of all possible input power parameters it was determined that not all energy sources are capable of meeting the minimum power requirements for cell phone charging (5V and up to 3A). The team came to the conclusion that two separate power charging circuit designs should be used to address high and low input parameter sources. Therefore, the prototype was designed to accept a variable range of input voltages and currents.

To design the device, the process was split into four separate design modules: a power monitoring system, two separate charging circuits, and a protective enclosure. The power monitoring system was intended to measure and display output power over time to the user. The objective of the first charging circuit was to charge a cellular device when input parameters were high, allowing for a change in input parameters to have a direct effect on output power. Conversely, the goal of the second charging circuit was to provide the necessary output power for cell phone charging even when input voltage was low and variable. The protective enclosure was intended to be watertight and serve as a barrier between electronic components of the design and outdoor operating conditions.

For the power monitoring system, a Raspberry Pi Zero W microcontroller was first selected as it has the necessary processing capabilities and is easily programmable. From there, the INA260 Power Sensor was chosen to provide digital output power measurements to the microcontroller. This power sensing module was selected over other methods of power measurement as it does not require additional power calculation to be performed by the microcontroller and consumes very little power itself. A Raspberry Pi compatible 5” LCD

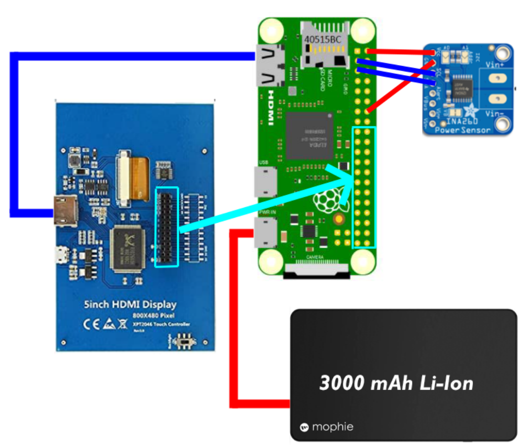

Figure 1: Power Monitor

touchscreen display was selected to communicate output power in a graphical format to the user. A 3000mAh portable Li-Ion battery pack was chosen to supply power to the power monitoring system. As indicated previously, an independent power source was necessary to ensure the accuracy of output power measurements. These components were integrated together in the configuration shown in Figure 1.

For the first charging circuit, a linear regulator based design was selected as it allows for an output capable of meeting cellular charging requirements while preserving the linear relationship between input parameters and output power. The LT1529CT was chosen as the linear regulator for this circuit, as it met the necessary input and output voltage and current specifications. The circuit schematic illustrated in Figure 2 from the linear regulator datasheet was constructed. Adjusting the voltage divider formed by resistors R1 and R2, allowed for the proper output voltage specification of 5V to be met. Calculation revealed that an R1 value of 10kOhms and an R2 value of 3.3kOhms allowed for a 5V output to be achieved. The addition of a low ESR 100 microFarad capacitor across the output served to ensure output stability.

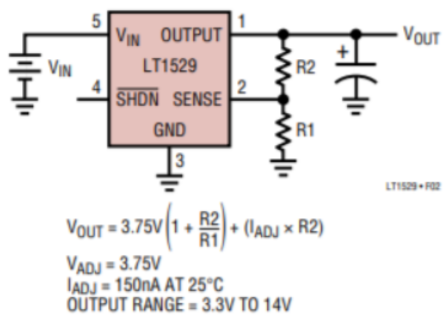

Figure 2: Linear Reg Schematic

For the second charging circuit, a switching regulator based SEPIC converter design was selected as it allows for cellular charging requirements to be met even in conditions when the input source power is low. The LT1371CT7 was chosen as the switching regulator for this circuit configuration. Figure 3 illustrates the chosen circuit schematic that was determined to best meet application requirements. To serve the role of the two coupled inductors pictured in the schematic, a 15.7 microHenry inductor array was selected. In addition all resistors used in the prototype of this design had low tolerance values and all capacitors were chosen with low equivalent series resistances.

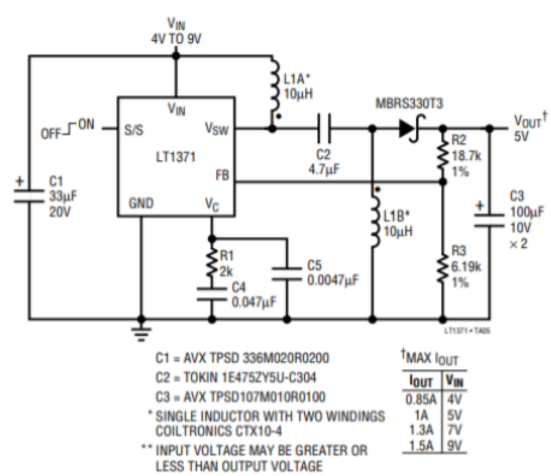

Figure 3: SEPIC Converter Schematic

For the protective enclosure, due to limited time, a prefabricated watertight container was selected and modified to better fit the electronic elements of the design. Holes were drilled and sealed for input and output wires and a shelf was constructed to hold the display of the power monitoring system. This shelf was made to be removable to ensure easy access to all components for troubleshooting and repair.

Integrating all of these modules together, the team was able to come up with a design for the prototype and begin its construction. The design that was developed went through three separate stages of prototyping. The first stage of prototyping consisted of the construction of two separate breadboards, one for each charging circuit. After the performance of these individual circuit designs was confirmed to match design expectations the team progressed to the second stage. In this stage, selected circuit components were soldered to blank PCBs and a bridge rectifier stage was added to allow for both AC and DC inputs. Furthermore, software development began at this stage utilizing Python and the MatPlotLib library to generate a displayable output power over time graph. The final prototype that was constructed involved the design and assembly of a custom PCB on which both charging circuits were soldered as well as a fully functioning power monitoring system and graphical display. This final prototype was able to successfully charge cellular devices from a variety of different manufacturers utilizing the full range of possible input power parameters.

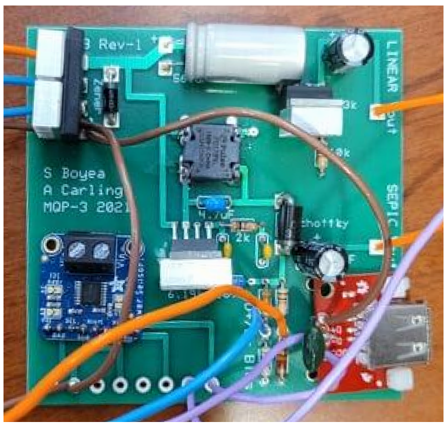

Figure 4: Final Circuit Prototype

Although the prototype that was developed performed well, the team does have several suggestions that could improve the overall design. The first of which pertains to the custom PCB design. It is recommended that more grounding points be added to minimize the quantity of jumper wires required. Additionally, the team feels as though touch sensitivity should be considered in display selection. Although the display used in the prototype was functional, low sensitivity made interaction difficult.

The team was able to successfully accomplish the objectives of this project. The design allowed for both AC and DC inputs ranging up to 25V and successfully generated an output capable of charging a cellular device. In addition to this, the power monitoring system that was designed was capable of displaying output power vs time in a graphical format. The watertight housing that was customized for this purpose ensures the successful operation of electronic components in outdoor conditions. With all aspects of the design integrated and working successfully together, this power converter is sure to help future generations understand the energy that powers the world around them.

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1. Background

Electrical energy, for many people, is a hard thing to visualise. From our perspective, there is little evidence that energy is being consumed at all in something like a smartphone. Daniel Oppliger, an educator from eastern Switzerland, wants to contextualize electrical energy for his middle and high school students, so they may better understand the power hungry world that we live in. We have been working with Daniel Oppliger and the OST Buchs faculty to make this possible.

The first question that Daniel asks his middle school students is: How many gummy bears worth of energy do you think it takes to charge a cell phone battery? The power storage of a children's snack must pale in comparison to a battery technology that has taken decades to develop? Surely the answer must be in the hundreds! However, if you could extract all the energy contained in the sugar of a single gummy bear (about 9 nutritional calories) you could fully charge your cell phone battery from 0%-100% (Using an Iphone X or equivalent.)

Energy (watt hours) in a typical gummy bear: $9\ kcal\ *\ 1.162\ \frac{Wh}{kcal} = 10.46\ Wh$

Energy (watt hours) in an Iphone X battery: $2.716\ Ah\ *\ 3.81\ V = 10.35\ Wh$

The point of this exercise was to illustrate how abstract electricity can be. It also helped determine what our device must do to clarify the relationship between electrical power, and tangible sources of energy.

For years Daniel Oppliger has been teaching middle and high school students about electrical energy using generators of his own design. He wants them to walk away from his activities, more conscious of the work that has to be done to power all of their electrical devices. Students carry buckets of water up a hill to power a hydroelectric generator, and run the manual hand crank to help understand what it takes to power a cell phone. The students also use solar panels and a steam generator to convert other familiar energy sources into cell phone charge.

Unfortunately, in the past, when they have been charging cell phones using these methods, it has been difficult for them to determine how much energy they have been producing, and how much of that energy has actually been making its way into their cell phone batteries. Thus, a device was needed to not only power the student’s devices efficiently, but also to display to them how much energy was being transferred.

In an ideal situation, nearly 100% of the energy put into the generator would make it to the cell phone, and a converter would display the charging rate. The students would see this charging rate and be able to draw a correlation between their mechanical effort and the amount of power consumed by their device.

1.1 Compatibility and Connectivity

The first consideration for this project was what exactly our device had to do. Daniel Oppliger has been working with machines of his own design that translate familiar sources of energy into electrical power. He has constructed a solar array, hydroelectric generator, steam generator, and a hand cranked AC generator. These devices have a variety of outputs ranging from 3V-20V (Under typical cell phone load) and including AC and DC outputs, so we knew that our device had to function in all of those conditions.

On the output side, Daniel has been using cell phone charging to familiarize his students with electrical energy conversion. Cell phones are widely available, familiar, and not particularly delicate when it comes to power sources.

For converting power, Daniel has been using a rugged but simple setup including a full bridge rectifier, “the biggest capacitor off the shelf”, and a USB-C controller board of unknown manufacturer and specification. This is the part of the system that our device would replace.

1.2 Prior Art Power Supplies

The problem with using a cell phone as a power sink (the device in which electrical energy is stored) for the classroom is the ever increasing complexity of these devices. Each manufacturer of cell phones has different charging requirements for the fastest charging possible. But all cell phones retain the ability to charge off of a charge-only 5V USB port [8]. So at a minimum, supporting a charge-only USB connection with 3A current available would catch the majority of cell phones and provide adequate performance for the average user at minimal cost. Additionally, high voltage quick charging solutions are typically disabled above 80% charge of the device’s battery, which would lead to inconsistent charging speed results.

Besides the output behavior, the type of voltage regulator is also important for efficiency and current delivery capability. Since we needed to supply 5V from an input range of 3V-20V, some form of combined buck/boost design would need to be used. These are common in applications that use batteries as a source, because batteries change voltage depending on state of charge. Much of the inspiration for our device came from the designs of voltage regulators used with li-po and li-ion battery packs [2].

To address the issue of the AC source, our design would need a rectifier and low pass capacitor like in the original converter. Based on the data collected with Daniel's design, no additional complexity was needed here.

Cell phone chargers also need to advertise their current and voltage capability to a user's cell phone. For variable voltage quick chargers this is a complicated process that requires a dedicated charging controller. In the case of a 5V charger, a floating voltage on the data pins of the usb port identifies it as a charging port with higher current capability [10]. Different manufacturers use different voltages to indicate a fast charging port (2.7V for Apple, 1.2V for Samsung.) All dedicated charging ports have their data pins shorted together though, to indicate there is at least 1.5A available [8]. Changing the voltage on that node can indicate to specific phones that greater than 1.5A is available.

1.3 Proposed Design Based on Background Research

From our background research, we knew what our device had to accomplish and the functional blocks it would need to include. On the input side, we would use Daniel's existing machinery with a full bridge rectifier option for the AC sources. For voltage regulation we would have a buck-boost topology based on a reference design intended for use with rechargeable batteries. On the output side we would set up a USB-A port in the charge-only configuration.

2. Design Requirements

In order to develop a successful technical solution, it is essential that customer requirements are first identified and itemized. Through several conversations held with Daniel

Oppliger and the OST Buchs faculty, we were able to compile a list of technical product requirements. This list aided in component selection and the formulation of a final design.

2.1 Customer Requirements

As the primary objective for the project is education, it was determined early on that the power converter must support this objective, first and foremost . This means that instead of focusing on developing the most efficient power converter regardless of input parameters, it is important that the selected design be able to illustrate how varied inputs affect output power. Further discussion revealed that renewable energy sources supply both DC and AC current. Sources also supply a wide range of current and voltage levels. Based on this determination the following customer requirements were identified.

- Must not correct for inconsistent or varied input parameters
- Accommodate entire voltage and current input ranges
- Accept both AC and DC inputs

It was noted that in order to appeal to more students the technical solution should be capable of charging a wide variety of output devices. Specifically mentioned were cellular devices manufactured by Apple, Samsung, and Huawei. In addition to the development of a power converter capable of charging this variety of cellular devices, it was identified that a power monitoring system would be helpful in accomplishing the educational objective of this set up. This monitoring system would ideally measure output power over time. The sponsors specifically requested that the device include a simple graphical display for power over time. In order to best illustrate how output power changes as the renewable energy source is manipulated, this graph should be displayed in real time. During the consideration of a power monitoring system some concern was expressed regarding how such a system may impact the accuracy of output power measurements. It was determined that the power monitoring components would need an independent power source in order to ensure output power data was accurate. This discussion prompted the addition of the following customer requirements.

- Must be able to charge cellular devices from a variety of manufacturers
- Needs to measure output power vs time
- Must display output power information in real time
- Power monitoring system must have independent power source

In addition to technical customer requirements, our project sponsor also had some considerations regarding the housing the electronic components will be contained within. Due to their size, many of the renewable energy generators are located in an outdoor setting. This would require a container that is sealed to the elements and that can tolerate outdoor conditions without compromising design function or efficiency. In response to these considerations the requirements listed below were added.

- Design must be enclosed in a water-tight housing
- Needs to be robust enough to tolerate outdoor conditions

The customer requirements that are outlined above aided in the development of final product requirements. The itemized list of customer requirements helped to ensure that the developed technical solution met all customer expectations.

2.2 Product Requirements

Although the customer requirements mandate that the power converter being developed does not correct for varying or inconsistent input parameters, further analysis led to some additional consideration regarding this requirement. Through analysis of average input specifications, it was determined that the minimum threshold for cell phone charging was not met by all renewable input sources. Namely, the AC hand crank crank fell short of these requirements. For this reason the decision was made to include two distinct charging circuit designs: one circuit design that actively compensates for varying input voltage, and one that passively maintains a <5V output. . This decision was made in order to enhance the educational potential of the convertor, allowing an output power graph to be displayed regardless of input parameters.

Based on both the customer requirements and our analysis of the wide range of possible input parameters the following overarching product requirements were determined.

<u>Power Monitoring System:</u> The design must include a system capable of measuring and displaying output power in real time. In order to ensure this monitoring system does not impact the accuracy of power data, it must have an independent power source.

Charging Circuit #1: This circuit must be designed in such a way that changing input parameters has a visible effect on output power data. Circuit must be able to accommodate both AC and DC current as well as the entire range of possible current and voltage input values. Output must be sufficient to charge cellular devices manufactured by Apple, Samsung, and Huawei.

Charging Circuit #2: This circuit must be designed in such a way that output power specifications are met regardless of input parameters. Circuit must be able to accommodate both AC and DC as well as the entire range of possible current and voltage input values. Like circuit #1, this circuit must also be capable of charging cellular devices from various manufacturers.

Housing: Electronic components must be contained within a robust and watertight housing for protection against outdoor operating conditions.

2.3 Product Specifications

Taking into consideration both customer and product requirements we identified that the preliminary design can be broken into four separate sections. The first being the power monitoring system, the second two being charging circuits with different features, and the last being the housing. Designing each of these sections separately will help to simplify the design process.

2.3.1 Power Monitoring Specifications

The power monitoring system must be capable of measuring output power of the converter with respect to time. In order to be able to accomplish this task it is known that the following electrical components will be required.

- Microcontroller: To perform data processing
- Current Sensor/ Power Sensor Module: To measure output power

Additionally, it was identified that the power monitoring system must be capable of visually displaying output power data in a graphical format. This requirement mandates the use of the following

- LCD Display: To display power data to user in real time

Furthermore, in order to address customer concerns regarding the negative effect the power monitoring system may have on the accuracy of output power measurements, an independent power source must also be provided.

- Li-ion Battery: To supply power monitoring system

2.3.2 Charging Circuit #1 Specifications

The first charging circuit must be capable of accommodating both AC and DC input. In order to accomplish this with minimal voltage drop it is known that the following component is required.

- Diode Bridge Rectifier: Capable of converting AC input to DC

Uniquely, this circuit must be designed in a way that a change in input parameters results in an almost immediate change in output power. In order to limit the correction that occurs within the charging circuit a linear configuration was selected. Since it is known that the required output specifications for charging are 5V and 3A, the circuit component in question must be able to scale input voltage and current to meet these. The component that best fits this selection is listed.

- Linear Regulator: Precisely allows current to bypass the output maintaining a fixed output voltage to meet charging specifications

2.3.3 Charging Circuit #2 Specifications

Much like the first charging circuit, the second must also be capable of accommodating both AC and DC input current. This indicates that a shared diode bridge rectifier may be used between the two circuit designs.

- Diode Bridge Rectifier: Capable of converting AC input to DC

However, unlike the first charging circuit, this charging circuit must be capable of supplying the proper voltage and current levels required for charging regardless of the input parameters. This would require the use of the following.

- Switching Regulator: Allows for more stable scaling of input voltage and current to meet charging specifications. Output power is less affected by changing input parameters. Very low theoretical power loss in power conversion.

2.3.4 Housing Specifications

Based on customer requirements it is clear that a housing would be required to protect electronic components in their intended operating environment. Since the renewable energy sources being utilized are outside, the containment unit must be watertight and robust enough to withstand accidental dropping. For this reason, a hard plastic case with rubber gaskets to create a watertight seal when closed was proposed.

3. Design Approach

Our preliminary design approach involved interfacing the four sub-modules explored previously together into one comprehensive design. As education is the primary objective of this technical solution, it is essential that the final design is able to accurately quantify and display the relationship between input and output power. The block diagram, as shown in Figure 1, illustrates the initial design.

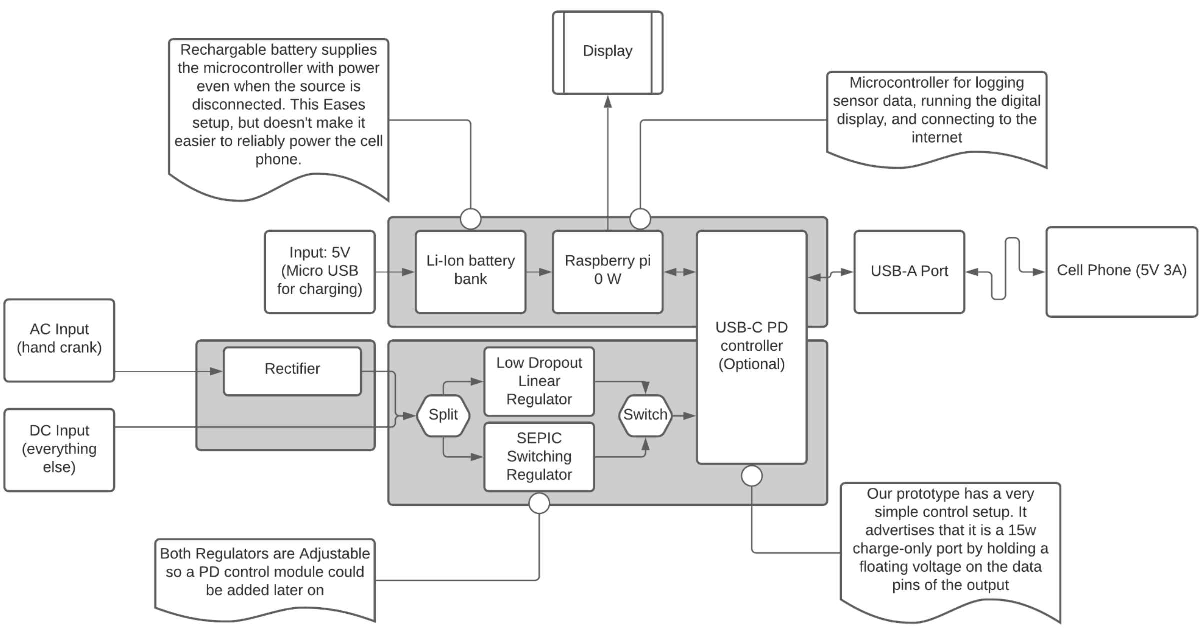

Figure 5: System Block Diagram

3.1 Power Monitor Design

As portrayed in Figure 1, the power monitoring system design occupies the top most section of the block diagram. Each component of this section of the design was chosen for its compatibility with all other components as well as its unique parameters. Below each component chosen for this design will be listed and its role explained.

- Raspberry Pi Zero W: This is intended to serve as the microcontroller for the system. The Raspberry Pi will take on the role of reading and interpreting the power data taken by the power measurement module. As this is a programmable microcontroller, a custom python script will allow power data to be displayed on the touch screen display in a graphical format. The Raspberry Pi Zero W was chosen over other microcontroller options, as it has the processing capabilities required for this application while consuming the minimum amount of power possible. The microcontroller's small size also helps to minimize the overall size of the power converter being developed [4].
- 3000 mAh Portable Li-Ion Battery Pack: This portable battery pack was chosen to act as an independent power source for the power monitoring system. As discussed previously, it was a concern that using the charging circuits themselves to provide power to the monitoring system would result in inaccurate output power measurements. A 3000 mAh battery was selected as this specification allows for several hours of operation between charges. This would provide adequate time for an educational demonstration. The Li-Ion battery type was selected for its output voltage and current stability as well as the fact that it can be charged directly from a wall outlet.
- 5” Raspberry Pi 800x480 TFT LCD Display: In terms of selecting a display, the most important factor under consideration is compatibility with the chosen microcontroller. The display serves the role of illustrating the output power vs. time graph generated by the microcontroller. This particular display was selected as it easily connects to the

Raspberry Pi Zero W through a direct connection to the HDMI and I2C ports.The 5” display size is just large enough for a user to easily interpret the data being displayed without excessive power consumption.

- INA260 Volt Current Power Sensor: This power sensing module serves the role of taking digital output power measurements to be interpreted by the chosen micro-controller. The important factors to consider in the selection of a power sensing module are compatibility and accuracy. As the Raspberry Pi Zero W is not capable of interpreting analog data without conversion, it was determined a digital sensor would be required. In order to minimize the amount of data processing required a power sensing module was selected as it is capable of outputting an accurate digital power reading without need for further calculation [5].

3.2 Circuit #1 Design

As can be identified in Figure 1, the first, or linear charging circuit occupies the block labeled low dropout linear regulator. As discussed previously, in order to ensure that the system's output power changes as the input parameters are altered, a linear regulator circuit is required. Below is a detailed description of the linear regulator that was selected for this task.

- IC REG LINEAR POS ADJ 3A TO220-5: A major consideration in the selection of a linear regulator was the input and output power specifications. Based on these specifications it is known that the regulator must be able to output 5V and withstand input voltages up to 25V. The maximum current that must be tolerated by the regulator is 3A. With these specifications defined, the listed regulator was selected as it meets the desired characteristics. Within the datasheet of this linear regulator the following circuit schematic was recommended to achieve maximum operating efficiency [1].

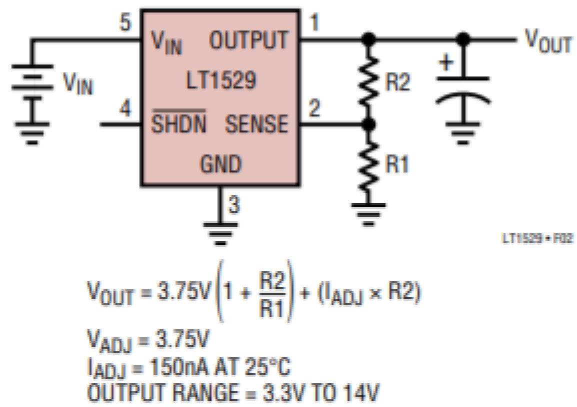

Figure 6: Linear Regulator Circuit Diagram [1]

As pictured in Figure 2, it can be noted that some passive components are required to ensure proper function of the selected linear regulator. In order to ensure an output voltage of 5V is achieved resistor values R1 and R2 must be selected. Following the equations listed below the circuit schematic, these resistor values were chosen as follows.

- R1 = 10K w/ 1% tolerance
- R2 = 3.3K w/ 1% tolerance

In this schematic the capacitor located on the output serves the purpose of limiting noise and ensuring stability of the output. For this reason the following low ESR capacitor was selected based on datasheet recommendations [1].

- C = 100 microFarads w/ 0.02 ESR

With the design of Circuit #1 almost complete, it is important to ensure that the design is capable of accommodating all expected inputs. This includes both AC and DC current. The following component was chosen to take on the role of rectifier block reference on the block diagram.

- Bridge Rectifier 1PHASE 50V 4A GBU: This bridge rectifier or diode bridge rectifier is capable of taking in both AC and DC inputs up to 50V and 4A. This is well beyond the expected maximum input voltage of 25V and maximum current of 3A. This particular rectifier is able to convert AC to DC with a voltage loss of approximately 1.2V. Unfortunately this voltage loss is unavoidable regardless of rectifier choice [3].

3.3 Circuit #2 Design

As shown in the Figure 1 block diagram, the second, or switching regulator circuit occupies the block labeled SEPIC Switching Regulator. The goal of this charging circuit is to be able to maintain a stable 5V output regardless of input power parameters. In order to achieve this goal a switching regulator is required. The following component is the switching regulator that was selected as the basis for the Circuit #2 design.

- IC REG MULT CONFG ADJ 3A TO220-7 : Similar to the selection of the linear regulator for Circuit #1, the most important consideration in the selection of the switching regulator is input and output current and voltage specifications. The chosen switching regulator is able to accept a DC input up to 30V and 4A. This is more than is required based on the expected input parameters. The chosen regulator is also capable of generating the required output of 5V and up to 3A. Within the datasheet there were several circuit schematics made available for various applications. The schematic most fitting to this power converter's design requirements is shown below [2].

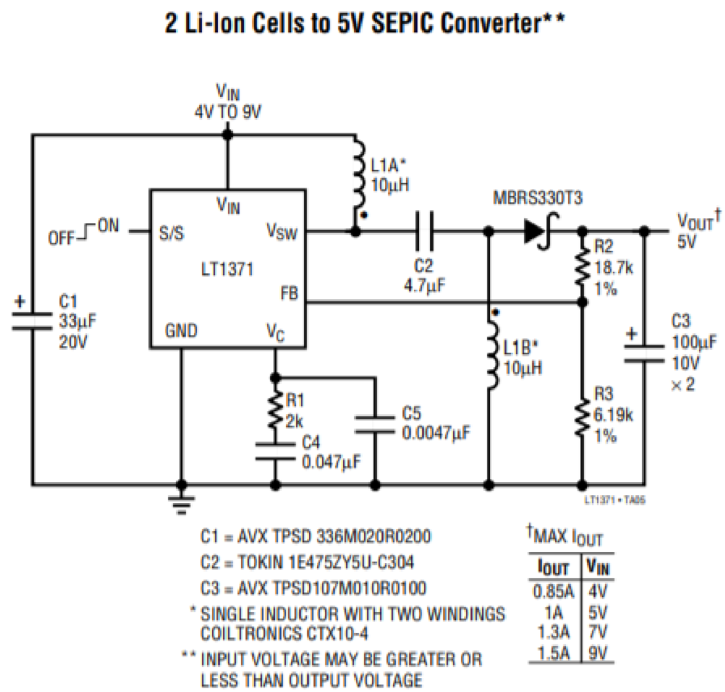

Figure 7: SEPIC Converter Circuit Schematic [2]

As can be noted in Figure 3, several passive components are required in order to ensure the circuit's proper operation. All capacitors were selected with the labeled values. It is important that all selected capacitors have low ESR values to ensure the most efficient operation of the switching regulator. All capacitors used in the design had ESR values less than 0.03. Resistors were also selected with the labeled values and with 1% tolerance to ensure the best performance. The circuit, illustrated in Figure 3, also contains more specialized components which are to be listed below.

- Inductor Array 2 Coil 15.7UH SMD: This inductor array was selected to take on the role of the two coupled inductors illustrated in the schematic. The inductor array that was chosen features two coils wrapped in the same direction around a shared toroid. Each of the inductors within the array has an overall inductance of 15.7 microHenries. According to the data sheet any inductor value between 10 and 22 microHenries is acceptable. It was also noted that the higher the inductance the greater the output current [6]. For this reason 15.7 microHenries was selected as it allows for the desired output current.
- Schottky Diode: Due to the unavailability of the schematic specified schottky diode, a similar schottky diode with the desired characteristics was selected. This diode was rated for a maximum current of 4A and a maximum voltage of 60V.

3.4 Output Hardware Selection

The individual designs of circuits #1 and #2 ensured that the necessary output current and voltage requirements for cell phone charging were met. However, we have yet to address the physical connection between the charging circuit and the cellular device to be charged. For this there were several options that were considered such as USB-C, USB-A, and micro-USB. In order to meet customer requirements the power converter being developed must be able to charge cellular devices of several different manufacturers. This automatically ruled out micro-USB as this particular port is not compatible with Apple devices. Due to the electrical and software complexities of USB-C it was thought that this particular charging port would not be feasible for the time frame allotted. Therefore, USB-A was selected to be the output charging port.

- Sparkfun USB Type A Female Breakout Board: This USB-A breakout board was selected for the design. A breakout board allows for easy solder connection to the output of both charging circuits. USB-A is universally compatible with Apple, Samsung, and Huawei cellular devices making it ideal for this application.

3.5 Housing Design

When it came to the design of an enclosure for our preliminary electronic components our primary goal was to create something that met the customer requirement of being water tight while also remaining portable. It was also important, as the design was not yet finalized, that the electronics remained accessible for alteration or repair. We recognized right away that, due to the short time frame of this project, a 3D printed enclosure would not be feasible. Instead it was decided that a prefabricated watertight housing would be used and modified to better fit the application. This modification included cutting out holes for input and output connectors as well as the construction of a shelf on the upper layer of the enclosure for the touch screen display to rest.

3.6 Software Design

With the hardware components selected, the last part of the design to consider is software development. The software objective is to instruct the Raspberry Pi Zero W to read output power data from the power measurement module in real time. From there, the developed software should be able to instruct the microcontroller to graphically display each output power measurement over time on the selected display.

In order to accomplish this task, the Python 3.7 programming language was selected for its compatibility with the Raspberry Pi micro-controller [4]. Additionally, the Python library MatPlotLib was utilized for the generation of the output power vs. time plot. Adafruit also supplied a driver in C++ for the INA260 power sensor. Below can be seen the preliminary software block diagram that was used to structure software development.

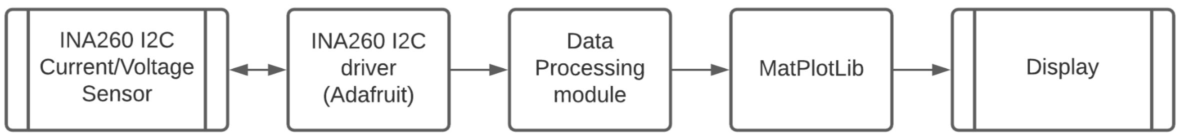

Figure 8: Software Block Diagram

4 Prototyping and Results

The preliminary design went through three stages of prototyping. First, a breadboard prototype of DC-only operation. Second, a soldered prototype on blank PCBs with a first prototype of the plastic enclosure. Finally, a near production-ready device on a custom PCB and a revised enclosure. Gerber files and assembly instructions are set to be delivered to Daniel Oppliger and OST Buchs where they could evaluate the design for themselves before starting production.

4.1 Prototyping Stage 1

For the first stage of prototyping we assembled all of our breadboard-compatible components without the rectifier block or the sensing/display components. The linear regulator and SEPIC circuits were assembled separately at this stage. At this stage we also did not advertise to the cell phone that the USB port was capable of high current operation. At this stage the test cell phone (A Motorola Z3 Play 3000mAh) charged slowly within the USB 2.0 spec under 500 mA [9]. Performance at this stage was low, but showed potential.

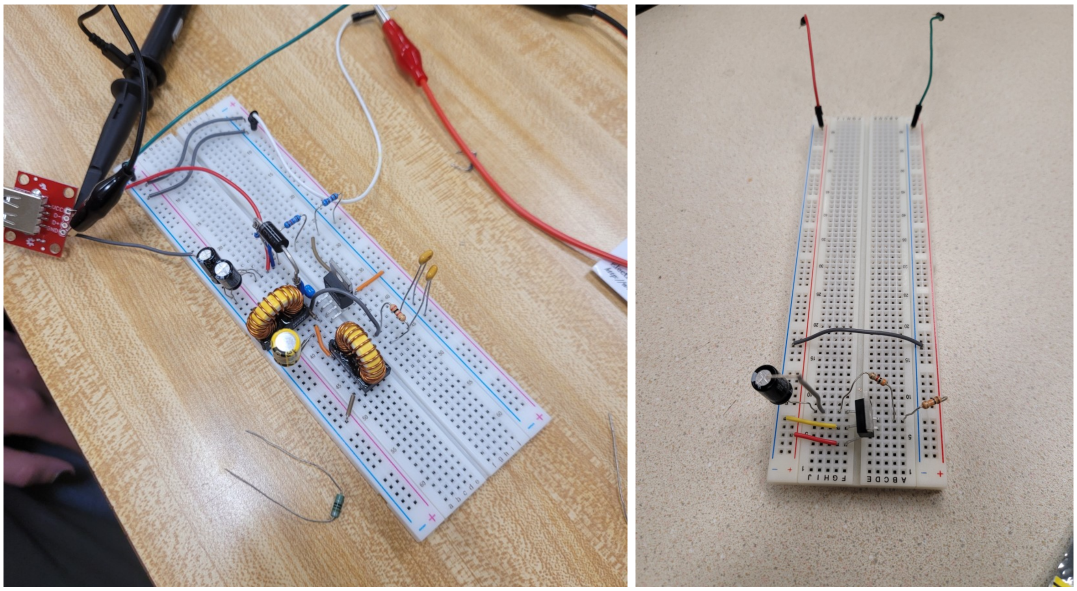

Figure 9: Stage 1 Prototypes (SEPIC left, Linear right)

4.2 Prototyping Stage 2

The second stage prototype retained the same basic design as stage 1, but all the components were soldered to blank circuit boards. In this stage we left the USB port in standard 500mA configuration while we were still changing out components. This was the first stage where we were able to test the AC input of our device with the hand crank. As expected, the test device charged within the USB 2.0 spec at 500mA in both AC and DC configurations [9]. Because we couldn’t comply with our switching regulators requirements using the parts we had on hand we continued with low current testing.

Stage 2 is also the first time we implemented our data display. The Raspberry Pi Zero W was now capable of displaying data in real time on a power vs time plot. The power electronics however lacked the onboard monitoring to communicate with the microcontroller at this stage. Monitoring and high current support would be added in the next stage.

Figure 10: Stage 2 Prototype

4.3 Prototyping Stage 3

The final stage of prototyping required the custom PCB, surface mount inductor array, and new low series resistance capacitors. This is the stage that tested the high current capability of our design. Different devices have different methods for detecting a high current power supply. Apple and Samsung Devices expect specific floating voltages on the data pins of a dedicated charging port, while most devices will draw additional current from any usb port with the data pins shorted together through a $< 200\Omega$ path (as per the USB battery charging standard [8].) This prototype included two high current modes of operation for both Samsung and Apple phones.

The Reference design we based our charger on is theoretically able to supply 1.5A (without the design changes we made to increase current output.) Theoretically our design can supply much higher current in buck configuration (up to 3.0A [2].) In testing of the final version performance was much better than previous iteration, but still had some room for improvement.

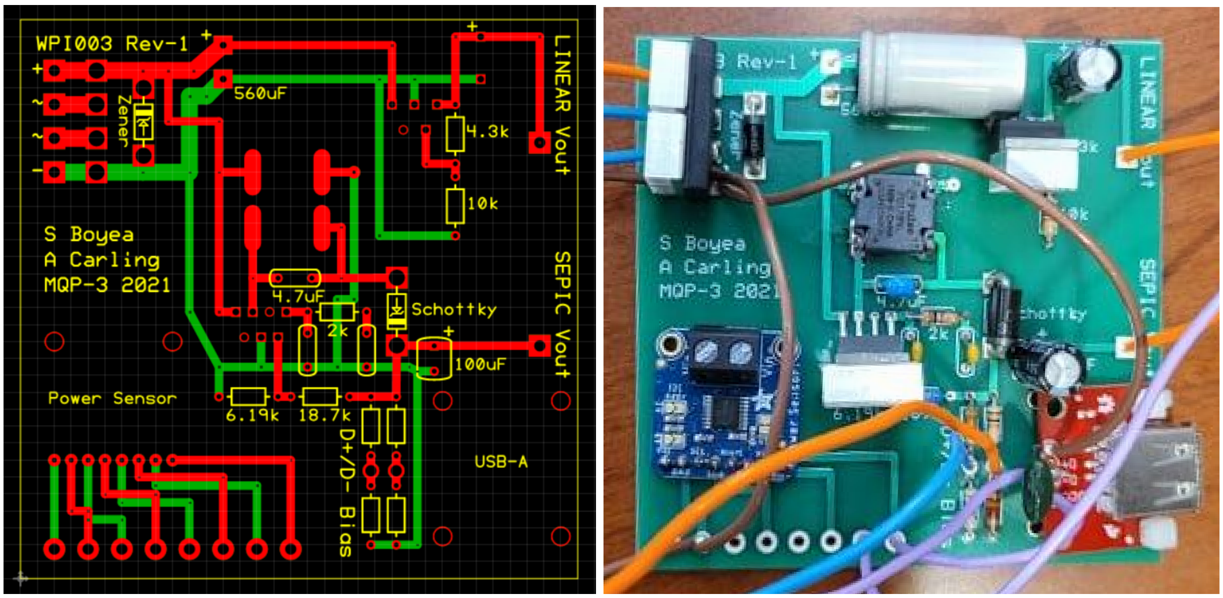

Figure 11: Custom PCB Layout and assembled prototype (missing I2C connectors)

The stage 3 prototype was also the first to integrate onboard voltage, current, and power monitoring. This prototype simply displayed a power over time graph using MatPlotlib, but delivered voltage, current, and power values are all available for use in other software via a simple circuit-python script.

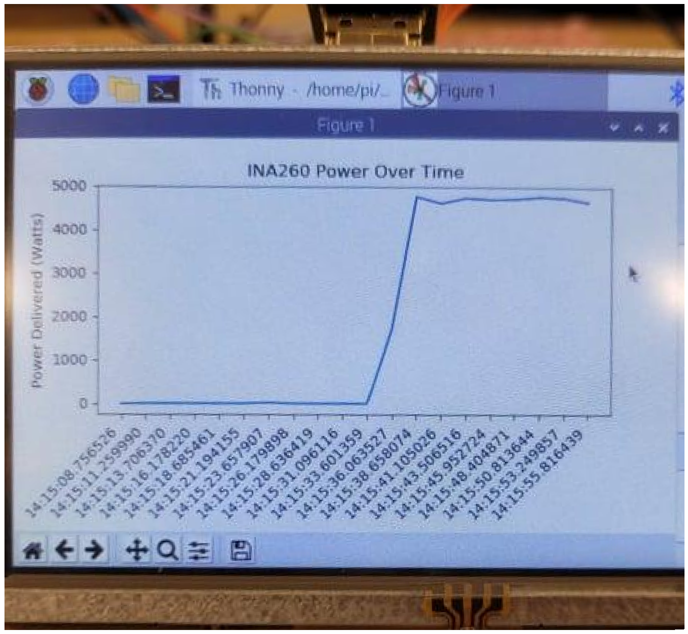

Figure 12: Power over time graph (Power is actually displayed in mW in this photo)

The last new feature added to the stage 3 prototype was some simple input protection. A 25V zener diode reverse biased across the power rails ensured no components received more than their maximum rated voltage. A new, larger input capacitor also helped to protect the sensitive components from voltage spikes. The user still needs to be careful not to use the linear regulator when a high voltage source is connected (for thermal considerations.) In a worst case scenario, a careless user may be able to cause a thermal shutdown on the linear regulator side of the circuit, but damage is unlikely even so.

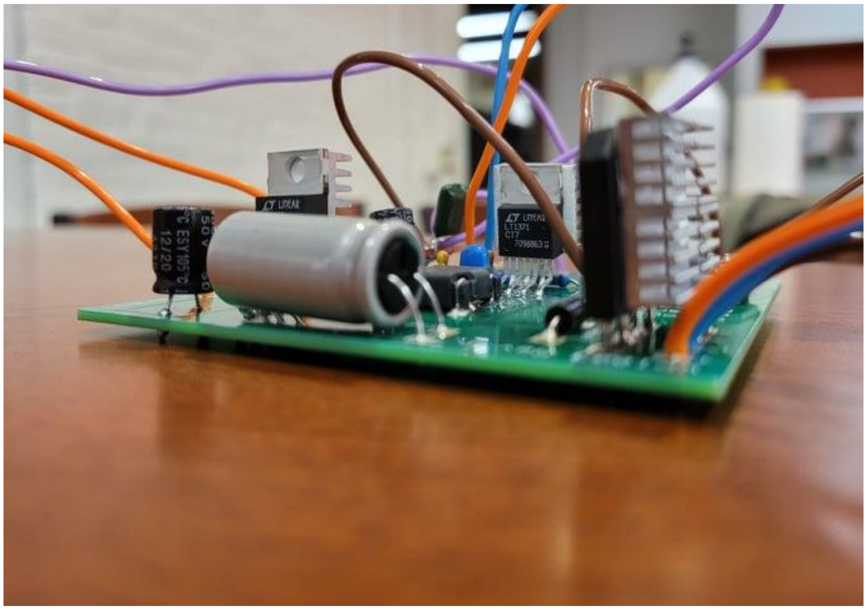

Figure 13: Final prototype side view.

4.4 Prototyping Results

Using the Stage 3 prototype, on the Samsung setting, the Motorola test phone typically drew between 700-1500mA of current (3.5-7.5W) depending on the input voltage that the switching regulator received. Running on the linear regulator, the phone drew a lower but more consistent 700-800mA (3.5-4W) at any input voltage above the minimum value of about 5.5V.

Results were very similar for a Samsung Galaxy Z Fold 2 that we tested using the same configuration. Performance was slightly lower overall, but very much within the expected range, especially for a phone with such a large and complex power system (Multiple batteries onboard because of its folding design.)

Overall, the performance still has room to be improved, and the device is yet to be tested with three of the four sources. However it has performed well in the worst case scenario and shows promise for being a substantial improvement over the current solution.

5 Recommendations

Although testing was successful and cell phone charging at a reasonable rate was achieved, there are several considerations that could improve prototype functionality. It is our recommendation that a different, Raspberry Pi compatible screen be utilized. The 5” LCD touchscreen display was capable of displaying the desired information to the user in graphical format. However, the low sensitivity of the touchscreen feature made interacting with the screen difficult.

We also advise that more ground mounting points are added to the PCB design for easier assembly. In the initial PCB design some needed ground connections were not included and wires were used instead to make connections. Specifically, there needs to be a mounting point to connect the Raspberry Pi ground to the board ground. Additionally there needs to be a ground mounting point to more easily ground the USB-A module.

Finally we recommend that the benefits of a third charging mode be explored, An additional voltage divider stage across the USB-A data pins would allow for this. Currently the design features a Samsung/Android charging mode with 1.2V across the data pins and an Apple charging mode with 2.7V across the data pins [10]. In our research, we discovered that an additional option to support even more device manufacturers is to short the data pins together. In other words, to directly connect them. We suggest that this option be tried and tested in future design iterations.

6 Conclusion

The prototype that was developed was able to meet all customer requirements and performed as expected. The design allowed for both AC and DC inputs ranging up to 25V and successfully generated an output capable of charging a cellular device. In addition to this, the power monitoring system that was designed was capable of displaying output power vs time in a graphical format. The addition of charging modes for Apple and Android devices served to ensure efficient cell phone charging regardless of cell phone manufacturer. The watertight housing that was customized for this purpose ensures the successful operation of electronic components in outdoor conditions. With all aspects of the design integrated and working successfully together, this power converter is sure to help future generations understand the energy that powers the world around them.

7 References

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[7] S. Hymel, "Graph Sensor Data with Python and Matplotlib", *Learn.sparkfun.com*, 2021

[8] T. Remple and A. Burns, “USB Battery Charging 1.2”, usb.org, 2010

[9] Tripplite, "USB Charging Explained | Tripp Lite", www.triplite.com, 2021

[10] obddiag, "USB charging without fear", Obddiag.net, 2021

8 Appendices

Included below is some supplemental material that will aid in the replication of the design that was developed.

Appendix A: Python Code

```
#WPI ECE MQP 003
#Samantha Boyea, Arden Carling
#10/12/2021
#Elements from example by Shawn Hymel (Sparkfun tmp102 example)

import time
import datetime as dt
import matplotlib
import matplotlib.pyplot as plt
import matplotlib.animation as animation
import board
import adafruit_ina260

#matplotlib.use('Agg')

# Create figure for plotting
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)
xs = []
ys = []

# Initialize communication with ina260
i2c = board.I2C()
ina260 = adafruit_ina260.INA260(i2c)

def read_power():
    power = ina260.power / 1000.0
    return power


# This function is called at 1Hz from FuncAnimation
# Formats and animates the real time power plot
def animate(i, xs, ys):

    # Add x and y to lists
```

```
    xs.append(dt.datetime.now().strftime('%H:%M:%S'))
    ys.append(read_power())

    # Limit x and y lists to 20 items
    xs = xs[-20:]
    ys = ys[-20:]

    # Draw x and y lists
    ax.clear()
    ax.plot(xs, ys)

    # Format plot
    plt.xticks(rotation=45, ha='right')
    plt.subplots_adjust(bottom=0.30)
    plt.title('INA260 Power Over Time')
    plt.ylabel('Power Delivered (Watts)')

# Set up plot to call animate() function periodically
ani = animation.FuncAnimation(fig, animate, fargs=(xs, ys),
interval=1000)
plt.show()
```

Appendix B: Parts List

Below is a list of part numbers of all of the components utilized in the design.

Circuit #1:

Description	Part Number	Purchased From
Bridge Rectifier	GBU4005DI-ND	DigiKey
Cap Alum 560uF	565-3811-ND	DigiKey
Diode Zener 25V 5W	1N5360BTPMSCT-ND	DigiKey
IC Reg Linear POS ADJ 3A	LT1529CT#PBF-ND	DigiKey
10K Resistor 5% Tolerance	N/A	N/A
3.3K Resistor 5% Tolerance	N/A	N/A

Circuit #2:

Description	Part Number	Purchased From
Inductor Array 2 Coil 15.7uH	P0178NL-ND	DigiKey
Cap Alum 100uF	399-6119-ND	DigiKey
IC Reg MULT CONFG 3A	LT1371CT7#PBF-ND	DigiKey
Cap Cer 4.7uF 25V	445-181709-ND	DigiKey
Res 18.7k Ohms 1%	18.7KXBK-ND	DigiKey
Res 6.19k Ohms 1%	6.19KXBK-ND	DigiKey
Cap Alum 470uF	1572-1750-ND	DigiKey
Schottky Diode 4W	N/A	N/A
10K Resistor 5% 0.25W	N/A	N/A
3.3K Resistor 5% 0.25W	N/A	N/A
43K Resistor 5% 0.25W	N/A	N/A
51K Resistor 5% 0.25W	N/A	N/A

Power Monitoring System:

Description	Part Number	Purchased From
INA260 Volt Current Power Sensor	1528-2955-ND	DigiKey/Adafruit
Raspberry Pi Zero WH	3708	Adafruit
DIY HDMI Cable Parts- Right Angle (R bend)	3549	Adafruit
DIY HDMI Cable Parts - Right Angle (L bend) Mini	3554	Adafruit
DIY USB or HDMI Cable	3560	Adafruit

Parts- 10cm Ribbon Cable		
5” LCD Touchscreen	Series RR050	Amazon
9” Micro-USB Cable	CERRXIAN	Amazon
Mophie Powerstation 3000mAh	N/A	Amazon

Other Components:

Description	Part Number	Purchased From
2-Layer ProtoPlus 2 Day Silver (RoHS)	N/A	ExpressPCB
Sparkfun USB Type A Female Breakout	1568-1300-ND	DigiKey
Switch Toggle SPDT 6A 125V	360-1801-ND	DigiKey
Conn Banana Jack	BKCT3134-9-ND	DigiKey