MOBILE MONITORING BOX FOR SOLAR

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Team No. 7

Table of Contents

Figures

Tables

1. Introduction

1.1 Objective

Photovoltaic systems will play a large role in the future; the decarbonized energy sector. Solar installations are projected to continue growing and the cumulative power produced will surpass 100 GW by 2021 [1]. Currently, the inverter systems that these panel arrays rely on include string/central, microinverters, or string with power optimizers. Microinverters and power optimizers make a system more efficient and mitigate the detriments that a lone, a poor-performing panel may have on the aggregate performance [2]. Popular microinverters, like those produced by Enphase, internally monitor and transmit data that is made available through their proprietary software [3]. Similarly, the top producer of power optimizers, SolarEdge, features module-level power electronics which monitor metrics that is sent through a built-in ethernet connection to be accessed through their monitoring server [4]. Although these modular options improve the system's efficiency and provide transparency in system failures or weaknesses, these installations involve extra infrastructure, come at a higher initial cost, and the data delivery is managed by the manufacturer's software. Without these devices, problems are experienced at the string level and localizing the issue can be difficult, if not impossible, without taking the string offline. The percentage of systems with the monitoring benefits of module-level power electronics is about 15% for residential and 35% for small non-residential arrays in 2018 [5]. The cost due to loss of energy production that an unmonitored system may face is the main factor in offsetting the extra initial costs for module-level power electronics [6]. If a monitoring system had minimal installation along with cheap and accessible data collection, then string inverter systems may benefit from its lower initial cost without the large risk for loss of energy production.

Our solution is a mobile monitoring device that can send direct measurements back to its user via Wi-Fi. The device centralizes the measurement components, which drives cost down but sacrifices monitoring resolution. The function of the tool essentializes data collection by reading only current and voltage values associated with an individual panel, DC or AC. Having data directly transferred over Wi-Fi avoids excess architecture and allows the user to have greater freedom with data analysis, rather than being bound by the manufacturer's software. Permanent installations would include a simple terminal block at each panel to measure the DC and AC values. Our goal is to lower the costs for a monitoring system by limiting resolution, simplifying the data set, and providing direct access to data analysis.

1.2 Background

AlsoEnergy's PowerTrack is an analysis and modeling platform for PV arrays [7]. However, there exists an overabundance of analysis tools and the program's subscription scales with system size. Our solution would supply only the fundamental data points necessary for system maintenance and places the responsibility and freedom with the user for analysis. The TS4 series, from Tigo, offers both retrofit modules and pre-installs that perform similar functions to our proposed device [8]. The optimization modules are comparable in price and operation to other power optimizers and their monitoring solutions use the PowerTrack Platform.

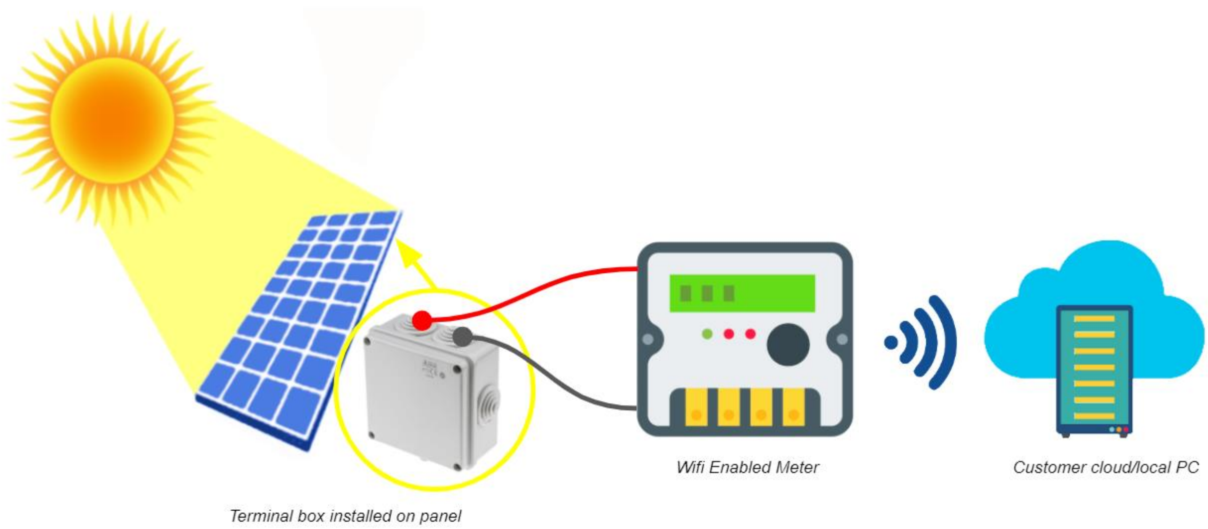

Figure 1: Visual Aid

1.3 High-Level Requirements

- Device must safely monitor voltage and current levels on load and line without significantly affecting performance.
- Device must transfer data packets through WiFi to a local PC
- Device must be durable enough to withstand reasonable outdoor weather conditions

2 Design

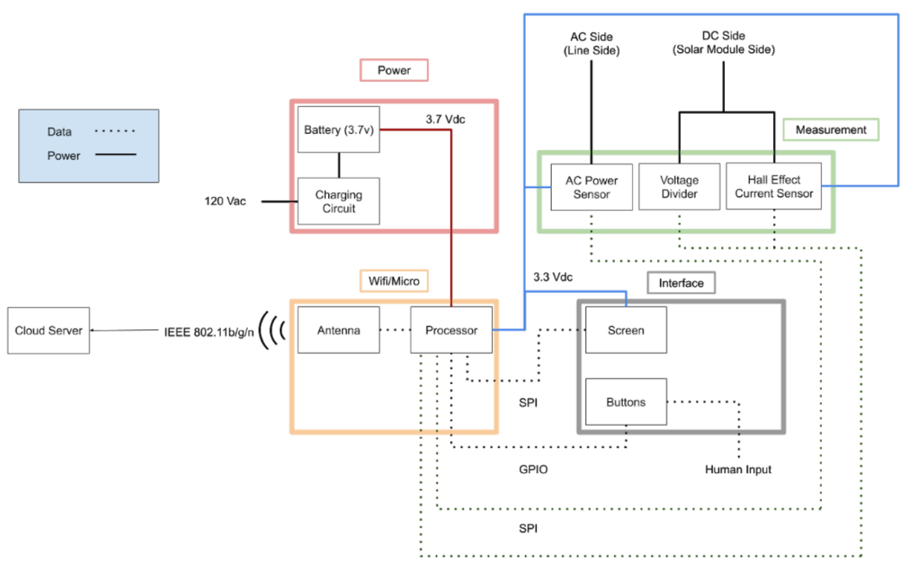

Figure 2: Block Diagram

There are 4 (5 if you include the terminal box) sections that allow this product to be accurate and easy to use. The power supply section provides the microprocessor with 3.3 V of power in order to run. The terminal box will connect to the photovoltaic system both before the inverter and after the inverter. The terminal box will do nothing to the PV system, but give us easy access to ports that can measure the voltage and current before and after the inverter. The measurement section will connect to the terminal box, and then go through protection, AC-AC conversion, and DC-DC conversion to match the ratings of the microprocessor. The microprocessor can only measure inputs of less than 1 V, and so the conversions will drop the voltage to be about .5 V. The microprocessor section will then display the data on the screen. The interface will then give the user the option to send the data and in that case, the processor will send the data over WiFi to a computer. The computer will have an interface that allows the user to view all the data collected.

2.1 Power Supply

The power supply is necessary to provide the microcontroller with the needed voltage to work. The power supply will run on a battery that will be rechargeable. The batteries' voltage will then be converted to the necessary voltage for the microprocessor using a buck converter.

2.1.1 Battery

The battery will be a 3.7V Li-Ion rechargeable battery. The battery will be charged using an external charging circuit. We will be wiring the battery to power the MCU. The specific battery that we will be using the Ultrafire FLB 18650. Included in the battery is a battery protection PCB that will protect the battery if the voltage over the battery is ever out of the range 2.5V - 4.25V. A set of 6 batteries will cost $7.95. That comes out to $1.325 per battery. Since there is a protection circuit built into the battery (and there will be more protection in the charging circuit), no extra external protection is needed.

Requirement	**Verification**
1. Rechargeable	1. Measure the battery's initial voltage. Then discharge the battery safely, measure the voltage. Then recharge the battery and re-measure the voltage over the battery.
2. Consistent 3.7V	2. Measure the voltage over the battery and see that it has a consistent 3.7V. Be sure to measure any noise created. (The noise level must be in the acceptable range of the MCU)

2.1.2 Charging Circuit

The charging circuit will be outside of the device. The circuit will take the line power from the wall and convert it to a waveform to charge the battery. There are two components to charging our battery, rectification of the 120Vac and overcharge protection of the battery. We will use a Smart Charger for a 3.7v battery, priced at $12.95. This charger is built to charge 3.7V Li-Ion batteries. It can detect and indicate when the battery is currently charging, done charging, and when it does not need to charge. The charger also prevents overcharging by preventing the charge from exceeding 4.2V. (Note: The charging circuit prevents the voltage from exceeding 4.2V and the battery's protection prevents the voltage from exceeding 4.25V, if one fails, the other can act as backup protection.) Given the ratings from the charger and the battery, the battery should take no longer than an hour to charge.

Requirement	Verification
1. A circuit that will safely charge the 3.7V battery over time	1. Once, the battery is discharged, it is no longer producing the voltage and current it is supposed to, the charging circuit resorts the battery to its original voltage (3.7V)
2. Charging stops once it is fully charged	2. When the battery is back to 3.7V check that the charger is indicated that it is no longer charging the battery.
3. Charging takes a reasonable amount of time to charge	3. Completely discharge the battery and then begin charging the battery while timing how long it takes to finish charging. (With the given ratings, it shouldn't take more than an hour)
4. Charging will not occur in unsafe conditions	4. If the voltage and current is ever at an unsafe value (above 4.2V) the charger will not work

2.2 Measurement

The measurement section interacts with the terminal box to collect the actual voltage and current from the photovoltaic system.

2.2.1 Terminal Box

The terminal box will provide access to the voltages and currents of the module while under load. It will be permanently installed on the panel at minimal cost in comparison to installing full measurement solutions. This allows measurement of the system without losing the power it generates and adds convenience for users.

While AC voltage/current and DC current measurement is possible through magnetic field interactions, out of circuit DC voltage measurement is currently developing and a delicate technology. The terminal box is a simple and rugged solution to this issue.

Our device leads will match those of the PV panels located on the ECEB building, so if users do not wish to use the terminal box, they can disconnect their system to measure DC voltage.

Requirement	Verification
1. Meets NEMA Type 6 standards to resist weather conditions throughout the year	A. Place anhydrous, color changing powder in case, submerge in water for 1 hour, check contents for signs of water B. Place in a box of small particulates (wood shavings, dirt, etc.), shake vigorously for 5 minutes, check for ingress C. Wet surface lightly with wet cloth, freeze overnight, repeat B, C

2.2.2 AC Power Monitoring (AC Sensing)

The power monitoring will measure the voltage and current amplitudes on the line side of the inverter. The AC sensing will be managed by Allegro's ACS71020 IC. This device has Hall-effect based current sensing and an input range of 0-30A. The voltage sensing occurs at a range of 275mV, a voltage divider circuit of four 1MOhm resistors scale the incoming line voltage across a calibrated sense resistor. At an expected RMS value of 120V, a low tolerance sense resistor of 4.7kOhm will be chosen. The peak voltage at the IC's input will then be rated at 199mV. Each of the 1MOhm resistors will dissipate a rated 0.9mW, which combined consumes far less than 1% of the panel's rated 425W generation.

The input signals are then converted to digital signals, that will communicate via an SPI protocol. The voltage levels of this digital signal may need further step down, which will be covered by another voltage divider. This reduced value is then sent to a protection circuit before it is sent to the microcontroller.

The current and voltage sensing is affected by temperature, but the IC includes an internal temperature sensor. The temperature readings then provide an input to the compensation logic.

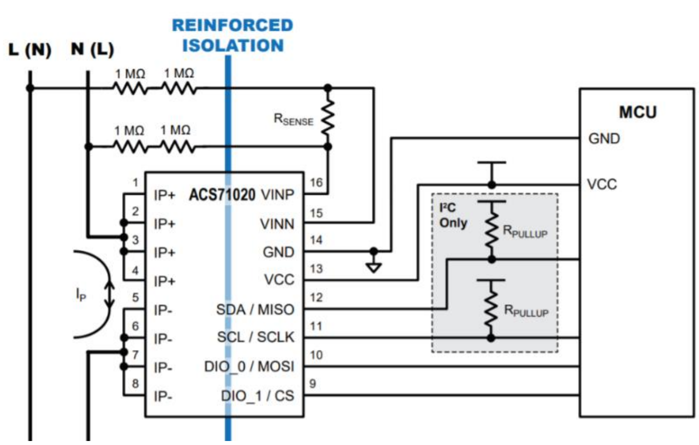

Figure 3: AC Sensing Schematic

Requirement	Verification
1. At rated line side voltage and current ratings of the inverter, the digital output will have a voltage that is less than 1V. 2. The power dissipation in the voltage divider's resistors will be considerably less than rated value.	1. Produce nominal currents that will occur pseudo-adjacent to hall effect-based sensor, verify negligible output current reading. Produce input linear and exponential signals for voltage, verify appropriate output shape in gathered data. 2. Test integrity of temperature compensation sensing and logic and the power dissipation with external temperature readings and performance measurements.

2.2.3 Protection Circuit

Our device will be interfacing with potentially dangerous voltage and current levels. To protect our circuits and users, varistors and fuses with be used to ensure that only nominal levels enter the main circuit. The varistors will be designed to help absorb transient responses into the microcontroller, under steady state the resistance will reduce in magnitude where the input is back to safe levels. Fuses will protect against input currents that exceed the tolerance of the microcontrollers digital and analog pins.

Requirement	Verification
1. Fuses rated to create an open circuit when current levels are too high 2. Varistors to block voltage transients and create open circuits with prolonged overvoltage conditions 3. Output of protection circuit does not exceed current or voltage ratings of microcontroller	1. Produce short circuit conditions to blow fuses. 2. Produce peaks above rated input of protection circuit to simulate transients. Ensure circuit returns to steady state conditions. 3. Measure output of protection circuit with oscilloscope during transient simulation.

2.2.4 DC Sensing Voltage Divider

When measuring the DC side of the Solar Module, the voltage will be dropped to a voltage significantly less than 1v. The rated operating voltage of the panel is 72.9V. As a preliminary calculation, a sense resistor of 33KOhm in series with 4 1MOhm resistors would scale the rated voltage to .597V and the rated open-circuit voltage to .7V. The power dissipation across the 1MOhm resistors will be about a third of a mW, which is much smaller than rated 425W of the panel. The resulting analog voltage is then sent to the microcontroller to be processed.

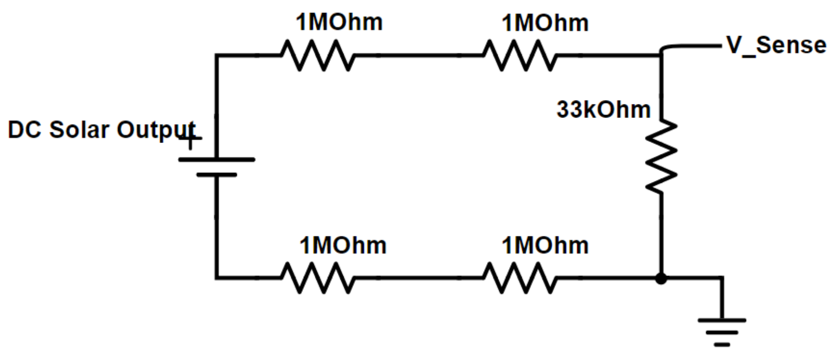

Figure 4: DC Voltage Sensing Schematic

Requirement	Verification
1. A circuit that takes the DC voltage, from the Solar Panel, and steps it down to less than 1V for the microcontroller 2. Power dissipation among resistors are low	1. Perform a DC sweep across input of circuit up to an output of 1V, compare results to voltage division scalar. 2. Measure current in network and heat of resistors after prolonged operation.

2.2.5 Hall-effect Based DC Current Sensor

A DC current sensor will be used to measure the panels output current and deliver that data to the microprocessor. The intended sensor will be Allegro's ACS722 series. This IC series is an Open Loop, Hall Effect-based current sensor. The rated operating current of the panel is 5.83A and the short circuit rating is 6.18A, so an input of up to 10A will be chosen. The primary conductor resistance for the input current is about 0.65mOhm, resulting in a power consumption of 22mW at nominal ratings. Thus, at a power generation of 425W, the DC current sensing will consume far less than 1% of power. The supply voltage is rated for 3.3V and will be connected to the appropriate, available bus. The output voltage is proportional to the input current, which can then be sent to an analog input pin of the microprocessor.

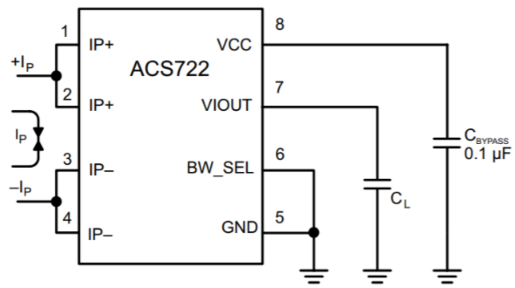

Figure 5: DC Current Sensing Schematic

Requirement	Verification
1. A circuit that takes the DC current, from the Solar Panel, and converts the signal to a proportional output voltage of less than 1V for an analog value to the microcontroller.	1. Perform a DC current sweep across input of circuit, compare processed data with input sweep. Verify possible adjacent currents are negligible in measurements.

2.3 Microcontroller + WiFi

The microcontroller converts the low power analog measurements to digital data. Additionally, it acts as the driver for the user interfaces (display/buttons) and runs the code needed for WiFi communication.

The Particle Photon was chosen for the Microcontroller + WiFi solution as it best matched our need for I/O pins in number and type, supports IDE's with deep WiFi libraries (Arduino), allows for external antennas (alternative to printed), and is sold at a competitive price point.

Requirement	Verification
1. Converts analog metrics to organized digital data with no more than 1% error	1. Connect a 500 mV DC signal to the MCU and a measurement device with < 1% error; confirm matching measurements to error limit
2. Communicates over WiFi using IEEE 802.11b/g/n	2. Using pre-built WiFi libraries, connect to 2.4 GHz WiFi network and send "Hello World!" to a terminal

2.4 User Interface

The user interface allows personnel to control the device through press buttons. The device can communicate with the user through the E-paper screen, displaying measurements, menus, and any other relevant information.

2.4.1 Electronic Paper Display (EPD)

The EPD will be used to convey the data that is measured from the PV system to the user. It will also have a menu to display possible commands such as when to send data over WiFi.

We will use a 2.13” EPD manufactured by Pervasive Displays. EFD’s have the advantages of extremely low power consumption (~5mW), low glare, and serialized communications (SPI).

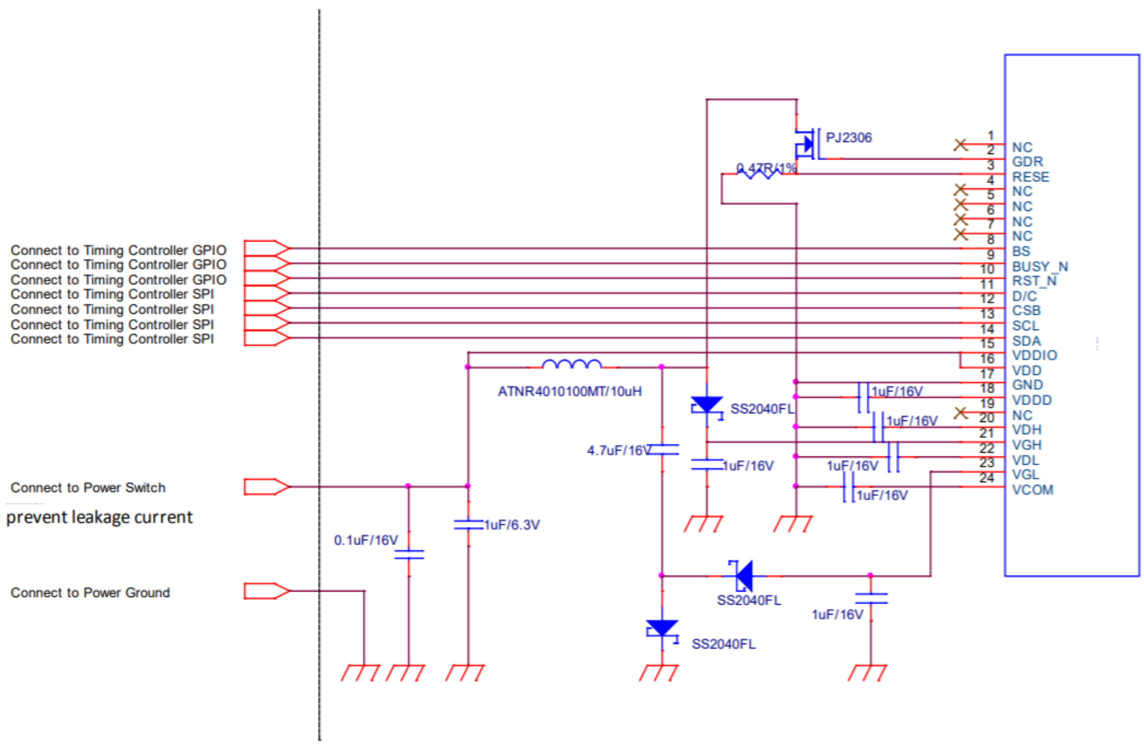

Figure 6: EPD Schematic

Requirement	Verification
1. Readable outside, under direct sunlight	1. Display Snellen Chart characters, holding screen outside at noon, ensure characters of at most ¼ of screen resolution (53 x 26) are readable
2. Readable from viewing angles up to 60°	2. Repeat above test with screen rotated 60°

2.4.2 Buttons

The buttons allow the user to communicate with the MCU to navigate menus and control the device. Waterproof and weather resistant sealant will be used to seal the openings made in the case to install the buttons.

Requirement	Verification
1. When installed, do not reduce the weather resistivity of the case	1. Repeat case verification testing with buttons installed

2.5 Tolerance Analysis

There are many elements of our design that are extremely important to the safety of our users and the PV system: circuit protection, battery monitoring, weather resistivity and more. However, the fundamental part of our design is measurement. Both our DC and AC voltage measurements rely on the implementation of a voltage divider, as seen in Fig. 6 below**.**

We will process our voltage data read across the sense resistor using the relation:

$$V_{sense} = \frac{2R + R_{sense}}{4R + R_{sense}} \times V_{line} \quad \text{(Eq. 1)}$$

This clearly marks the resistors as the key elements in possible error. Although analysis could be performed mathematically, it is simple to model this system in LTspice and increment the resistor values, observing the change in voltage across the sense resistor.

First, we can analyze the larger resistors. Performing a short transient simulation with DC voltage (no reactive elements so this effectively models AC as well), we can alter the resistor value by 1% and observe the relative change in the voltage. Note that it doesn't matter which or how many of the large resistors have error, only the net error. Then we can repeat this simulation, this time altering the sense resistor. This leads to the relations:

$$1\% \text{ Change in } R \;\Rightarrow\; 0.00031\% \text{ Change in } V_{sense}$$

$$1\% \text{ Change in } R_{sense} \;\Rightarrow\; 0.166\% \text{ Change in } V_{sense}$$

This indicates that the sense resistor is the key element in determining precision. To maintain error <1%, the sense resistor needs to have tolerance <6% which influences our purchasing options.

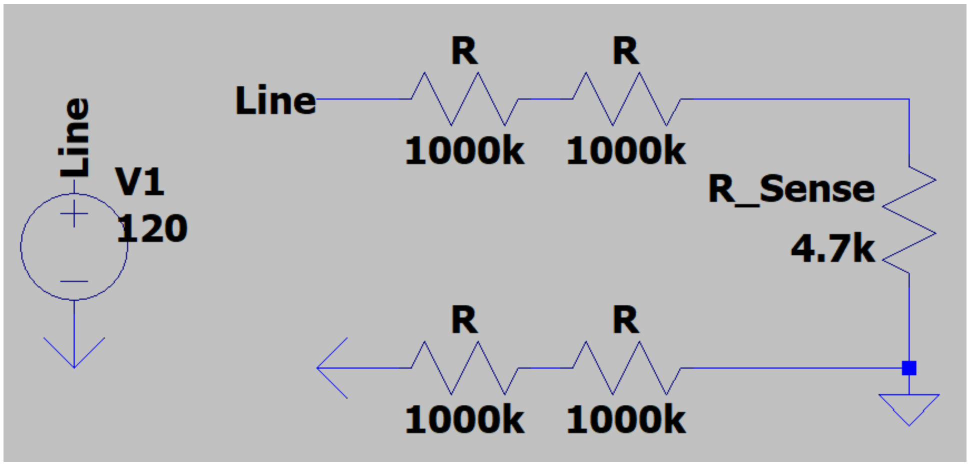

Figure 7: Voltage Divider

2.6 Physical Design

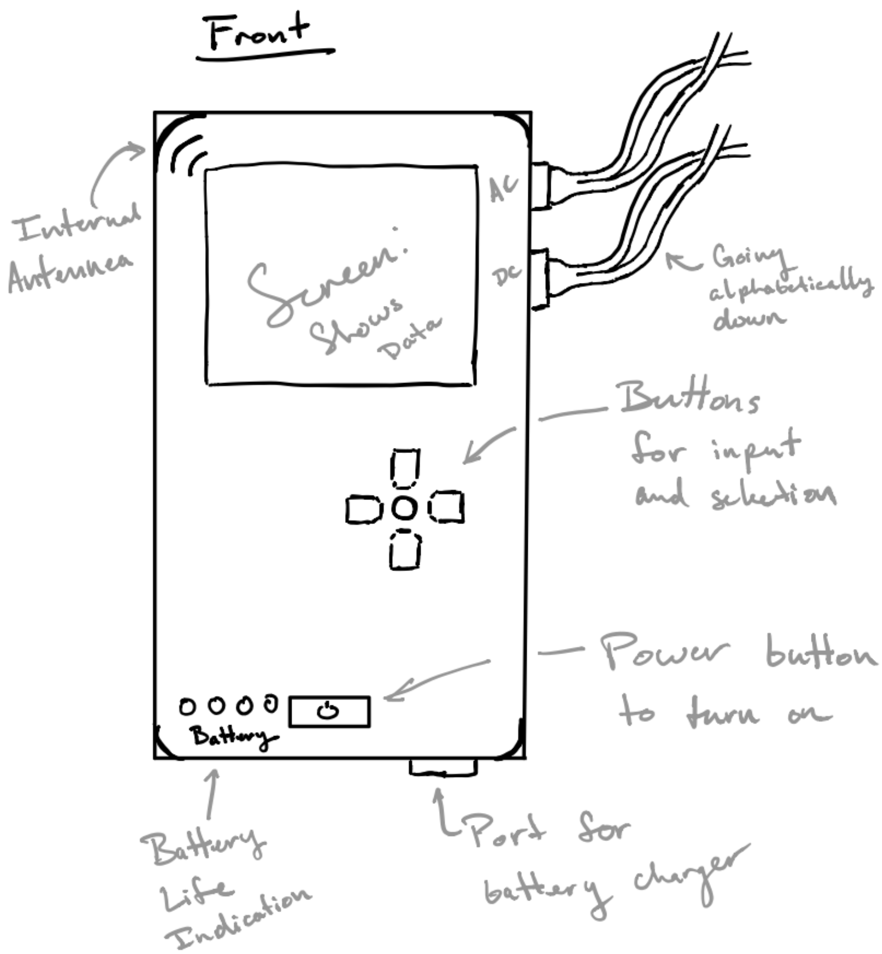

Figure 8: Front View of Physical Design

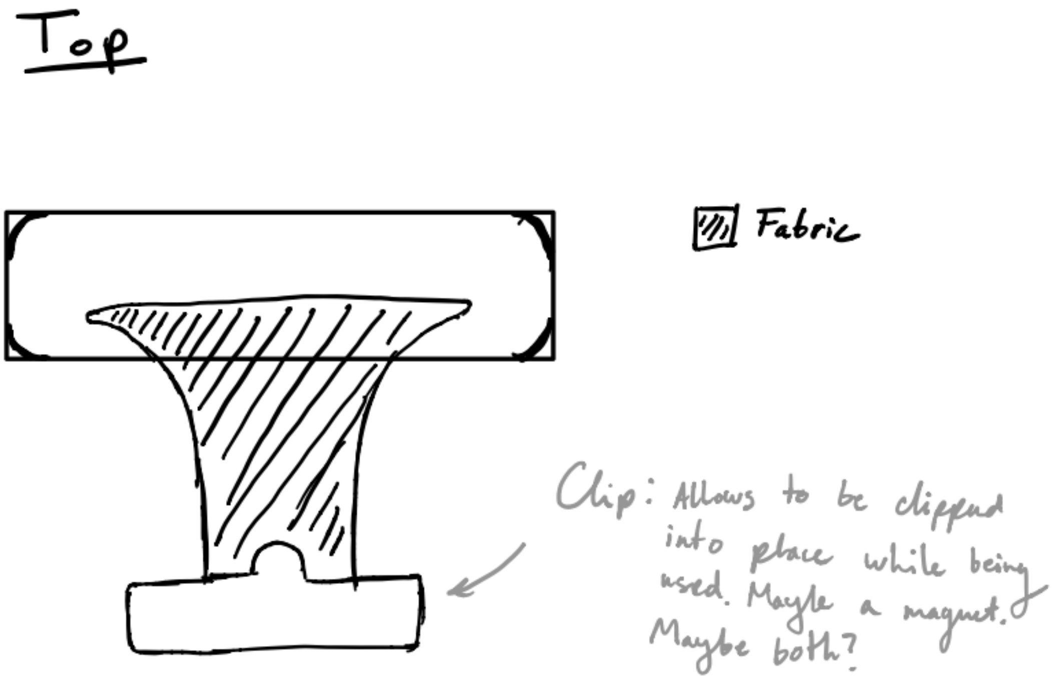

Figure 9: Top View of Physical Design

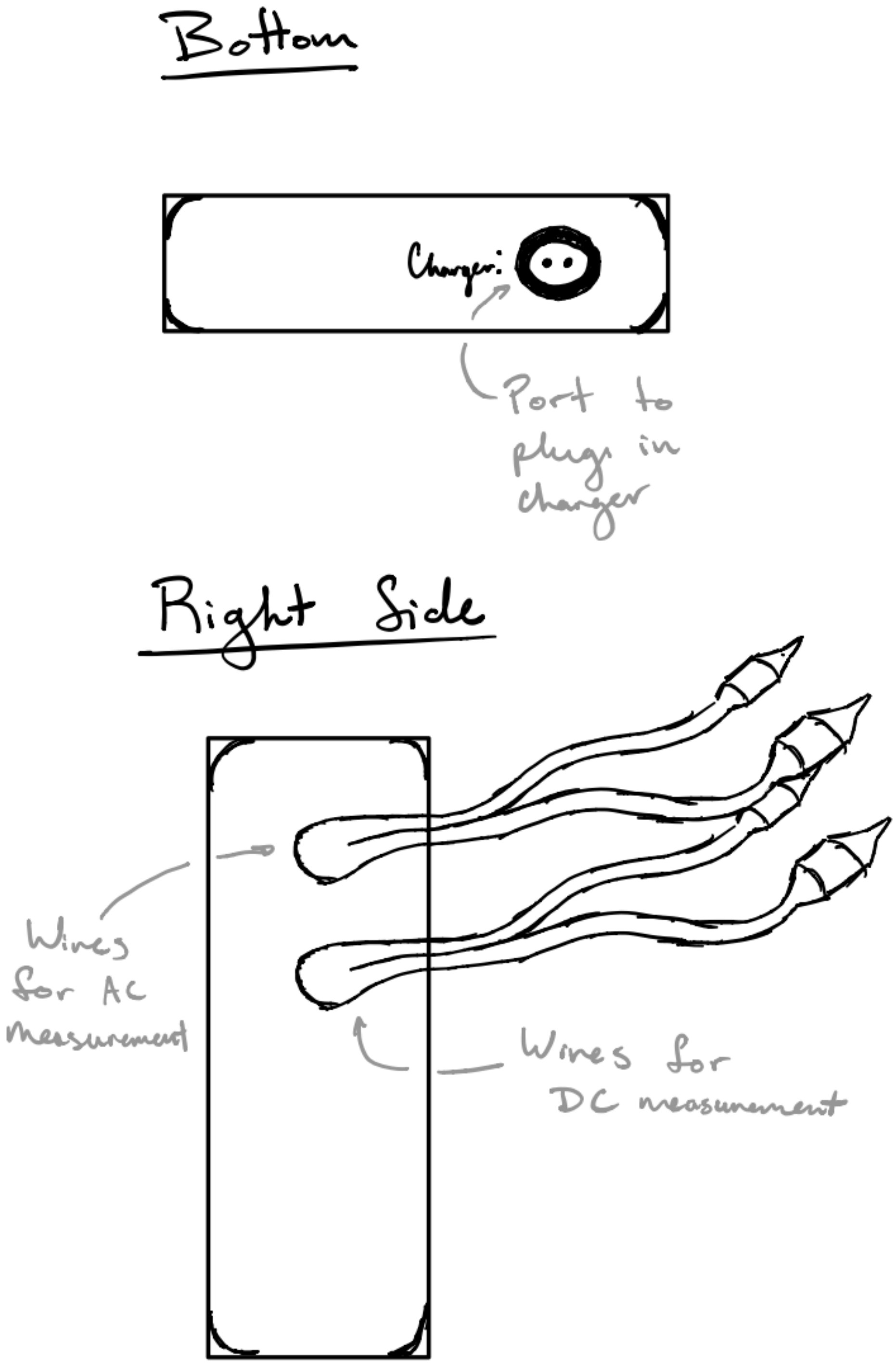

Figure 10: Right and Bottom View of Physical Design

3 Cost

We can estimate our labor costs assuming roughly 10 hours of work per week (2 hours per day, standard work week). The current average salary for an entry level electrical engineer in Illinois is $54,713.00 or roughly $23.30/hr [9].

$$23.30\frac{\$}{hr} \times 10\frac{hr}{wk} \times 16\,wk \times 3 \;=\; \$11{,}184$$

Part	Cost (Inv.)	Cost (Bulk)
MPU (Amazon, Particle Photon)	$19.00	N/A
E-Paper Display (DigiKey, E2213CS091-ND)	$14.34	$7.78
Enclosures + Buttons (Handheld + Terminal Box)	$20.00	$10.00
3.7V Li-Ion Battery (Pack of 6)	$7.95	N/A
Smart Charger (AA Portable Power Corp)	$12.95	N/A
AC Power Sensor (DigiKey, ACS71020)	$5.09	$4.49
Current Sensor (DigiKey, ACS722)	$1.97	N/A
TOTAL:	$81.30	$74.16
WITH LABOR:	$11272.16	$11258.16

Table 1: Costs

4 Schedule

Dates	Cole	Joe	Matthew
10/7 - 10/13	Begin developing code for WiFi communication	Design DC Voltage Divider and implementation of sensing ICs in Eagle	Design PCB Power Supply module
10/14 - 10/20	Begin developing E-paper screen driver code	Develop code for processing digital output of sensing ICs	Test Battery Charging Circuit
10/21 - 10/27	Test E-paper screen w/ MCU for basic measurement display	Include protection circuit and test the output of Measurement, prepare it for MP	Integrate the Battery + Charging Circuit with the DC/DC convert use to power the MC
10/28 - 11/3	Develop GPIO code architecture for measurement data	Perform individual tests for Measurement section.	Test the power supply module separately from the other modules (Debug)
11/4 - 11/10	Begin testing integration of measurement modules w/ MCU module	Integrate Measurement section with MCU, handle processing of measurement signals.	Integrate Power Supply Module with MCU module
11/11 - 11/17	Finish full integration testing with other modules	Finish full integration testing with other modules	Finish full integration testing with other modules
11/18 - 11/24	Develop general data organization/analysis program (MATLAB)	Develop data analysis program	Collect data on the performance of the power supply module
11/25 - 12/1	Fall Break	Fall Break	Fall Break
12/2 - 12/8	Final Demo	Final Demo	Final Demo

12/9 - 12/15	Final Presentation	Final Presentation	Final Presentation

Table 2: Schedule

5 Safety and Ethics

5.1 Safety

Our solution is intended to be operated by personnel in normal outdoor weather conditions. This creates many potential hazards in terms of damage to equipment and/or operators.

Foremost, our terminal box connects directly to the AC side of the inverters for the panels. In some systems, this could be directly tied to the supply side of a facility's utility connection. This requires that we follow strict guidelines created by the NEC, specifically those in NFPA 70. Section 110 covers general requirements for electrical devices, but our project will need to adhere to more strict regulations in sections 690, 691, and 705 which provide relevant standards for grid-tied PV installations. Section 690 covers circuits connected to PV installations (690.8.A.2), over-current protection (690.9), disconnects (690.15), wiring (690.31), and grounding (690.41). Section 691 covers additional requirements for large scale PV installations. Section 705 covers general grid-tied connections [9]. While each PV system may not require adhering to all of these standards, the versatility of our solution requires that we follow the strictest practices.

Our design will meet these standards by attention to detail in the PCB design. Trace widths will be wide enough to handle higher current levels on inputs from the panel and inverter. Special care will be taken in trace buffers (the distance between two traces) to avoid arcing from high voltage potentials. Consideration will also be made in plane buffers (distance between the ground plane and top plane for example) to avoid arcing in the vertical dimension. Properly rated fuses and varistors will be installed to protect against overcurrent and transient conditions respectively.

Furthermore, both our enclosures (monitoring device and terminal box) must be able to withstand weather conditions. The enclosures must meet at least NEMA Type 3 specifications, with the terminal box requiring the strictest standards, Type 6 or better. These specifications cover outdoor enclosures and their resilience to water, ice, and particle ingress [10].

5.2 Ethics

Our design should follow the Ethical Engineering Code proposed by the IEEE council. Most notably, #9: "to avoid injuring others, their property, reputation, or employment by false or malicious action.'' Following the above safety standards will assist us in making sure our solution is safe for personnel handling and equipment installation, but we must consider the safety of persons and property with each device element. This means performing testing for worst case conditions and always assuming the worst-case scenario, as in our verification testing for the enclosures. Additionally, since our device collects and transmits data, we must adhere to #5 and #6 by assuring that our data is reliable and improves the development and use of PV installations [11]. It will be difficult to prove our data improves PV installations in the timeframe of the course, but we are assuring <1% error in our measurement data.

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