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AC Power Monitoring System

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AC Power Monitoring System

Abstract

Motivated by high energy costs, people and organizations want to cut back on their energy consumption. However, the only feedback consumers typically receive is a monthly bill listing their total electricity usage (in kWh). Some companies have begun developing systems that allow households and organizations to monitor their energy usage for individual circuits. Available systems are expensive so a CU engineering senior design team has designed, fabricated, and tested a system for use at Cedarville University. The AC power monitoring system has the ability to measure energy consumption for each individual circuit in the breaker panel, store the data, and then provide the user with visual feedback on energy usage behavior. The basic system provides the proof of concept for future senior design teams.

After more testing is completed, further development of this product will be needed by other senior design teams. Eventually, this energy monitoring system could be expanded to include larger loads such as HVAC systems and refrigeration units. It is also envisioned that future projects might be able to provide the user with suggestions for changing and improving energy usage behavior. Failure prediction of equipment on individual circuits could also stem from this initial project. For this project, it has been clearly shown that the concept is feasible, expandable, and cost-effective.

Keywords

Power, power monitoring, energy, energy efficiency

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Cedarville University Senior Project: Building an AC Power Monitoring System

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Introduction and Background

To consumer and commercial users alike, electricity usage is often only understood as a dollar amount to be paid each month. However, as the world becomes increasingly connected, users often desire to have a more detailed understanding of how they consume energy. On Cedarville University's campus, breaking down exactly how energy is being used can be difficult. For our project, we've chosen to address this problem by providing a solution to monitor individual circuits in a breaker box. This will be a helpful step because users will have better access to knowing how much energy they consume. We are working with Jeff Cunningham, the Utilities coordinator at Cedarville, to prove that we can provide a custom and inexpensive solution to this problem. We are using the Chemistry building as the testing ground for our project.

Our product is not an entirely new idea. There are commercially available systems made by companies like Neurio and Veris Industries that accomplish this goal. However, these systems can be quite expensive, and they only have the ability to monitor two to three circuits at a time. We have made a solution that costs less while providing expanded functionality. The basic system we are developing will monitor every circuit within a single breaker box and then display collected data on a cellular application. To accomplish this task, we will be taking advantage of a few different pieces of technology, such as Current Transformers, PIC Microcontrollers, and a Raspberry Pi. All of these pieces will come together to create a fully functional system.

After our basic system is installed, we hope to encourage other senior design teams to further develop this product. Eventually this energy monitor could be expanded to include larger loads, such as HVAC systems and refrigeration units. We also envision that future projects might be able to provide the user with energy behavior suggestions that will improve efficiency. Automation and failure prediction could also stem from this initial project. Thus, our main goal is to prove that the concept is feasible, expandable, and cost-effective.

Project Specifications

After meeting with our advisor and our customer, we established a set of specifications for our project to create feasible outcomes as well as develop a manageable scope for the project. After deliberation and multiple modifications, the following specifications were developed:

- System
    - The system must be safe to install and operate.
    - Thirty individual circuits must be monitored for their energy consumption.
    - Energy consumption data must be displayed to the user in an organized and understandable manner.
    - The system will be installed on a circuit breaker box in Cedarville University's Chemistry Lab Building.
    - Any user should be able to install the system with simple instructions.
    - The system should be easily mounted on the wall next to circuit breaker box.
- Safety
    - Direct connections to any active part of the breaker panel must be fully enclosed and electrically isolated from the rest of the system.
    - The voltage signal coming from the breaker box must be stepped-down to the monitor.
    - Current transformers should be non-invasive to avoid disconnecting wires within the breaker panel.
    - Current transformers must have voltage protection built in to avoid high-voltage open circuits on their output.
- Power
    - All power must come either from the two 120-V 60-Hz outlets that are inside the circuit breaker box, or through a direct connection to the bus bar.
        - The Raspberry Pi should be powered by its supplied AC-DC converter, so it takes one outlet.
        - The other outlet must supply power for the rest of the system, as well as be the monitored voltage signal.
    - Positive and negative supply voltages must come from the same source.
        - PIC supply voltage: +5
        - Operational Amplifier positive supply voltage: $+3.5 < V_{cc} < +18$
        - Operational Amplifier negative supply voltage: $-3.5 > V_{cc} > -18$
- Calculations
    - Our system must be able to calculate the following information about each circuit:
        - Instantaneous Current
        - Instantaneous Voltage
        - Instantaneous Power

        - Total Energy Consumption
        - Power Factor
- Data Acquisition
    - Current Monitoring
        - Our system must have the monitoring capability of up to thirty circuits.
        - Each circuit can have a maximum of 20-A based on the fuses in the breaker box.
        - Device must be unobtrusive, meaning no wires should have to be disconnected from the breaker box to install the system.
        - Device must also fit comfortably within the circuit breaker box.
    - Voltage Monitoring
        - The device must have the complete voltage monitoring capability for one breaker box.
        - 120-V supplies will be the only voltage monitored.
        - A step-down transformer must be used to capture the voltage waveform, creating a safe voltage level to measure.
        - The device must not leave 120-V circuitry exposed.
    - Waveforms
        - Both current and voltage signals must contain full-wave signals.
            - Accounts for dissymmetry of any signals.
        - Waveforms must be accurate to +/- 2%.
- Circuit Protection
    - The PIC Microcontroller must be protected from any signal outside of its signal input range.
        - Both current and voltage signals must be clamped under 5.3-V.
        - Both current and voltage signals must be clamped above 0-V.
- Filtering
    - Noise above 100-Hz must be filtered out of each signal.
    - Any RC delay constant must be consistent between voltage and current signals.
- Analog to Digital Conversion
    - Uses a PIC Microcontroller to accurately convert thirty current signals and two voltage signals from analog to digital.
    - Sample at a rate high enough for an accurate conversion.
- Printed Circuit Board
    - Must be under 60-in^2.
    - Should be easily reproducible for scaling purposes.
    - Does not have to be all on one PCB.
    - Should be easily mountable into data acquisition unit.
- Packing and Sending Data
    - Uses a Raspberry Pi to aggregate the digital data.
    - The Pi should also be responsible for performing the power and energy calculations so the PIC can focus on A/D conversion.

    - The Pi must be able to send information to the internet via Wi-fi or Ethernet connection.
    - Information should be sent to the internet once every five minutes to avoid overloading our data storage.
- Backend
    - Uses a third-party backend known as a service (BaaS) so that we do not have to focus on creating our own server to store data and handle queries.
    - Be able to store power and energy data for the past six months online.
    - Select a backend that can be the intermediary between the Raspberry Pi and the mobile application.
- Mobile App
    - Displays information for the user in an iOS mobile app.
    - Home screen must contain basic information:
        - Real-time instantaneous power
        - Real-time voltage level
        - The day's energy consumption
        - Energy cost
            - Based on users' energy price input.
        - Have the ability for the user to name individual circuits.
        - Shows power data on a graph with respect to time.
            - For the entire breaker box
            - For each individual circuit
        - Be able to show long term energy consumption.
            - Daily, weekly, thirty days, sixty days, ninety days, six months
            - For the entire breaker box
            - For each individual circuit
- Documentation
    - Provides circuit board schematics.
    - Provides wiring diagram.
    - Provides data acquisition software code.
    - Provides iOS app development code.
    - Provides system installation procedure.

Constraints

We have developed the following constraints based on budget, time, or safety factors. These issues will force us to make certain design decisions:

- Limited to breaker boxes with 120-V bus bars and 20-A breakers.
    - Keeps the project cost reasonable.
    - Makes the environment safe for us to work in.
- Limited the system to one breaker box containing ten circuits.

  - We are deriving this requirement from the number of circuits in the Chemistry Building that Jeff Cunningham recommended we monitor.
  - We are limiting the number of circuits keeps the project cost reasonable.
  - This allows for proof of concept to be the main focus.
  - Our final design will be easy to duplicate in the future so that more circuit breaker boxes can be monitored.

Engineering Design

To meet our objectives and specifications, we have developed the following design for our project. Figure 1 depicts the analog portion of our system, while Figure 2 depicts the digital portion.

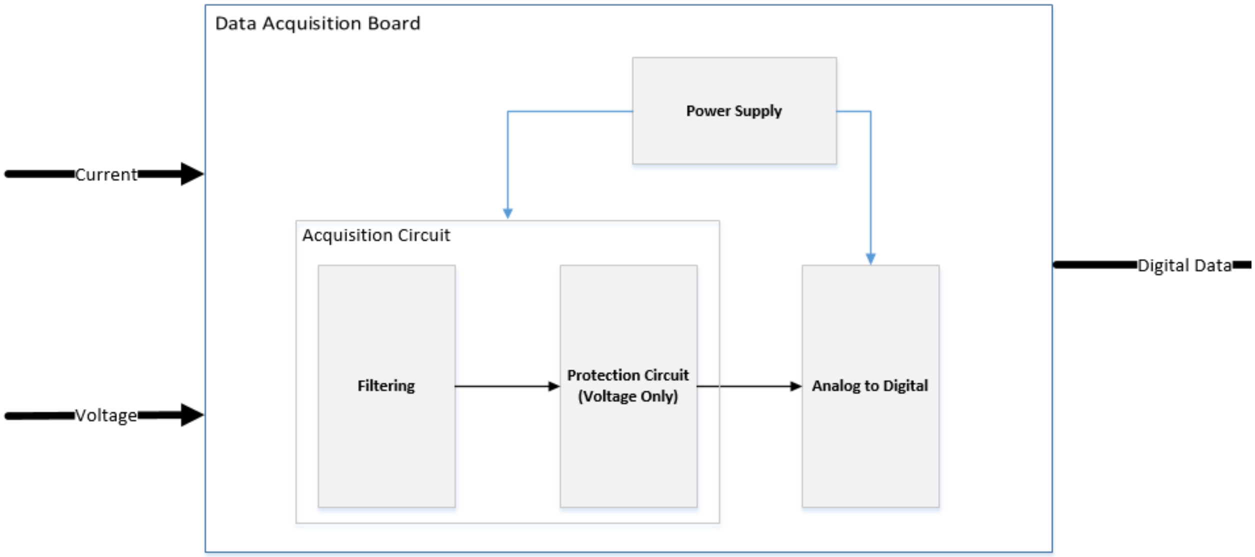


Figure 1: Analog Design

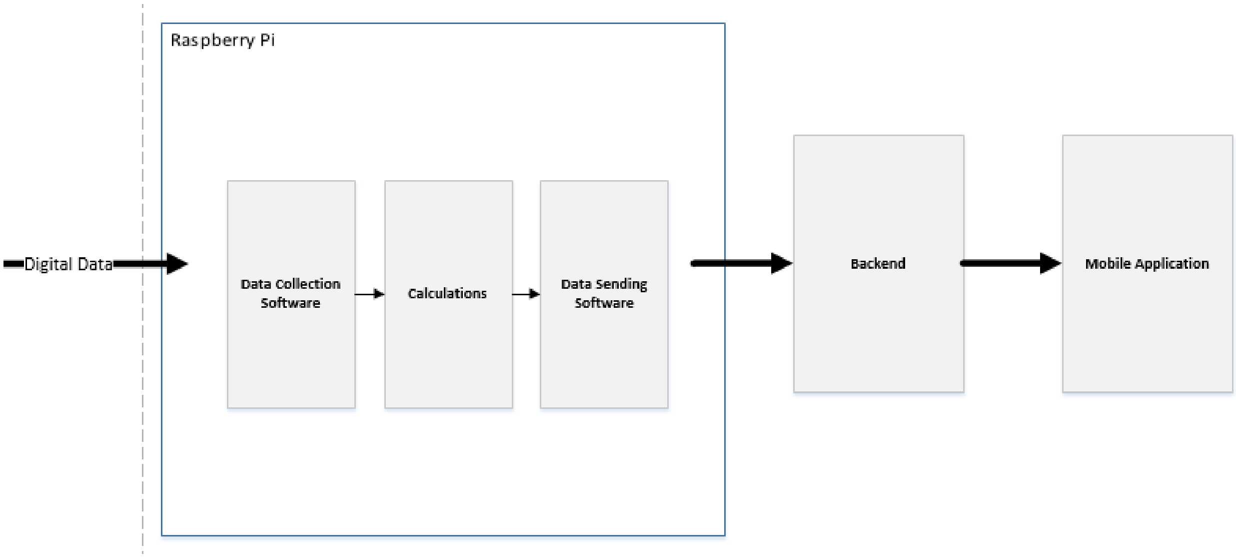


Figure 2: Digital Design

The system is broken up into the following subsystems:

- Power Supply
- Current Acquisition
- Voltage Acquisition
- Data Acquisition Board
  - Acquisition Circuit
  - Filtering
  - Circuit Protection (Voltage only)
  - Analog to Digital Conversion
- Calibration
- Raspberry Pi
  - Calculations
  - Sequencing
- Backend
- Mobile Application

This sections will look at each of these in detail, indicating any design decisions as well as rationale for these decisions.

Power Supply

The entire system is powered from 120-V, 60-Hz connections. Due to specifications, we powered the Raspberry Pi using its own AC - DC converter, which allowed us to focus on the more pertinent parts of our project. Other than the Pi, we still needed to power our acquisition circuit and the PIC microcontrollers. The printed circuit board is powered by one supply and contains sixteen acquisition circuits, fifteen current, and one voltage, as well as one microcontroller.

This supply comes from a voltage transformer with connections that can be inserted into a standard, 120-V, 60 Hz power outlet. By doing this, we can conveniently use the voltage transformer for voltage acquisition as well. The acquisition circuit, which will be explained later, needs a positive and negative supply voltage. In order to obtain a two-sided supply, a diode bridge configuration has been implemented off the center-tap of the transformer. These positive and negative voltages are rectified to +6.2-V, +5-V, and -5-V DC by linear regulators and capacitors. The power supply circuit can be seen in Figure 1 of the system schematic diagrams' section.

Linear regulators were chosen because of their price and simplicity. They have the potential to be less efficient than buck converters, but their operating conditions were chosen to allow for minimal waste heat. The specific linear regulators purchased were chosen based on their current ratings. By testing the acquisition circuit as seen in appendix Figure 5, we knew each operational amplifier, containing two channels, would draw about 4-mA. Multiplied by the eight op-amps that is 32-mA, the 100-mA regulators we chose are sufficient. The only regulator that is pushing its power limit was the +6.2-V, but that was easily taken care of with a heat sink. The voltage transformer was then selected to supply all three regulators, as it is rated at 300-mA and 20-V.

Current Acquisition

The amount of current being drawn by each circuit in the breaker box is required to calculate power and energy consumption. There are multiple ways to measure current in a circuit, so the project specifications and budget were considered when choosing which method would be the best. We required that the current acquisition device must be unobtrusive. Therefore, none of the energized wires in the circuit breaker box being monitored can be disconnected. This rules out hall effect sensors and solid-core devices; however, split-core devices were still an option. These devices have a hinge and can be clamped around wires without disconnecting them.

The decision came down to either split-core current transducers or split-core current transformers (CT's). Current transducers sense AC current and convert it to a low-level DC voltage value, corresponding to the amplitude of the current signal. This is beneficial in that it has a safe output voltage level and is easier to implement in software for ADC than an AC signal. However, it was desired for the AC waveform to be monitored, so that power factor calculations and power calculations could be more accurately measured. Current transformers step down the current from a primary to secondary winding, allowing the current to be monitored to maintain a relatively low, safe current level. The only problem with these is that they can produce dangerously high output voltages if unloaded, but the CT we purchased protects against this.

The CT we decided to go with is the SCT-013-xxx Series, which is seen on the data sheet in Figure 6 of the appendix. They are split-core devices, and they have a built in burden resistor for high voltage protection. Rated current values range from 5-A to 30-A and are accurate from 10% - 130% over their rated current, so we can measure down to 0.5-A and up to 39-A. Lastly, the SCT Series comes with a standard 3.5-mm output jack, which could easily be broken out with an adapter onto our data acquisition board.

We tested these CT's in order to characterize their behavior. To produce up to and greater than 39-A, we took advantage of the transformer's action. By wrapping multiple turns as seen in appendix Figure 7, we created a multiplication factor that raised approximately 1-A up to whatever value we needed. This test data is plotted in Figure 8 of the appendix, showing the extremely linear response and high R^2 value of the SCT-013-015 CT. The SCT-013-030 and SCT-013-005 have similar responses.

Voltage Acquisition

The other information needed to calculate power is voltage, so we acquired that signal as well. In order to do this in a safe manner, our system needed to be able to step down the acquired voltage from about 120V at the breaker panel. The primary side of the transformer connects to a regular receptacle outlet, as explained in the power supply section. The step down of voltage is accomplished by a 6-VA transformer that induces a voltage of 20-V on the secondary terminals. This voltage supplies the regulators that are used to power various components on the Data Acquisition Board, and also serves as the voltage signal we need to capture.

Depending on the building in which a circuit breaker panel is installed, half the breakers are fed from one bus bar and the other half are fed by a second bus bar. In residential buildings, these bus bars are both at 120-V and 180-degrees out of phase. Commercial buildings, however, have two 120-V bus bars that are 120-degrees out of phase. To account for this, we determined that two voltage acquisition circuits are necessary. For a full system, two PCB's are to be fabricated, identical to one-another, with the ability to monitor 15 channels of current and both channels of voltage on each board.

Acquisition Circuit

For the circuit that acquires the current and voltage waveforms, we had to refer to our specifications. The goal of this circuit is to transform the signal into one that can be used as an input to the PIC microcontroller. The PIC has an input range of 0-V to 5-V and we wanted to take full advantage of this range for A/D resolution. We also wanted to account for any dissymmetry in the voltage and current waveforms, so we could not simply rectify the signals. Lastly, we needed to be able to filter any noise above 100-Hz.

The circuit we developed to meet all the stated requirements was a simple inverting amplifier with a DC offset, which can be seen in system schematic Figure 2. Gain is easily adjusted using this equation.

$$A = \frac{-R_2}{R_3}$$

A 2.5-V volt DC offset is also added to the response through a voltage divider. One voltage divider will add the DC offset to all 16 channels on the PCB, so they will all be the same. This offset can also be fine-tuned by picking resistor size to make sure we have close to 2.5-V. The transient response of this circuit is shown in Figure 9 of the appendix. Lastly, the acquisition circuit also includes an active low-pass filter, which will be explained next.

Filtering

Our specifications call for a 100-Hz low-pass filter to limit the amount of high frequency noise in our signals. This was done conveniently in the acquisition circuit by adding a capacitor in parallel with the feedback resistor on the op-amp. By adjusting the value of this capacitor, we were able to obtain a cut-off frequency of 100-Hz, as seen in the LT Spice simulation of Figure 10. We were also careful to make sure the RC time constant would not hinder the accuracy of our waveforms. There is a slight delay in the signals, but because we are using the same acquisition circuit for current and voltage, this delay will be the same, within the tolerance of the resistors and capacitors.

Circuit Protection

The PIC microcontroller on our PCB is an integral part of our system; it is also more fragile than many of the other components. Its data sheet claims that it can withstand input signal voltages between -0.3-V and 5.3-V, so we wanted to keep our signals within this range. This means that protection must be provided for both the current and voltage channels, but we handled each case differently.

For the current signal, we debated on what type of protection to use. Protecting 30 channels with a Zener diode did not seem reasonable or cost effective. Instead, we decided to allow the fuse in the circuit breaker box to protect the PIC from over-voltages. The circuits in the breaker box have a fuse that is rated for 20-A, so this is the maximum current we will be measuring. By adjusting our gain in the acquisition circuit, we made a 0-V to 5-V peak to peak signal represent a 20-A current. If the current exceeds 20-A in the circuit, the breaker will trip, returning our signal to the DC offset of 2.5-V rather than exceeding the PIC signal range.

The voltage signal, on the other hand, cannot use the same protection scheme. Technically, the voltages on the bus bars could exceed their rated 120-V, so we have to protect against this case. This was done by adding two Zener diodes to act as voltage clamps, which can be seen in Figure 3 of the system schematics. Appendix Figure 11 then shows how the PIC is protected.

Analog to Digital Conversion

After looking at different microcontrollers with A/D Converters built in, we decided to go with a PIC18F45K22 due to the number of channels of ADC Modules and our familiarity with the microcontroller, seeing as it is the one we used in Microcontrollers class. One microcontroller is on each PCB, with 16 channels of ADC being used (15 for current and 1 for voltage) on each microcontroller.

The PIC18F45K22 has 10 bits of resolution for the A/D conversion process, which should be enough for the accuracy we are wishing to obtain. The microcontroller will be referenced between 0 and 5 V, which means that the range of voltages that can safely be at the input to the A/D channels to -0.3V and +5.3V. Protection, as talked about in the section above, will be used to help ensure that the voltage does not exceed these ratings.

Calibration

With the digital data collected we were able to calibrate our system to make sure we were getting accurate waveforms. This was done using a Fluke 41B, which is a power analyzer that does something very similar to what our system does but for only one channel. The Fluke 41B monitors voltage using leads, as well as current by using a clamp-on current transformer. These waveforms are collected by the Fluke 41B, stored, and then downloaded to Excel. To calibrate our system, we used a microwave load as a test. The microwave was 900 W, and sure enough the Fluke 41B monitored the microwave to be pulling 900 W. Collecting the voltage and current waveforms, we downloaded the data to Excel in order to compare to the waveforms we collected on our system. Before we could directly compare the two; however, we had to readjust our waveforms based on the acquisition process. For voltage, we had to multiply the waveforms by the voltage ratio of the power transformer, as well as by the gain constant of the inverting amplifier, which produces the following equation:

$$V = V_{digital}\left(\frac{V_{primary}}{V_{secondary}}\right)\left(\frac{R_2}{R_3}\right) = V_{digital}\left(\frac{170}{17}\right)\left(\frac{82}{10}\right) = (82)V_{digital}$$

The current waveform was readjusted in a similar way, as seen in the equation below.

$$I = I_{digital}\left(\frac{I_{primary}}{I_{secondary}}\right)\left(\frac{R_2}{R_3}\right) = I_{digital}\left(\frac{15}{1}\right)\left(\frac{7.87}{10}\right) = (11.805)I_{digital}$$

After readjusting these waveforms, we plotted the two sources against each other to see how accurate our system was. We wanted to be within +/- 2%. In Figures 13 and 14 of the appendix, you can see that we met this criterion for both voltage and current. You will notice a slight difference between our system and the Fluke 41B on the current waveforms where there are high frequency spikes. This is simply because we are not sampling as fast as the Fluke 41B, but the differences are well within our specification limits.

Raspberry Pi

The Raspberry Pi is the piece of the design that takes our raw digital data, turns it into something meaningful, and sends it off out of our system's local environment and into the cloud. We needed a device that could communicate with a low level microcontroller as well as send this data over the internet. The Pi provided a perfect solution to this problem as it has nice GPIO pins as well as Ethernet and Wi-Fi capabilities. The Pi is responsible for two things, data acquisition and calculation and sending the data to the cloud. This is discussed in the following two sections.

Calculations

There are five calculations that we desire to perform when sampling the voltage and current waveforms before displaying the data on the Mobile App: Power Consumption, Energy Consumption, RMS voltage, RMS current, and Power Factor.

To calculate power, a point-by-point multiplication of the digital current samples and digital voltage samples is performed, resulting in power. This power is averaged over a specified amount of time to obtain the average power.

To calculate energy, power is multiplied by the time the energy is taken over, and that results in a measurement of kWh. From this calculation, the amount of money spent on the energy consumption can be easily calculated.

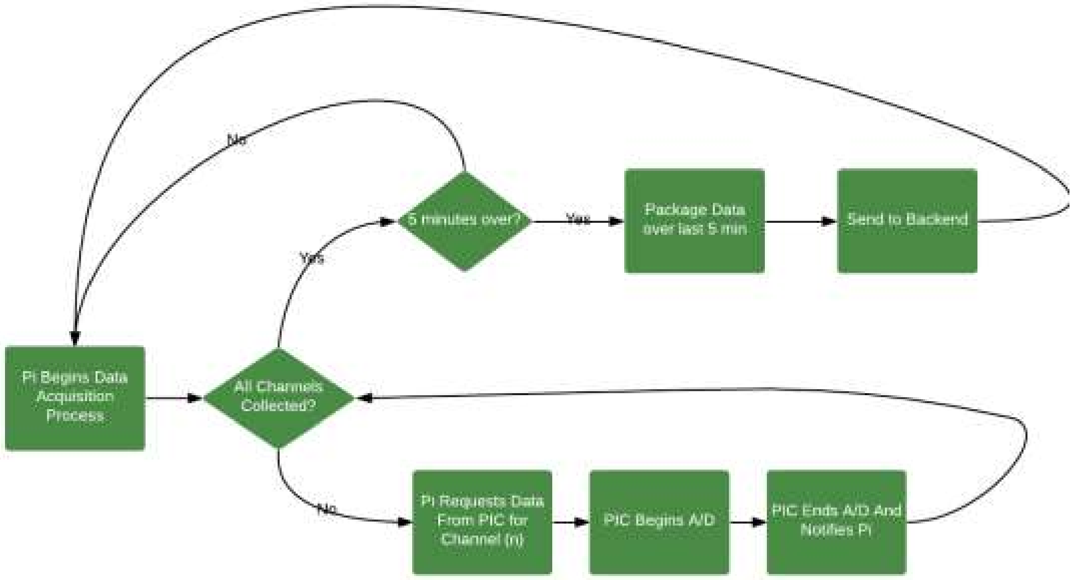
To calculate RMS voltage and RMS current, we made sure that we had complete electrical cycles before performing this calculation. We took six full electrical cycles worth of data, squared every data point, took the average of those values, and then took the square root to obtain RMS. Sampling a whole number of electrical cycles ensured that we had the most accurate calculations of RMS current and voltage possible.

To calculate power factor, we had to find the zero crossings of both the current and voltage waveforms. Because our sampled waveforms had DC offsets to them, we shifted the sampled waveforms down by the DC offset so that each sampled waveform was centered around zero. This allowed us to easily find the zero crossings. Once we found one of the zero crossings on the voltage waveform, we found the zero crossing on the current waveform that was within plus or minus 90 degrees of an electrical cycle, since the current should never lead or lag by more than 90 degrees. Taking the cosine of the difference between those two waveforms yields the power factor calculation that we desired.

Sequencing

Because the PIC is very limited in its processing ability, we wanted to limit how much simultaneous work it was responsible for. As such, we decided to sequence through each of the channels to collect data. In this way, the PIC would perform A/D and let the Pi know, via an extra pin, that that channel is done acquiring. After this, the Pi requested the next channel. The Pi continued this process for each of the active channels. This process is shown in figure 3.

Figure 3. Sequencing Flow Chart



We were comfortable making this decision, even though it is possible that some data could be missed. However, the sequencing happened often enough that a power event would only be missed if it lasted less than about 15 seconds. This reasoning led us to this decision.

Backend

The next piece of our design is our backend. We chose to use a backend for several reasons. First, a backend allows the Pi to focus only on sending data, not servicing potentially numerous client requests. Second, a backend allows us to access data from anywhere rather than limiting us to a local network connection. Thirdly, it keeps our system modular and does not put too much burden of functionality on one piece of the system.

Rather than implement our backend from scratch, we chose to use a backend as a service (BaaS). We originally intended to use a service called Parse, but this service is shutting down and we were forced to find an alternative. The alternative we found is a service called Firebase. Firebase provides free storage and a rich set of Software Development Kits (SDKs) for many platforms. Firebase is owned by Google and consequently has good reliability and support. The beauty of Firebase is that it allowed us to make simple API calls in our code rather than dealing with low level socket programming. It addition, it eliminated the need to implement a server to handle all requests. When the Pi wishes to give new data to Firebase, it calls a simple HTTP POST request and the data arrives immediately. Firebase also provides a web interface for the developer to view the data in real time, making debugging easier. Firebase also provides SDKs for web and mobile platforms. This feature made Firebase an even more attractive option.

Mobile Application

The final piece of the design is the viewing of our collected data. In our case, we chose to do this with an iOS app. We chose to focus on the iOS platform because that is where we had the most development experience, saving us from learning how to program on an entirely new platform. The app's main purpose is to display data in a way that is helpful to the user. We have accomplished this by using graphs, charts, and an easy-to-read dashboard.

The iOS app has the ability to view power usage over various time intervals. These intervals include daily, weekly, 30 day, 90 day, and 6 month intervals. The user also has the ability to input their kWh price so that cost information can be seen based on their energy consumption.

Results

At the beginning of the year, we set out to design, build, and test an AC power monitoring system. We wanted this system to measure the power and energy consumption of individual circuits in a circuit breaker panel located in Cedarville University's new chemistry lab building. We then wanted this data to be uploaded to the internet where it could be organized and displayed on a mobile application to give the user beneficial information on power and energy consumption in the lab building. Following is a summary of our project's performance.

Backend Initial Goal (Chemistry Lab Building)

The AC power monitoring system designed and installed by our senior design team was very successful. We accomplished our main objective of monitoring individual circuits within a circuit breaker panel in Cedarville's Chemistry Building, and we were able to collect data over a lengthy span of time. We monitored the energy consumption behavior of the building, noticing everything from people opening handicap doors to the outside floodlight coming on every night.

The final system we installed contains one PCB and 11 current transformers due to reasonability. We could easily add another PCB, however, and utilize every available channel to monitor up to 30 circuits. As far as the system itself, we have met most of the specifications we originally laid out. The system can monitor thirty 20-A circuits, it is easy to install using two outlets and a clamp on current transformers, and our cellular application provides useful feedback to the user.

You can see the actual data we collected from the Chemistry Building circuit breaker panel in Figures 3 – 6. The most interesting loads in that breaker panel were an energy management system, a utility room/attic, and an outdoor light pole. These loads constitute most of the daily power curve seen in Figure 3, and the breakdown of their peak power percentage is in Figure 4. The light pole was the highest energy consumer for 36% of the day, the energy management system was 42%, and the utility room/attic 22%. Total energy consumption from another day can be seen in Figure 5, where the light pole consumed 4.78 kWh, and the energy management system consumed 6.45 kWh.

Lastly, Figure 6 displays the long-term energy consumption of the light pole over a span of four days. The light turned on every night when the sun went down and turned off every morning when the sun came up. The large 900 Watt halogen bulb costs about $42 dollars a month to run, which adds up over time, especially when there are hundreds of other lights like it on campus. Collecting long-term data is where a system like this can really be useful. The university would receive energy consumption behavior data for loads like this light pole. The light appeared to be on a timer (a good energy behavior that our system reinforced) because the light does not need to be on when the sun is out. Other behaviors and suggestions could be made as well, such as the following: does the light actually need to be on all night, or could it be turned off from 2 AM – 5 AM? Making this simple change would save $10 a month. Multiplied by hundreds of campus lights, the savings would be $1000. Our results show the usefulness of the system and where it could potentially be used to be more energy efficient.

Extra Goal (Dr. Harmon's House)

After the test in the chemistry building, we wanted to scale up the system to be used in a different application, so we moved it to Dr. Harmon's house. In order to do this, we made a few changes to be able to monitor circuits up to 40-Amps and 240-Volts. Those changes were simply made using SCT-013-030 CT's and making a few assumptions with voltage signals in our calculations. We got the system installed and working, but unfortunately, that was short lived. Soon after starting our program, we ran into issues with the Pi sending data to Firebase. Without sufficient time left in the semester and without access to the Pi outside of Dr. Harmon’s network, we were not able to complete a full test at his house. With that being said, however, we still accomplished our main goal, and we could easily complete this second test if we had more time.

Finances

After completing our senior design project, we found that we finished at a reasonable expense. Table 1 in the appendix shows every expense from this year. We finished under our original budget by $362.37. The appendix also contains Table 2, which shows the per unit breakdown cost of our system. It comes out to be $368.55. Table 1 below summarizes the developmental cost of this product.

Table 1: Total Spending

Payment	Amount
Engineering Cost	$34,825.00
Prototype Cost	$439.63
Total	**$35,264.63**

Energy Today (kWh)

20.73

Projected This Month

699.01 kWh $78.29

124.0 Real Time Voltage (V)

658.1 Real Time Power(W)

ch11 Peak Channel

Figure 4: Dashboard

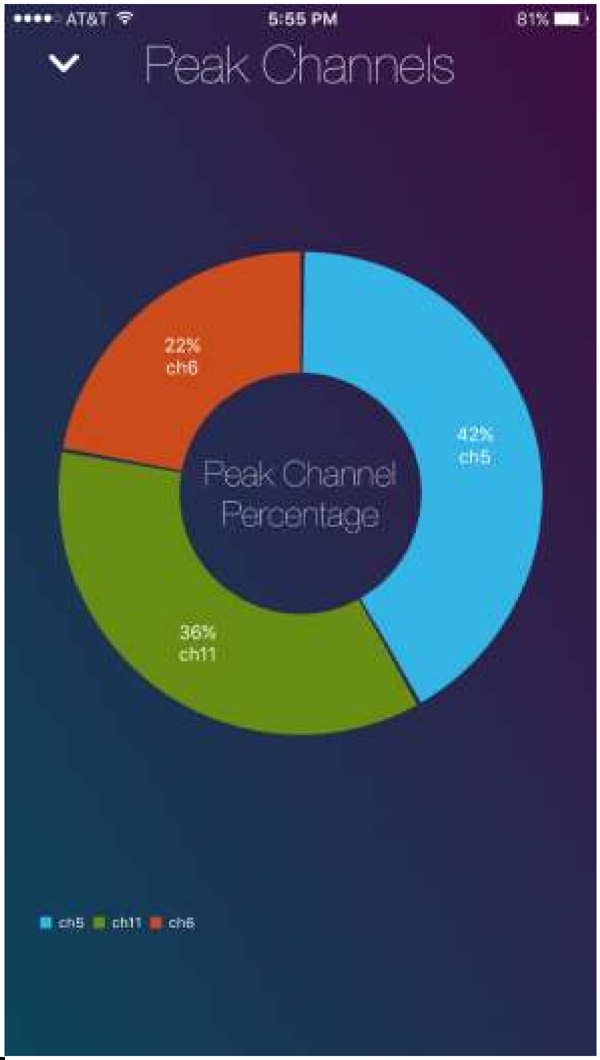


Figure 5: Peak Channel Breakout

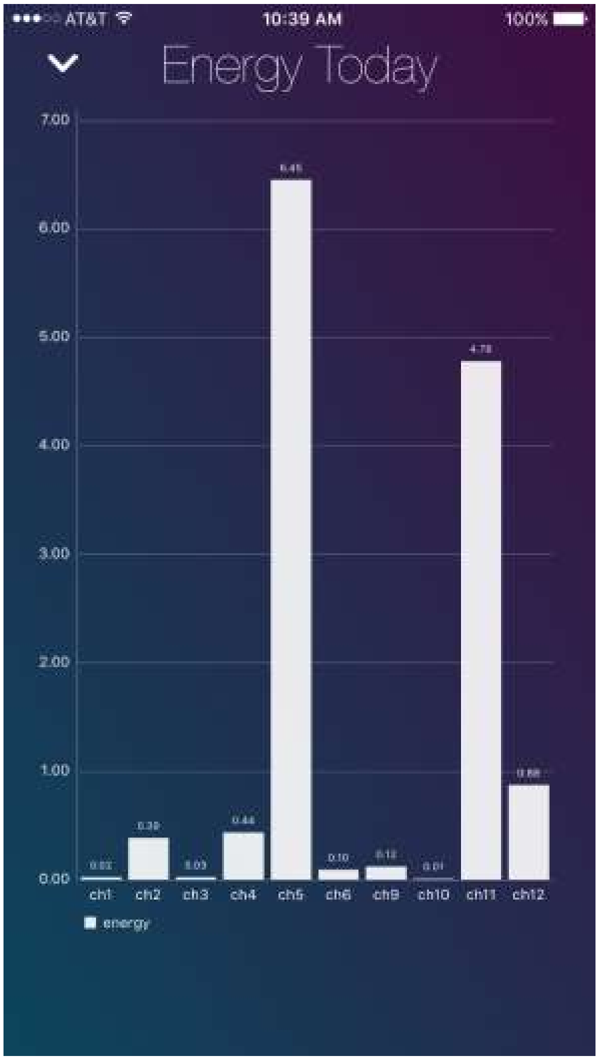
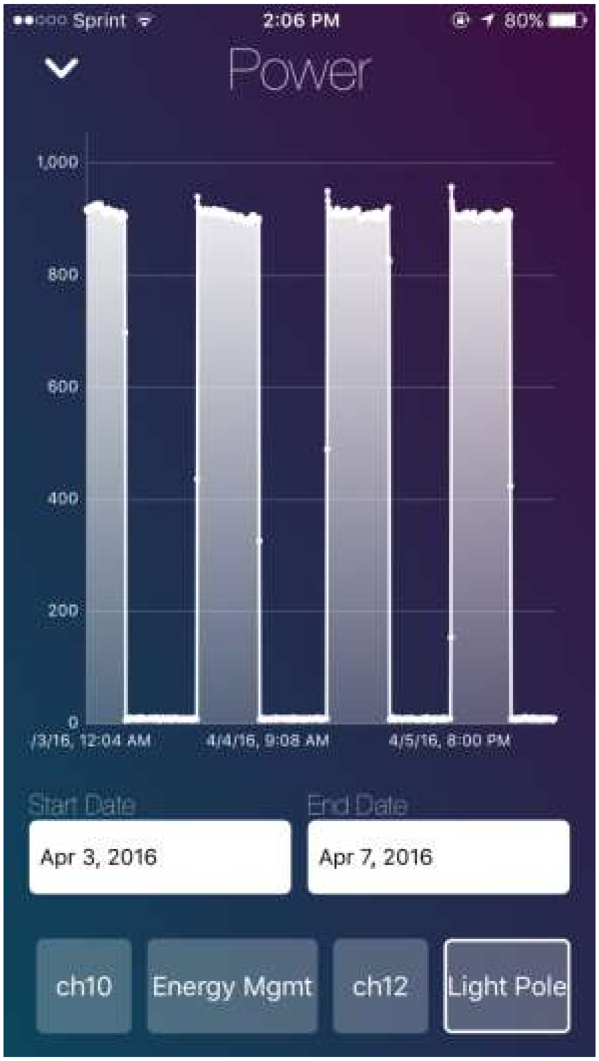


Figure 6: Energy Consumption Breakout



Start Date: Apr 3, 2016

End Date: Apr 7, 2016

Figure 7: Long Term Usage

Personal Contributions

Jared (CEO)

My main contribution to this team was generally overseeing the project as well as designing the analog portion of our system. We all worked together on many parts of the project. However, I completely created some parts, such as the power system and current monitoring device. I also played a role in printed circuit board fabrication, Raspberry Pi calculations, and the installation procedure. Following are more details of my work throughout the year.

During the first semester, my work was focused on the data acquisition board. This is the front end of the system, which consists of the power supply, current and voltage acquisition, the acquisition circuit, and analog to digital conversion. Of these tasks, I was directly involved in the power supply, current acquisition, and the acquisition circuit.

I began with researching what we would need to calculate energy consumption. From that research, we decided that the best way to do this would be to capture voltage and current waveforms of each individual circuit. I then began figuring out the most reasonable and safest way of pulling these signals from a circuit breaker box. For current acquisition, I decided that would be split-core current transformers, and Grayson decided that a step-down transformer would be the best for voltage acquisition.

After this decision, I spent a great deal of time looking for CTs that would best fit our specifications. They needed to be small enough to fit into the breaker box, they needed to have over-voltage protection, and they needed to be accurate up to 20-A. Thus, I chose the SCT Series. The overseas shipping took a long time, but once they arrived, I ran multiple tests to characterize their response.

While I was waiting for the CTs to arrive, I built the power supply that has been described. I also developed an acquisition circuit that's called a precision rectifier. We originally planned on half-wave rectifying the signals in order to calculate RMS currents and voltages. However, I began to run some tests with a Fluke 41B to look at real-life load waveforms, such as microwaves and electronics. To our surprise, we found that none of the current waveforms were sinusoidal. This would make calculating RMS current very difficult. We began to think of new ways to calculate power.

This new power calculation is simply multiplying the voltage and current waveforms together, which we could not do with a half-wave rectified signal. I went back to the drawing board and developed the DC Offset Inverting Amplifier that we are now using. Along with this circuit came filtering and circuit protection. The new circuit performs in a way that meets all of our specifications. Grayson created our array of acquisition circuits in PCB artist, and after some final tests, we sent the board off to be fabricated before Christmas break.

When we returned for spring semester, we unfortunately did not have a PCB yet, but it came in soon after we started classes. After receiving the PCB, I began to populate it with all of our parts, starting with the power system, which worked very well. To complete our milestone for the power subsystem, I built the entire system on a breadboard as well, but the PCB arrived just in time to demonstrate on that as well. However, soon after the power system, we started having issues with the board. I spent a great deal of time troubleshooting the issues we were having. Thankfully, we were able to get a couple of channels to work for testing, and we knew what we needed to fix on our next iteration of the PCB.

During this PCB process, we started testing with the few channels that were functional. Obtaining a microwave as a load, I began collecting data on the PIC to see what our waveforms looked like and to determine how difficult the calculations would be. Everything on the analog side of our acquisition worked well, but the rest of the acquisition took more time to figure out. Luke and I worked on I2C issues for significant amount of time, and after a lengthy conversation with Dr. Kohl, we produced the idea of a busy pin on the PIC. We eventually found the issue: the Raspberry Pi was requesting data from the PIC too quickly, and the PIC could not keep up. The busy pin fixed our issue, and we added that to our PCB design. Just in time for our first milestone, we were able to acquire data on the Raspberry Pi using one channel on the PCB. Soon afterward, Grayson and I submitted our PCB for the second fabrication.

While waiting for the PCB to come in, Grayson and I turned our attention to all the power calculations we would need to make on the Raspberry Pi. Luke decided to write that code in Python, so he quickly taught us the Python basics. We then created functions to calculate average power, RMS current, RMS voltage, energy consumption, and power factor. Grayson focused on the power factor calculation while I concentrated on the others. At this stage in the project, we focused on calibrating the system as well. To see how accurate our results were, I obtained a Fluke 41B from Dr. Brown and monitored the loads we were testing, which consisted of a microwave, a space heater, and some electronics. All of our calculations were accurate to within +/- 5% of the Fluke 41B, which we demonstrated on one channel as our second milestone.

After this, the PCB arrived, so we began to populate it. Grayson completed the first half of the board, and I finished the rest. Thankfully, we did not have any catastrophic issues with the board this time. However, a few things did change while running a full 15 channels rather than just 1. I had never seen the issue before, but the power system was having trouble keeping pace with the current the operation the amplifiers were drawing. The +6.2 V regulator was entering thermal shut down. This was perplexing at first because I had measured the input current from that regulator to be around 60 mA, and the regulator was rated for 100 mA. After some research, I realized that rating was meant with proper heat sinking, so I added a heat sink, which took care of the problem. The other issue we had was with the -5 V regulator's DC voltage. This voltage had a slight ripple in it, and that was problematic since we were using it for our DC offset. To fix it, I simply added more capacitance to the linear regulator output. After these changes were made, the PCB was complete and didn't require any more work.

Once we had the PCB ready to operate, I began organizing the installation and testing of our system. I was in charge of communication with Jeff Cunningham, the Universities Utility Coordinator, who was going to work with us to install the project. After some discussion with him, we decided to test a circuit breaker panel in a room on the back side of the Chemistry Lab building. We met with him as a group to look at the panel, and then I met with him by myself to prepare for installation. During these conversations, he informed us that we needed to put our system in an enclosure for fire safety reasons, so I began working on that.

After this, I obtained a box from Dr. SanGregory to put our system in. The transformer, PCB, and Raspberry Pi all had to fit in one box, which took some ingenuity. I made it possible to screw down all of the parts within the box, and I made more permanent connections between the PCB and Raspberry Pi. We also drilled through the outside so we could attach all of the CT's as well as the power cords. In the end, the enclosure worked very well, and we had a permanent housing for our system.

While I was completing the enclosure, Luke worked on the cellular application. We brainstormed and helped design the user interface while Luke did the actual programming. The app was still being finished when we did our first installation, but this worked well because we could store data online and pull it into the app later. Jeff and I successfully installed our system in the Chemistry Lab building. Soon afterward, we started up the system and began collecting data.

The first test went so well that we wanted to try the system in another environment. Because of this, I came up with the idea of moving it to Dr. Harmon's house. We will be attending Cedarville's Research and Scholarship Symposium, and I believed looking at the load of a house could be interesting data for this event. We decided this would be feasible after talking with Dr. Harmon, so I contacted Jeff to retrieve the system from the Chemistry Building. Unfortunately he was on vacation that week, so we had to wait until the next Monday to get the system. This gave us a very short window install the system at Dr. Harmon's house. We still decided attempt this, so I went with the team to help install the system. As mentioned earlier, we began to run the system, but we encountered issues shortly afterward.

While I would have liked to see the test in Dr. Harmon's house work, I am still very pleased with my contribution to this project. I believe I provided good oversight for the team that kept us on schedule to complete the project. Also, the individual parts of the system that I designed and built have been successful.

Grayson (CFO)

During the fall semester, I worked on the voltage acquisition circuit, as well as the microcontroller coding (which includes the A/D conversion) and Printed Circuit Board design. For the voltage acquisition circuit, we needed to transform the 120V that exists in the breaker panel into a safe voltage that can be monitored by the PIC. This is done by the acquisition circuit that is talked about in one of the subsystems above.

Some of the microcontroller coding I did in the fall semester was working toward computing the RMS value of the voltage being acquired. Up to that point, the code was being used under the assumption that the waveform we would acquire is a sinusoidal waveform. However, after testing, we discovered that the current waveforms we acquired were not sinusoidal, which makes computing the RMS value more difficult than just knowing the peak of the waveform. Therefore, more coding was worked on in the spring semester to find the true RMS value of the waveforms being acquired.

The PCB design was finished by the end of the fall semester. We sent it off for fabrication over Christmas break. The PCB was redesigned so that only 15 channels are going to be monitored from one PCB. Having that PCB sent off over the break allowed for population to take place in the spring semester of the board.

In the spring semester, I started out with populating a few channels on the PCB with Jared. We found some mistakes but were able to cut traces and get a couple channels to work. We used these couple channels, along with some preliminary code, to acquire data and send them to the very beginning stages of the mobile application being developed by Luke. Once we were able to verify that our PCB could send data and that Luke's app could display small amounts of data, we went to work improving our PCB design. Jared and I worked on that and were able to send off the new PCB for fabrication a few weeks before spring break. Once that came in, I populated half of it while Jared worked on populating the other half.

In addition to the work on the PCB, I was the primary team member who wrote the code to perform the calculations, primarily power factor. Luke set me up with Python, which I used to write a function that could measure power factor. That was accomplished by reading in both current and voltage waveforms, finding the zero crossings, and finding the difference between those points with respect to the period of the signals. Using the cosine function, the power factor could be computed. This calculation took up most of my time. I spent a little time on the power, energy, voltage rms, and current rms calculations, but Jared came along and improved those calculations so that all our calculations are working well and accurately.

I helped Jared a little on the box used to contain our data acquisition system; however, Jared put in a majority of the work. I have worked on the user's manual for our system and the quick start guide, which will teach customers how to best use the system we have created.

From a financial perspective, our project has come in under budget. To date, we have only used about half of the money that we budgeted for this project. The reason for this surplus is due, in part, to the fact that we have changed our design somewhat since we originally made the budget, and these improvements have helped to cut down on the expected costs. Despite the surplus, I believe that our system is working sufficiently for the scope of this project and that we can monitor power and energy consumption in individual circuits accurately.

Luke (CSO/CTO)

My part of the project primarily consists of the digital portion of our system. Thus, my main pieces of the project are PIC and Pi communication, Pi data acquisition software, software to send the data to the backend, and our app. This semester, I worked in each of these areas. During the first part of the semester, I determined the overall design for the digital part of our system. After some research, I chose to use Raspberry Pi which would talk to Parse, our backend, which would, in turn, communicate with a mobile app. My main method of attacking my portion of our project was to try get each link in the communication chain to work independently. First, I set up the Pi and got it connected to the internet. I researched various libraries and decided to use C++ for the Pi coding. My next task was to attempt to get the Pi to send some dummy data to Parse using the low-level C API provided by Parse. After some work, I could get dummy objects to send to Parse. Parse has a nice development web interface, where I can see the raw data in real time without needing my own client application.

After proving that the Pi could send data to Parse, I moved to the next link in the chain, having an iOS app pull this data. The Parse SDK for iOS was inherently more challenging to figure out and implement than it was for the Raspberry Pi, but I was able to use simple data fetches to accomplish this relatively smoothly. I attempted to organize my app to be as modular and object oriented as possible by implementing a custom data service object that could perform the fetches and return them to the caller. At first, I was not doing this, but I realized that for it to be a quality and extensible app, my code needed to be clean from the outset. After getting the raw data objects from Parse, I needed a way to display them. I chose to implement a simple table for raw data as well as display these objects on a chart using a third party charts library. The charts library has somewhat of a learning curve, so getting it to look right took some time.

At this point, I had dummy data going from the Pi, to Parse, and to the app. Grayson had recently finished some voltage acquisition, so I then moved on to my final link, the PIC to Pi communication. I chose to implement this via I2C. I2C proved to be a bit more challenging than I initially expected. There is a lot built into the protocol and trying to understand it was time consuming. After several issues with clock stretching and PIC I2C slave implementation, I was able to get this communication channel to work. Grayson had done some A/D coding for the PIC and was getting voltage acquisition readings. However, when I merged my I2C code with his A/D code, it did not work very well. So, I ended up rewriting and simplifying the A/D code to get accurate voltage readings. Once I had real data, I could send it to the Pi via I2C and through the rest of the system. Overall, this semester I proved that data can make it from one end of the system to the other. In order to meet our objectives at the end of the year, I need to put a lot more work into the app and data aggregation software to scale up to 30 channels.

The spring semester has largely consisted of scaling our system's ability as well as writing the mobile app. Before I could get any meaningful data on the app, I worked to get the Pi and Pic communicating consistently. There were some timing issues between the Pi and the Pic. In addition, I2C proved to be a challenge. After that, we chose to add a third wire to fix some of timing issues. This wire told the Pi when the Pic was done with A/D conversion. This made the whole communication process more smooth and consistent.

After knowing that the Pi and Pic could communicate well, it was time to make sure it could collect data consistently. I wrote a program to systematically sequence through each channel on the board as many times as possible in our 5-minute interval. These values would then be averaged over that interval and sent to Firebase, which replaced Parse. Grayson was responsible for writing the actual power calculations, but I wrote the code that collected and sent the data. Once data collection was consistent, significant work on the app could begin.

The minimal functionality of the app from the first semester was largely restructured due to the switch to Firebase. This was not a huge loss because not much had been done yet. The main functionality of the app was to grab any new data points, store them locally, and, then, display the data. It was not difficult to grab data from Firebase. The more difficult part of dealing with the data was figuring out Core Data, iOS's local storage framework. This took some time, but I was finally able to get the app to persistently store data.

The biggest challenge of the app was aggregating and storing data. Because all the data comes in as raw points, calculations had to be made constantly. I wrote a class to do this for me, which would give me aggregated data. This way, I kept calculations out of UI code. The other interesting design point was deciding how we wanted to display the data. We chose to have a daily dashboard as well as long term trends. The dashboard is shown in Figure 3.

The dashboard is the main function of the app and provides daily energy amounts as well as power graphs. Each of these areas will take the user to a summary for that metric as shown in Figures 4 and 5. This allows the user to see a breakdown of how a given metric is being used. We also included UI for graphing long-term trends. In this view, the user can select a start and an end date and view a graph over that interval for their metric of choice. This screen is shown in Figure 6.

Engineering Hours and Cost

Table 2 shows the hours our team worked during the first and second semesters as well as the engineering costs associated with these hours worked.

Table 2: Engineering Hours and Cost

	Fall Hours	**Spring Hours**	**Total Hours**	**Hourly Rate**	**Engineering Cost**
Jared Newman	123	122	245	$50.00	$12,250.00
Grayson Dearing	117.5	96.5	214	$50.00	$10,700.00
Luke Tomlinson	92.5	145	237.5	$50.00	$11,875.00
				Total	**$34,825.00**

Recommendations for Future Students

We proved that a system like this can work, and we have laid the groundwork for this project to be continued. If a team were to take this project next year, we would have some recommendations for them. Hopefully we can provide an easy transition for them to expand the system where we have left off. Our recommendations are as follows:

- Replace the operation amplifiers that are currently being used. We chose the LF353 because that is what we have in the lab, but they are an old technology and not very efficient. They draw up to 4 mA each, which burdens the power system. You should use more efficient two-channel operation amplifiers.

- Change the capacitor sizes that go with the linear regulators to eliminate all ripple in the voltage. We simply soldered on bigger through-hole capacitors because the footprint of the PCB did not allow for surface mount components to be changed.

- Add another analog to the digital conversion channel to read in the DC voltage offset to the PIC. We did not have this, so once we measured the DC offset voltage and put the system in the box we were stuck with it. If you run this voltage into the PIC then you would have a very accurate value when doing calculations.

- Fix channel 7's input into the PIC. The input pin on the PIC for channel 7 is already being used by the PIC for something else. You would simply have to change the trace on the PCB design.

- Expand the system to monitor both bus bars in the circuit breaker panel. We have only done one side due to cost reasonability, but we would only have to make a duplicate PCB. Monitoring both voltages would provide very accurate results in calculations. In order to monitor both sides of the breaker panel, we are making an assumption with the voltage waveform and shifting it either 120 or 180 degrees, depending on the type of building. This is a fair assumption, but monitoring both voltages would be more accurate.

- Figure out a good way to monitor 240 V breakers. This was out of the scope of our project, but we foresee this being an interesting issue to solve.
- The current transformers we chose, the SCT-130-xxx series, goes up to 100 A, which is hopefully enough for all future endeavors. But be aware that if you use the 100 A version you will need to add a burden resistor to its output.

- We were sequencing through channels because the PIC did not have enough physical storage to do every channel at once. If you wanted to collect all data at all times, you could possibly use a PIC with more internal storage.

- Build a more permanent backend. We used Google Firebase so we could focus on more pertinent parts of the project, but developing your own backend might be better.

- Look to expand the feedback portion of the cellular application to provide energy behavior suggestions and cost saving tips.

- Expand the mobile application to operate on an Android device.

Bibliography

Data Sheets

- SCT-013-xxx Current Transformer, Seeed Studio
- 3.5 mm Adapter, 4UCON Technology Inc.
- 241-4-20 Power Transformer, Signal Transformer
- 1N4003 Power Diode, Micro Commercial Components
- L79Lxx Linear Regulator, STMicroelectronics
- uA78Lxx Linear Regulator, Texas Instruments
- FK1E100R Capacitor, Panasonic
- LF353 Operational Amplifier, Texas Instruments
- PIC18F45K22, Microchip

Other Sources

"AN734 Using the PIC® Devices' SSP and MSSP Modules for Slave I2CTM Communication", *MicroChip*. 5 Dec. 2015. <http://ww1.microchip.com/downloads/en/appnotes/00734b.pdf>

Firebase. <https://www.firebase.com/>

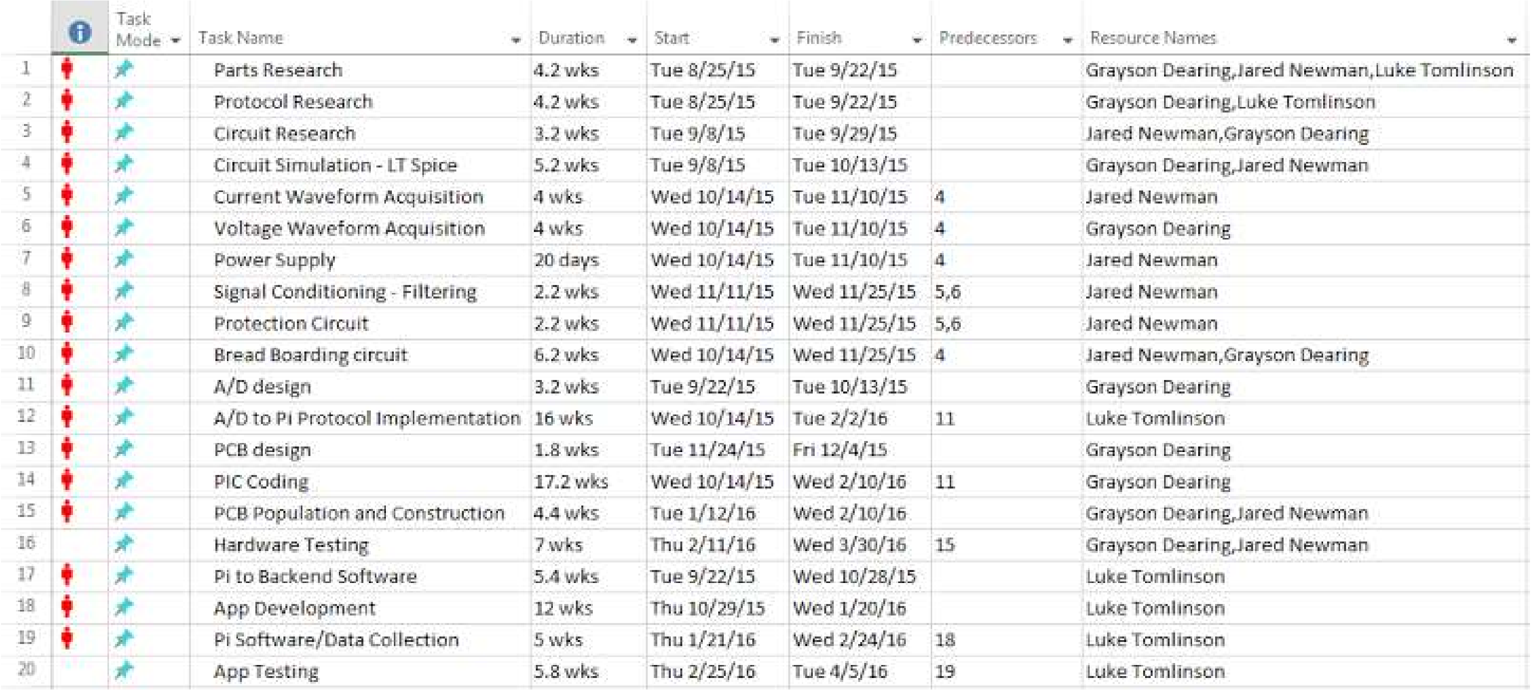
"ios-charts." *GitHub*. Web. 6 Dec. 2015. <https://github.com/danielgindi/ios-charts>
Keeping, Steven. "Understanding the Advantages and Disadvantages of Linear Regulators." *Digi-Key Electronics*. 8 May 2012. Web. 6 Dec. 2015. <http://www.theautomationstore.com/what-is-a-ct-current-transformer-or-current-transducer/>
The smart way to save energy and protect your home. (n.d.). Retrieved April 14, 2016, from http://neur.io/

Parse. Web. 7 Dec. 2015. <https://www.parse.com/>
Providing the finest test equipment solutions since 1992. (n.d.). Retrieved May 02, 2016, from http://www.testequipmentdepot.com/fluke/powermeter/39and41b.htm

Veris Industries. Web. 6 Dec. 2015. <http://www.veris.com/>
"What Is a CT? Current Transformer vs. Current Transducer?" *The Automation Store - TW Controls*. Web. 6 Dec. 2015. <http://www.theautomationstore.com/what-is-a-ct-current-transformer-or-current-transducer/>

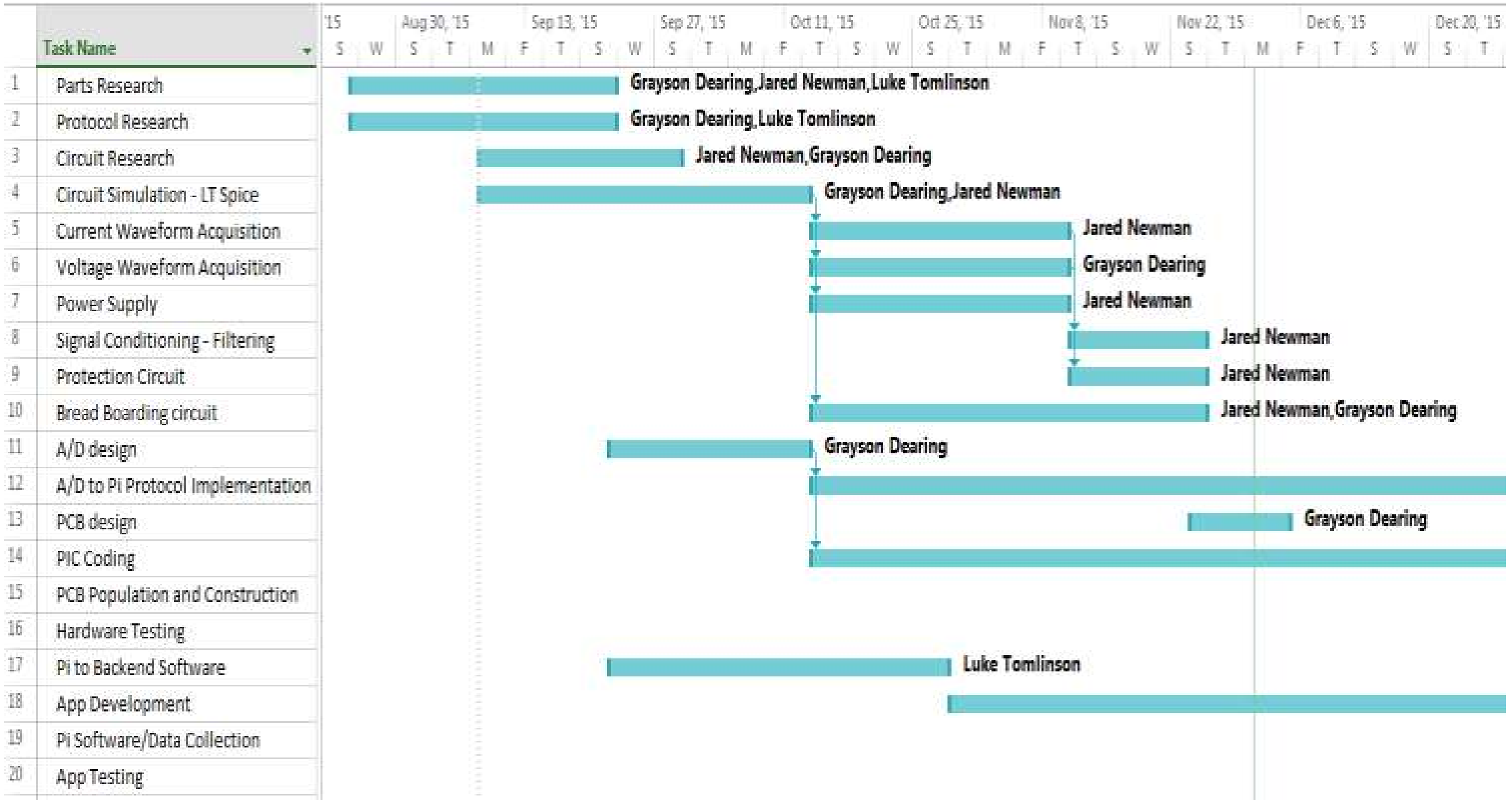
Final Gantt Charts

Gantt Chart Table



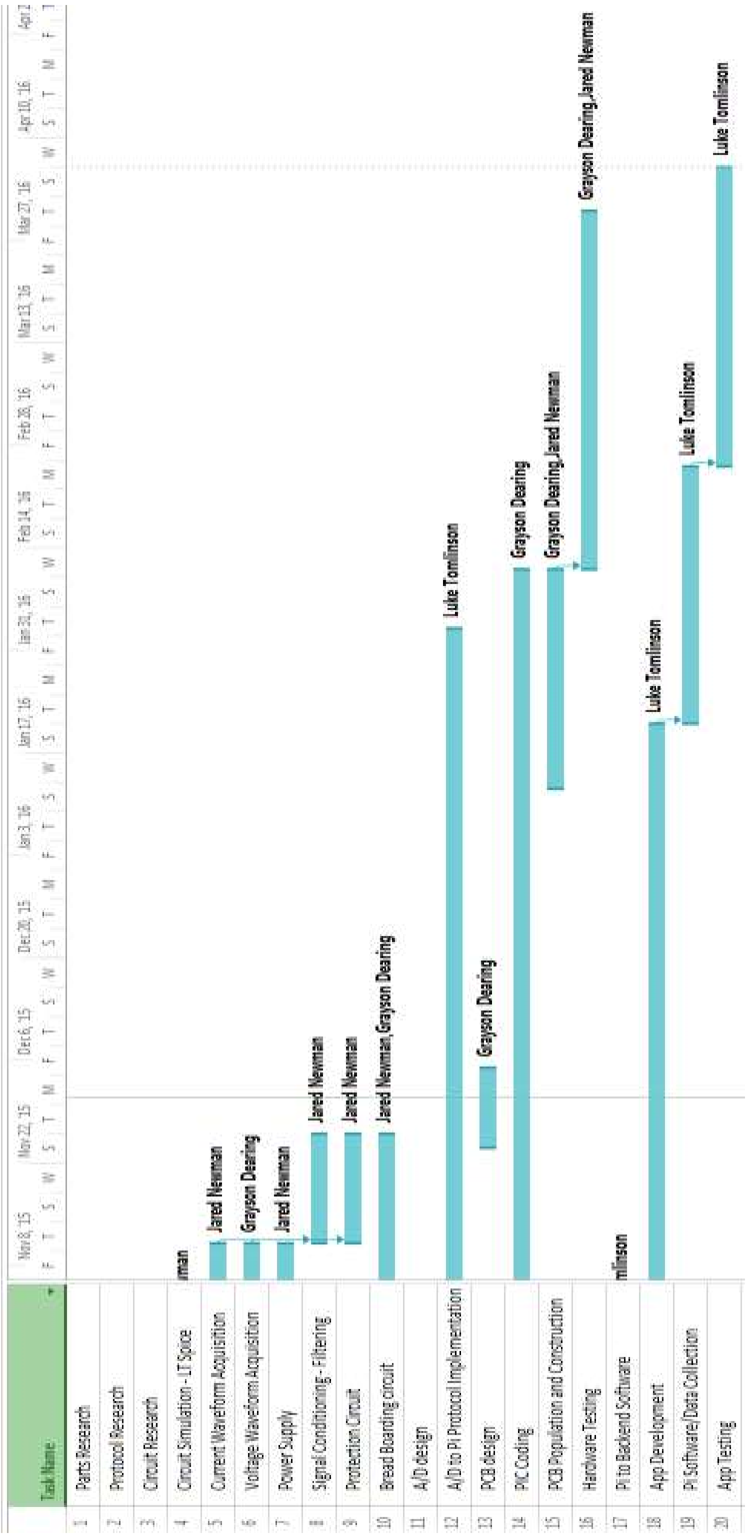
		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1			Parts Research	4.2 wks	Tue 8/25/15	Tue 9/22/15		Grayson Dearing,Jared Newman,Luke Tomlinson
2			Protocol Research	4.2 wks	Tue 8/25/15	Tue 9/22/15		Grayson Dearing,Luke Tomlinson
3			Circuit Research	3.2 wks	Tue 9/8/15	Tue 9/29/15		Jared Newman,Grayson Dearing
4			Circuit Simulation - LT Spice	5.2 wks	Tue 9/8/15	Tue 10/13/15		Grayson Dearing,Jared Newman
5			Current Waveform Acquisition	4 wks	Wed 10/14/15	Tue 11/10/15	4	Jared Newman
6			Voltage Waveform Acquisition	4 wks	Wed 10/14/15	Tue 11/10/15	4	Grayson Dearing
7			Power Supply	20 days	Wed 10/14/15	Tue 11/10/15	4	Jared Newman
8			Signal Conditioning - Filtering	2.2 wks	Wed 11/11/15	Wed 11/25/15	5,6	Jared Newman
9			Protection Circuit	2.2 wks	Wed 11/11/15	Wed 11/25/15	5,6	Jared Newman
10			Bread Boarding circuit	6.2 wks	Wed 10/14/15	Wed 11/25/15	4	Jared Newman,Grayson Dearing
11			A/D design	3.2 wks	Tue 9/22/15	Tue 10/13/15		Grayson Dearing
12			A/D to Pi Protocol Implementation	16 wks	Wed 10/14/15	Tue 2/2/16	11	Luke Tomlinson
13			PCB design	1.8 wks	Tue 11/24/15	Fri 12/4/15		Grayson Dearing
14			PIC Coding	17.2 wks	Wed 10/14/15	Wed 2/10/16	11	Grayson Dearing
15			PCB Population and Construction	4.4 wks	Tue 1/12/16	Wed 2/10/16		Grayson Dearing,Jared Newman
16			Hardware Testing	7 wks	Thu 2/11/16	Wed 3/30/16	15	Grayson Dearing,Jared Newman
17			Pi to Backend Software	5.4 wks	Tue 9/22/15	Wed 10/28/15		Luke Tomlinson
18			App Development	12 wks	Thu 10/29/15	Wed 1/20/16		Luke Tomlinson
19			Pi Software/Data Collection	5 wks	Thu 1/21/16	Wed 2/24/16	18	Luke Tomlinson
20			App Testing	5.8 wks	Thu 2/25/16	Tue 4/5/16	19	Luke Tomlinson

Gantt Chart 1: First Semester



	Task Name
1	Parts Research
2	Protocol Research
3	Circuit Research
4	Circuit Simulation - LT Spice
5	Current Waveform Acquisition
6	Voltage Waveform Acquisition
7	Power Supply
8	Signal Conditioning - Filtering
9	Protection Circuit
10	Bread Boarding circuit
11	A/D design
12	A/D to Pi Protocol Implementation
13	PCB design
14	PIC Coding
15	PCB Population and Construction
16	Hardware Testing
17	Pi to Backend Software
18	App Development
19	Pi Software/Data Collection
20	App Testing

Gantt Chart 2: Second Semester



System Schematic Diagram

The following circuits will be on the data acquisition board:

1. Power Supply
2. Current Acquisition
3. Voltage Acquisition

Figure 4 shows the entire PCB Schematic that will be fabricated.

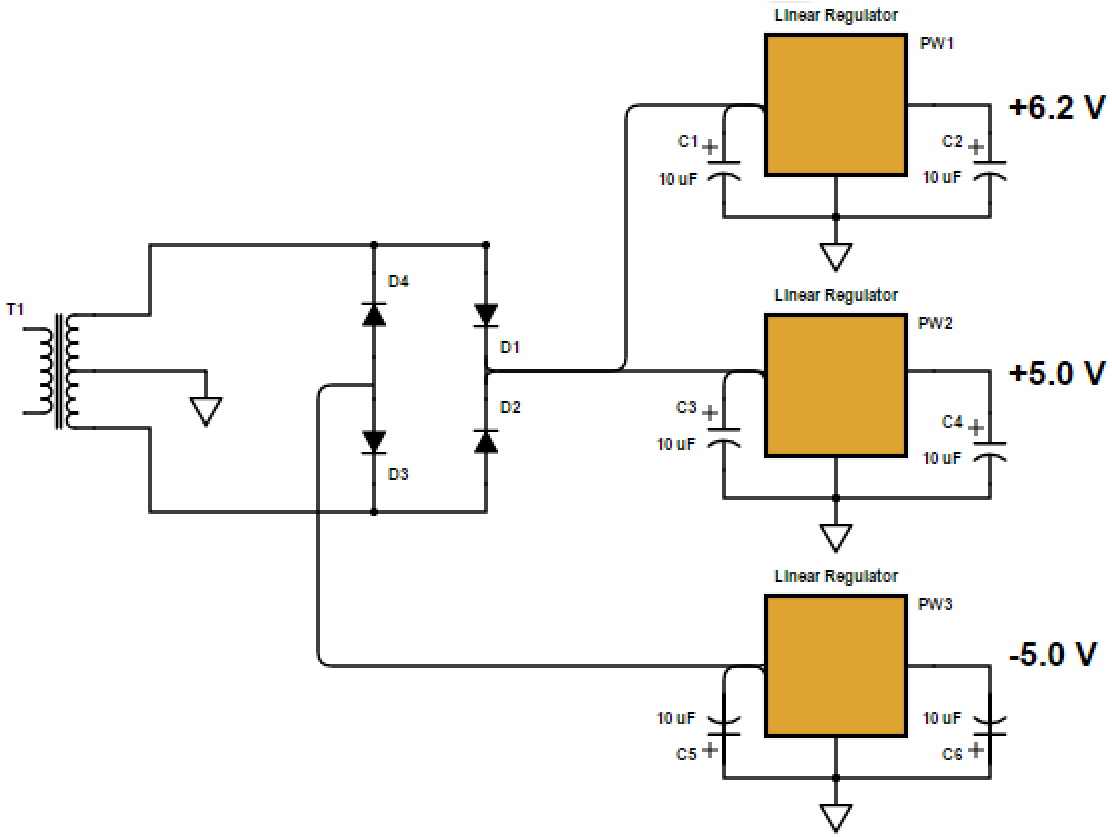


Figure 1: Power Supply Circuit

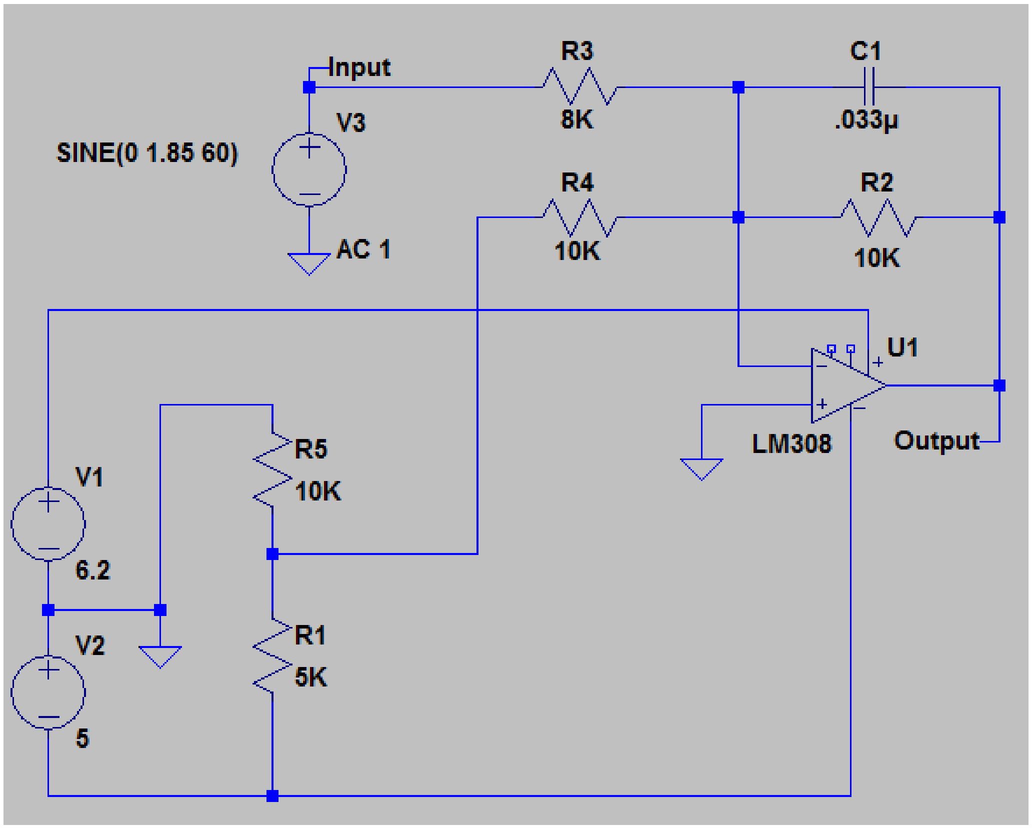


Figure 2: Current Acquisition Circuit

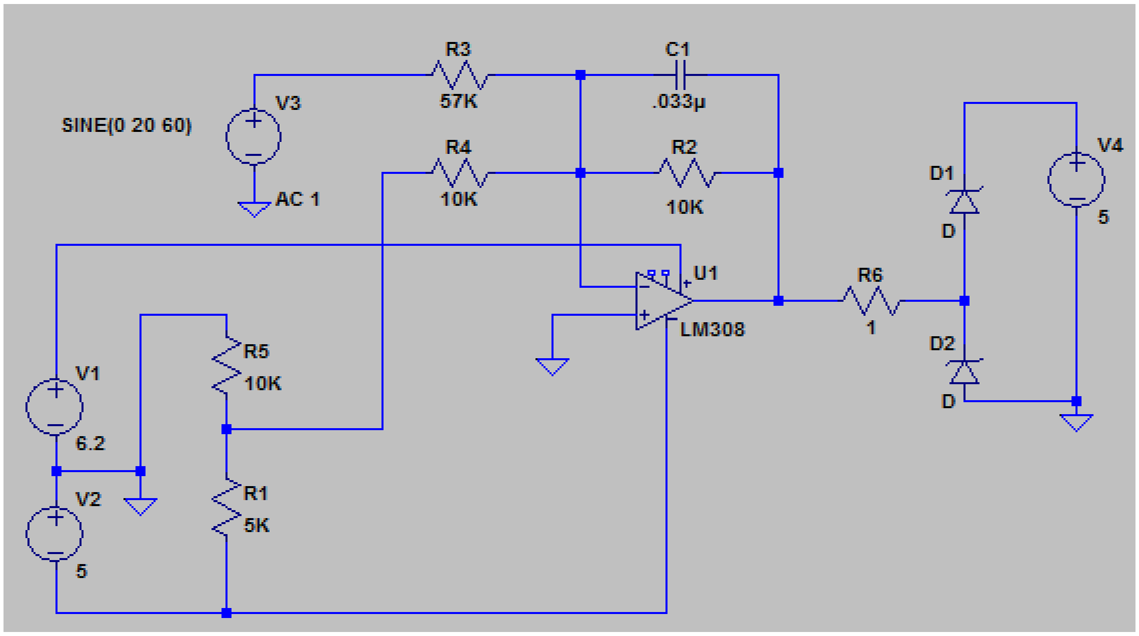
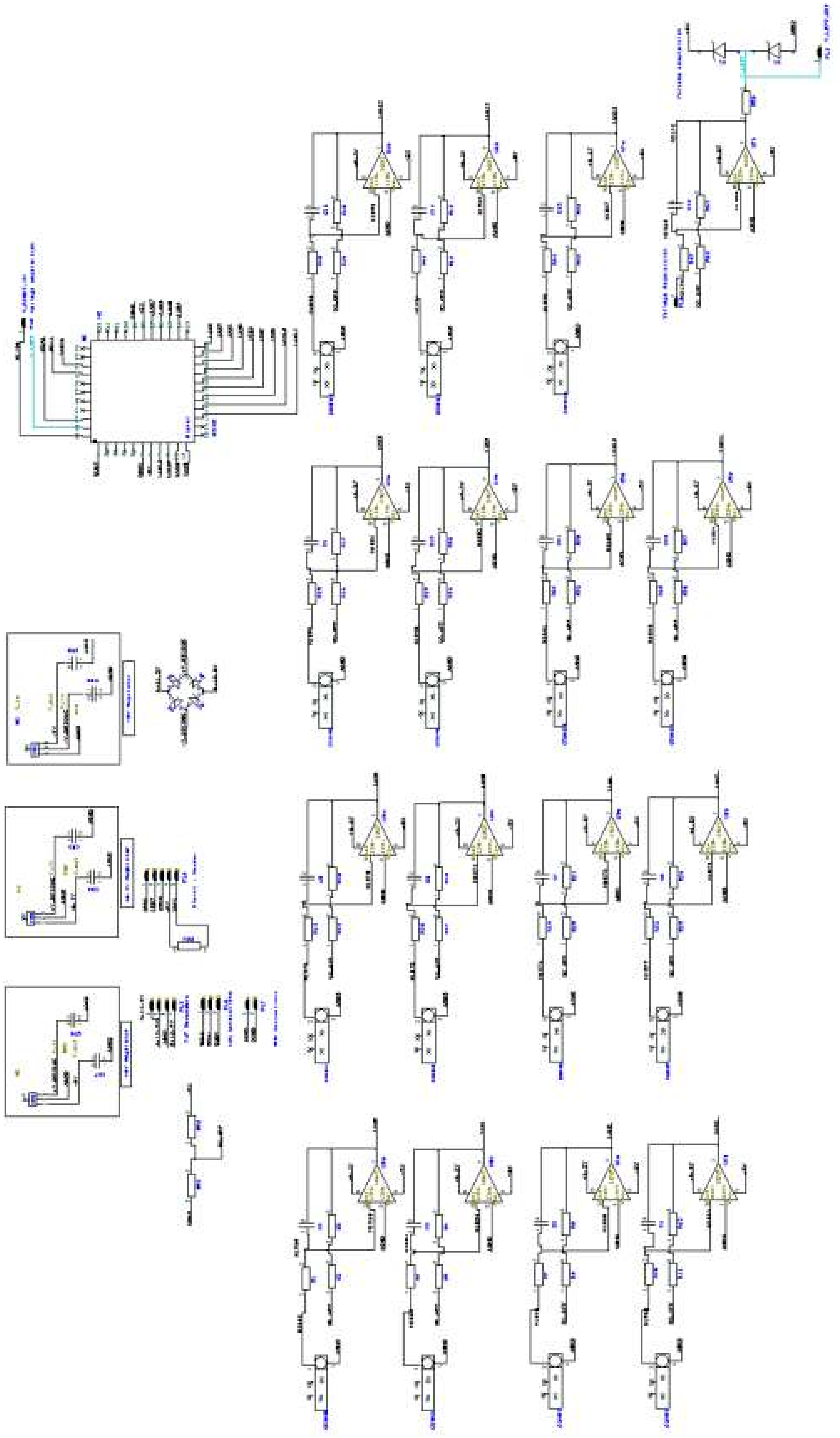


Figure 3: Voltage Acquisition Circuit with Voltage Clamp Protection



Bill of Materials

Table 1: Per Unit Cost

Power Supply

Part	Manufacturer	Part #	Price	Qty	Total
Power Transformer	Signal Transformer	241-4-20	$5.35	2	$10.71
Regulator (+6.2V) - SM	Texas Instruments	uA78L06	$0.15	2	$0.30
Regulator (+5V) - SM	Texas Instruments	uA78L05	$0.31	2	$0.63
Regulator (-5V) - SM	STMicroelectronics	uL79L05	$0.13	2	$0.27
100 uF Capacitor	Panasonic	EEE-OJA101WR	$0.13	2	$0.26
10 uF Capacitor	Panasonic	FK1E100R	$0.13	8	$1.00
220 uF Capacitor	Nichicon	UWX1A221MCL1GB	$0.10	2	$0.20
Power Diode	Micro Commercial Components	1N4003	$0.10	8	$0.79

Current Acquisition

Part	Manufacturer	Part #	Price	Qty	Total
Current Transformer - 15A	UXCell	SCT-013-015	$8.80	30	$264.00
3.5 mm Adapter (SM)	SparkFun	12639	$0.86	30	$25.80

Voltage Acquisition

Part	Manufacturer	Part #	Price	Qty	Total
Zener Diode (5.1V)	ON Semiconductor	1SMB59xxBT3G	$0.11	4	$0.46

Acquisition Circuit

Part	Manufacturer	Part #	Price	Qty	Total
Operation Amplifier	Texas Instruments	LF353DR	$0.21	16	$3.36
10K Resistors	Yageo	311-10.0KCRCT-ND	$0.00	66	$0.25
7.8K Resistors	Yageo	311-7.87KCRCT-ND	$0.00	16	$0.06

Printed Circuit Board

Part	Manufacturer	Part #	Price	Qty	Total
PCB Submission	Advanced Circuits		$5.10	2	$10.20

Analog to Digital Conversion

Part	Manufacturer	Part #	Price	Qty	Total
PIC18F45K22	Microchip	PIC18F45K22	$2.16	2	$4.32

Enclosure

Part	Manufacturer	Part #	Price	Qty	Total
Plastic Enclosure			$10.00	1	$10.00

Signal Processing and Sending

Part	Manufacturer	Part #	Price	Qty	Total
Raspberry Pi			$45.95	1	$45.95
				Total	**$368.55**

Table 2. Project Spending

Power Supply

Part	Manufacturer	Part #	Price	Qty	Total
Power Transformer	Signal Transformer	241-4-20	$10.31	1	$10.31
Regulator (+6.2V) - SM	Texas Instruments	uA78L06	$0.36	3	$1.08
Regulator (+6.2V) - TH	Texas Instruments	uA78L06	$0.36	3	$1.08
Regulator (+5V) - SM	Texas Instruments	uA78L05	$0.48	3	$1.44
Regulator (+5V) - TH	Texas Instruments	uA78L05	$0.48	3	$1.44
Regulator (-5V) - SM	STMicroelectronics	uL79L05	$0.48	3	$1.44
Regulator (-5V) - TH	STMicroelectronics	uL79L05	$0.38	3	$1.14
10 uF Capacitor	Panasonic	FK1E100R	$0.53	10	$5.30
Power Diode	Micro Commercial Components	1N4003	$0.10	10	$0.99

Current Acquisition

Part	Manufacturer	Part #	Price	Qty	Total
Current Transformer - 30A	UXCell	SCT-013-030	$11.00	6	$66.00
Current Transformer - 15A	UXCell	SCT-013-015	$11.33	11	$124.63
3.5 mm Adapter (TH)	SparkFun	8032	$1.50	6	$9.00
3.5 mm Adapter (SM)	SparkFun	12639	$0.95	30	$28.50

Voltage Acquisition

Part	Manufacturer	Part #	Price	Qty	Total
Zener Diode (5.1V)	ON Semiconductor	1SMB59xxBT3G	$0.47	3	$1.41

Acquisition Circuit

Part	Manufacturer	Part #	Price	Qty	Total
Operation Amplifier	Texas Instruments	LF353DR	$0.46	20	$9.28
Diode	Vishay Semiconductor	1N4148	$0.11	60	$6.48
10K Resistors	Yageo	311-10.0KCRCT-ND	$0.02	25	$0.38
7.8K Resistors	Yageo	311-7.87KCRCT-ND	$0.02	35	$0.53

Printed Circuit Board

Part	Manufacturer	Part #	Price	Qty	Total
PCB Submission	Advanced Circuits		$50.00	1	$50.00
PCB Submission	Advanced Circuits		$50.00	1	$50.00

Analog to Digital Conversion

Part	Manufacturer	Part #	Price	Qty	Total
PIC18F45K22	Microchip	PIC18F45K22	$2.60	2	$5.20

Signal Processing and Sending

Part	Manufacturer	Part #	Price	Qty	Total
SD Card			$14.00	1	$14.00
Raspberry Pi			$50.00	1	$50.00
				Total	**$439.63**

Appendix

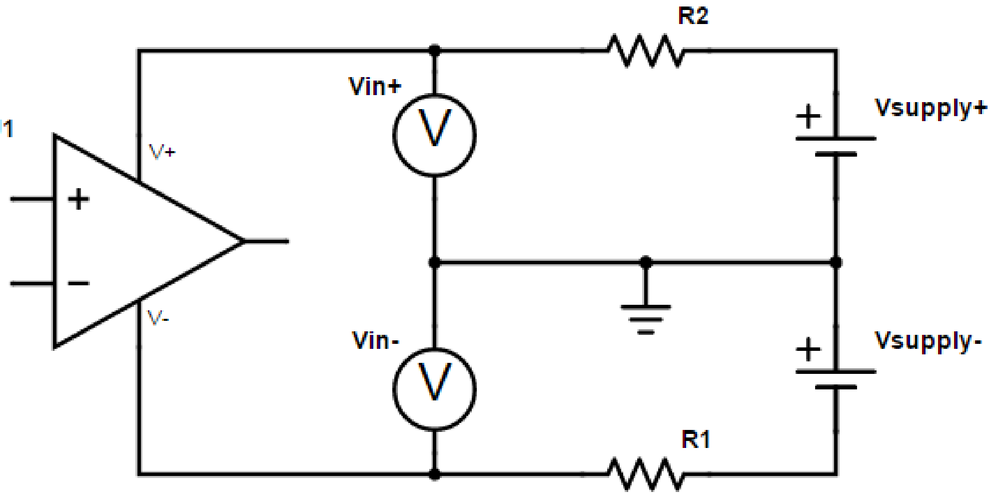


Figure 5: Acquisition Circuit Input Power Test

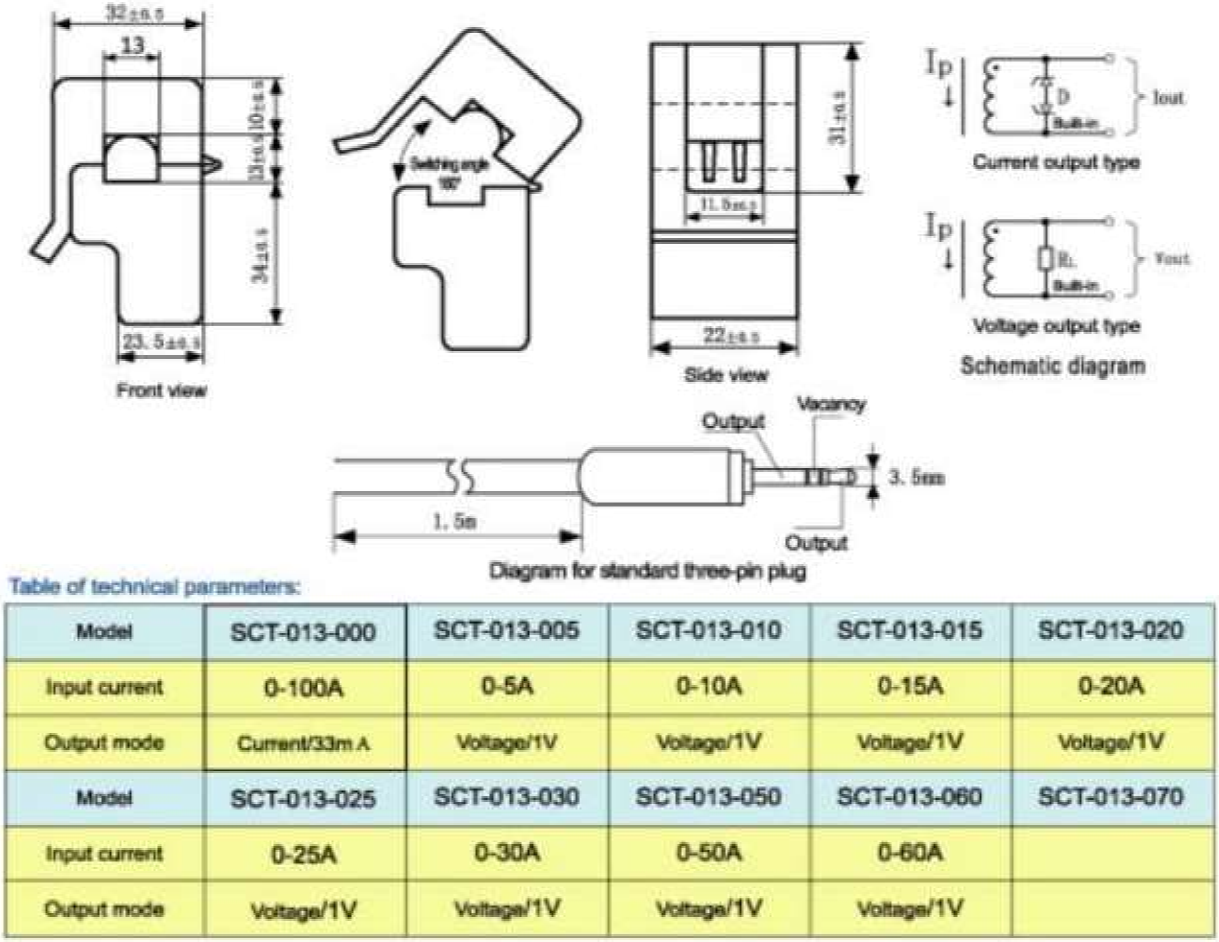


Table of technical parameters:

Model	SCT-013-000	SCT-013-005	SCT-013-010	SCT-013-015	SCT-013-020
Input current	0-100A	0-5A	0-10A	0-15A	0-20A
Output mode	Current/33mA	Voltage/1V	Voltage/1V	Voltage/1V	Voltage/1V
Model	SCT-013-025	SCT-013-030	SCT-013-050	SCT-013-060	SCT-013-070
Input current	0-25A	0-30A	0-50A	0-60A	
Output mode	Voltage/1V	Voltage/1V	Voltage/1V	Voltage/1V	

Figure 6: SCT-013-xxx Current Transformer Series

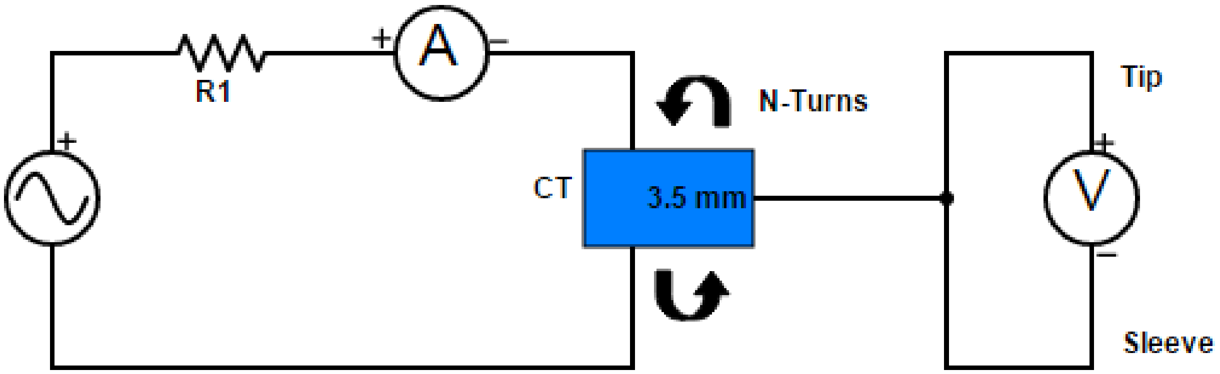


Figure 7: CT Characterization Test

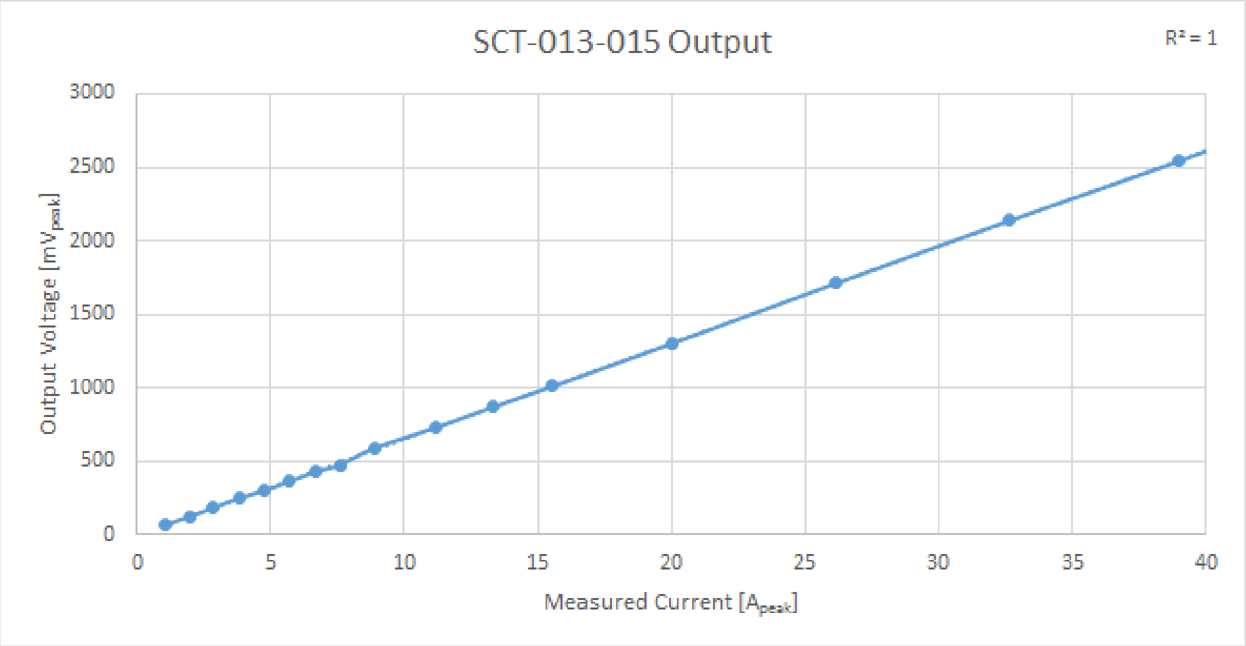


Figure 8: SCT-013-015 Characterization

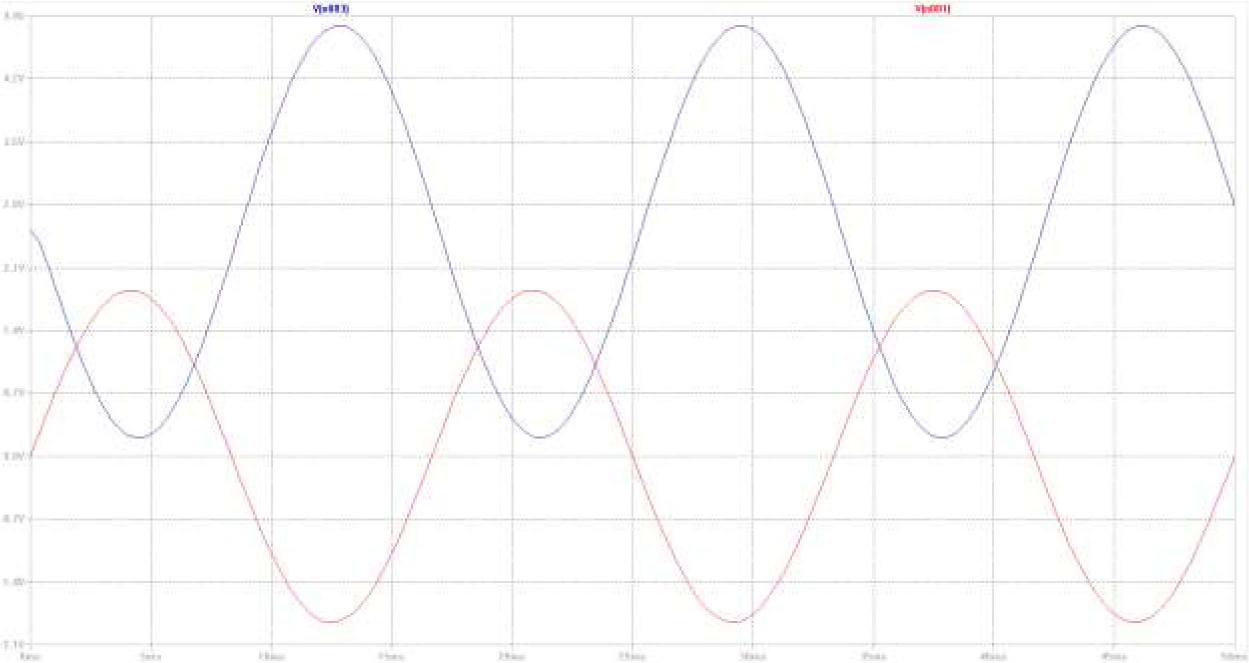


Figure 9: Acquisition Circuit Transient Response

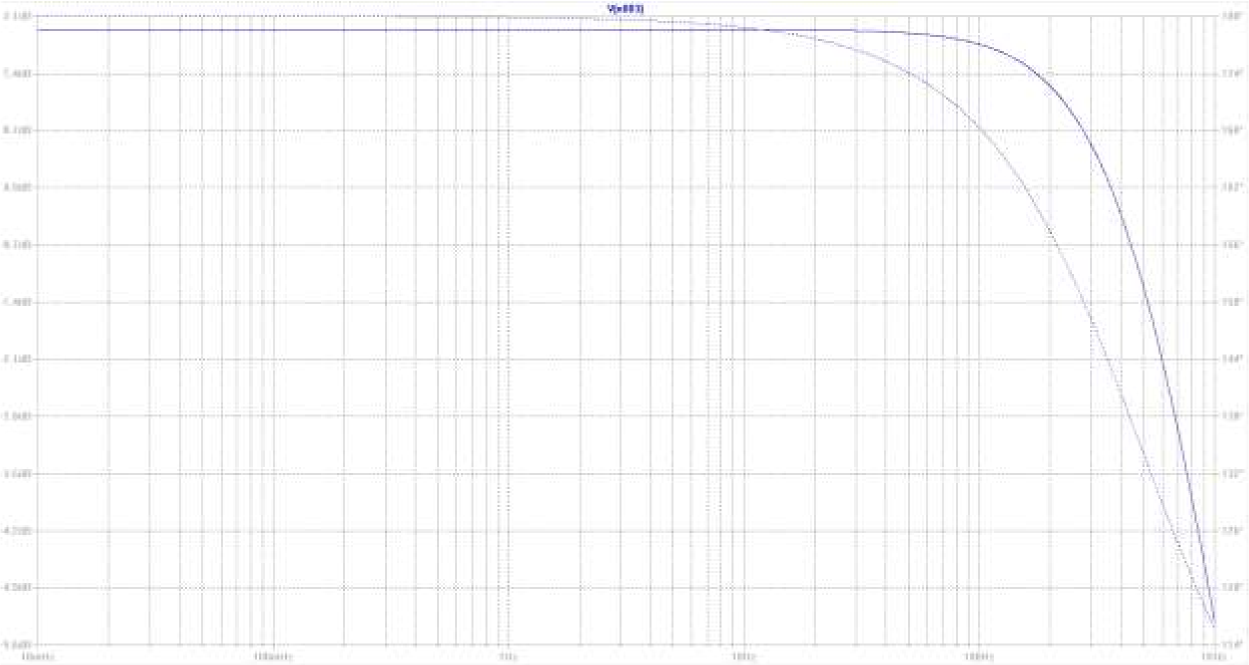


Figure 10: Acquisition Circuit Frequency Response

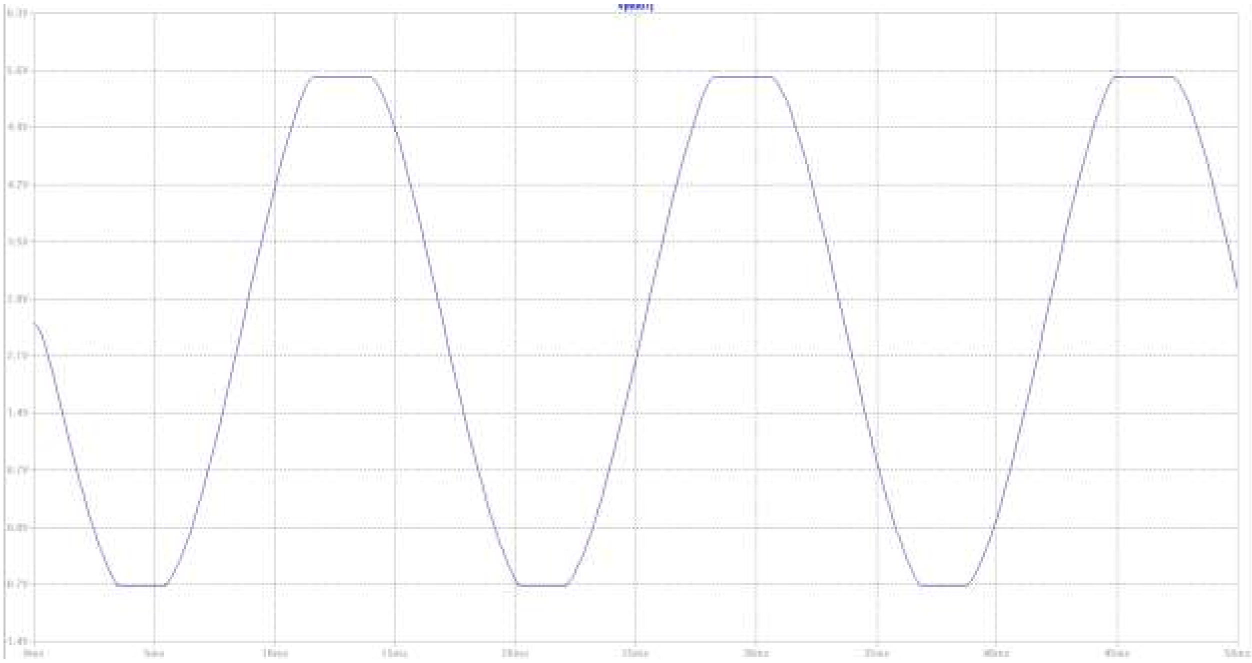
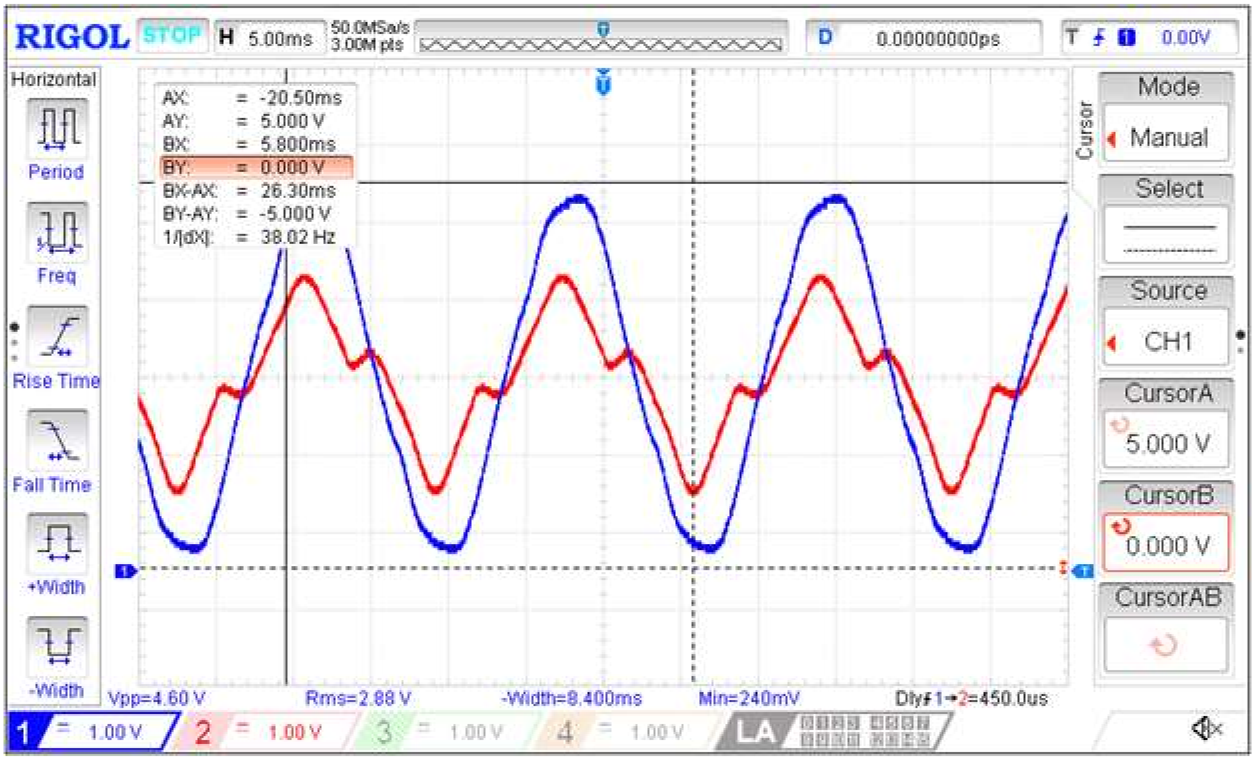


Figure 11: Voltage Acquisition Circuit Response with Over-Voltage



AX: = -20.50ms
AY: = 5.000 V
BX: = 5.800ms
BY: = 0.000 V
BX-AX: = 26.30ms
BY-AY: = -5.000 V
1/|dX|: = 38.02 Hz

Vpp=4.60 V Rms=2.88 V -Width=8.400ms Min=240mV Dly1→2=450.0us

Figure 12: PIC Input Signals from Microwave Load Test

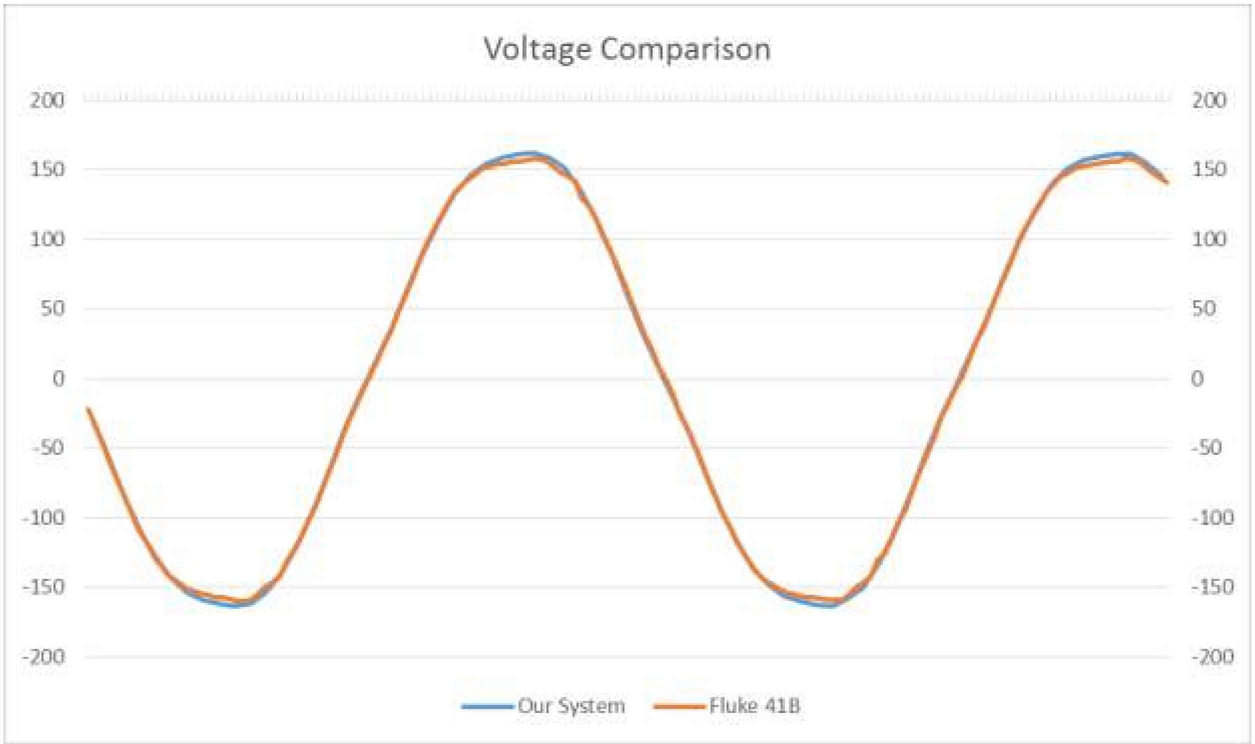


Figure 13: Calibration Test – Voltage Comparison

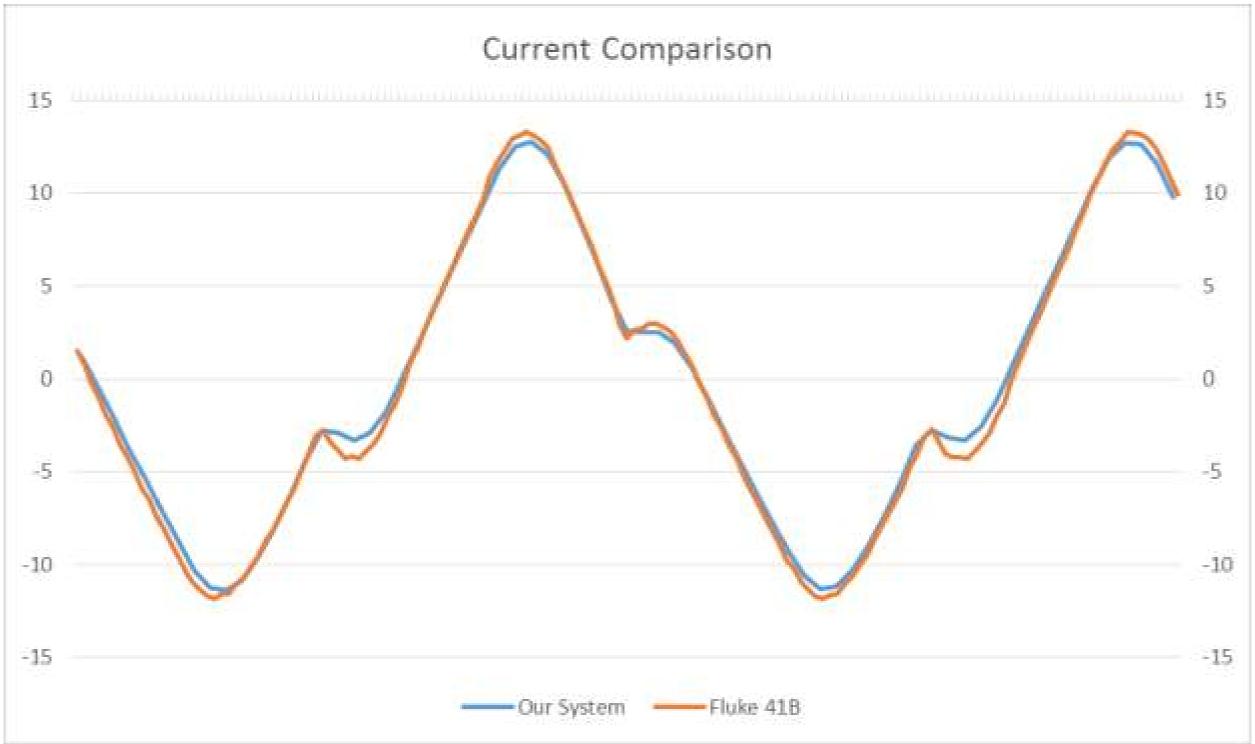


Figure 14: Calibration Test – Current Comparison