Power Scraping Module

DESIGN DOCUMENT

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Client: Honeywell
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Executive Summary

Engineering Standards & Design Practices

1) Digital design standards

- Quartus prime circuit design for FPGA board.
- Cadence simulated circuit testing.

2) Circuit standards

- Readable circuit designs that follow design conventions.

3) Electronic safety standards

- Follow all electrical safety procedures.

Summary of Requirements

1. Use an input of 1.1 V AC to charge a super capacitor and provide an p-p output voltage of at least 3 VDC.
2. The sinusoidal input is the only input in the system.
3. Must provide indication that the selected device is charging.
4. Provide estimation of how long a 20mA LED can be powered for every hour of charge time.

Applicable Courses from Iowa State University Curriculum

- EE 201: Electric Circuits
- EE 230: Electronic Circuits and Systems
- EE 224: Signals and Systems I
- EE 324: Signals and Systems II
- EE 330: Integrated Electronics
- CprE 281: Digital Logic
- CprE 288: Embedded Systems I: Introduction
- MATH 165: Calculus I
- MATH 166: Calculus II
- PHYS 221: Introduction to Classical Physics I
- PHYS 222: Introduction to Classical Physics II
- ENGL 314: Technical Communication

New Skills/Knowledge acquired that was not taught in courses

- Product research and acquisition
- Budget management
- Professionalism and communication

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1. Introduction

1.1 Acknowledgement

Our team would like to thank the Department of Electrical and Computer Engineering for providing our team with resources, consultations, and experiences of the highest quality. We would like to thank our advisor professor Gary Tuttle, our client from Honeywell, Mr. Michael Retzler and Mr. Dakota McGilton for meeting with us bi-weekly and guiding us through the development process of our product. The team also appreciates the University's Electronics and Technology Group (ETG) for providing all the components for our project.

1.2 Problem and Project Statement

As the power needs for remote data transmission gets more efficient, there is a benefit to being independent of a replaceable power source. Collecting, converting, and storing low voltage energy has its own unique challenges.

The goal of this project is to take a small and almost unusable AC voltage as a source and convert it to a usable DC voltage that can power various components in a system.

To accomplish this, an AC voltage of 1.1V peak-to-peak signal will be converted and boosted to a higher DC voltage preferably 3.3 V or greater, at which point it will be used to charge a power source, a battery, or a supercapacitor. The charged source can then be used to power elements in the system. We would be using a 20mA LED to make sure that our system is charging. Our LED will also show whether our supercapacitor has charge or is charging.

1.3 Operational Environment

Most of the low power transmission devices such as embedded devices or remote sensors require batteries that have a limited timeframe in which they can operate and will eventually need to be replaced. Low power energy harvesting allows virtually unlimited amount of operating life for these low power devices. This makes the use of rechargeable batteries impractical and is financially more viable over time.

The product is intended for a general use application, but it may be tailored to fit specific needs. For example, there may be cases where a remote microcontroller will be transmitting signals to a collection site. This application would be ideal when transmissions are infrequent or located in an unserviceable site.

1.4 Requirements

The technical requirements for this project are as follows:

- Use an input of 1.1 V AC Peak to Peak to charge a supercapacitor and provide an
- output voltage of at least 3V DC.
- The sinusoidal input will be the only input in the system.
- Provide indication that the selected device is charging.
- Provide estimation of how long a 20mA LED can be powered for every hour of charge time.
- The overall device must be contained within a 6” by 6” space.

1.5 Intended Users and Uses

The purpose of this project is to research a device that can collect, convert, and store low voltage energy. The intent is to create a device that is an independent rechargeable power source to support power needs of remote data transmission, remote corrosion monitoring systems, implantable devices and remote patient monitoring, structural monitoring, RFID, IOT and equipment monitoring. Our device would harvest and manage surplus energy from an energy harvesting device that would serve as low voltage input. An example use case would be for a photovoltaic cell to input into our device that will store energy over a period of time until enough is stored to power a wireless sensor in a network for a photovoltaic power station. Similarly, another application would be in the field of medicine where such devices could be used to detect, store, and transmit vital information about the parameters such as heart rate, oxygen saturation, respiratory rate that are measured in real time.

1.6 Assumptions and Limitations

Assumptions:

- The device will be protected by an encasing to prevent exposure to extreme operating conditions.
- There will not be any current limitations.
- There would be enough power for charging the supercapacitor.
- The charge would be enough to power an LED for at least 5 hours.

Limitations:

- The cost to produce prototype and product cannot exceed client budget.
- Time constraint on exploring different approaches to generating a solution.
- Whole system must be within 6” by 6” space.
- Only one AC power source that is less than or equal to 1.1 V peak-to-peak.
- Limited current if the signal generator is used as the power source.
- Limited booster module designs that work with specific voltage or power limitations.

1.7 Expected End Product and Deliverables

Semester 1:

1. **Project Timeline and Responsibilities document**
   A project timeline including technical tasks to be accomplished, and a tentative schedule of our meetings was requested by our client. In addition, the team was asked to show which member of our group was responsible for each task to ensure that all members are contributing.

2. **Final Presentation**
   The purpose of this presentation was to extensively review our system design, give a progress update on the prototype construction and testing, and discuss next semester milestones.

3. **Mid-year Report**
   This design document will serve as the mid-year report as requested by the client. This document includes the research that went into the project, design proposal, and performance expectations.

Semester 2:

4. **Project Timeline and Responsibilities document**

   A project timeline including technical tasks to be accomplished in the second semester, and a tentative schedule of our meetings. An updated responsibilities document will outline the roles that members performed for the finalization of the project. This is included in section 4 of this document as well.

5. **Final Presentation**

   The final presentation in April 2020 will revolve around the analysis of our completed circuit design, and explaining the choices made for a specific design. This includes the rationale for choosing specific parts and mentions the alternate parts that were available and could have been used. A final analysis will include the reasons why we did not choose alternate parts and what were the limitations that were associated in using them. In addition, test results will be provided to demonstrate the performance of the design and will disclose the work that went into making it.

6. **Year-end Poster.**
   This poster will display the work accomplished this past year. It will include all the essential requirements of the project, the uses of the projects, the design and the parts used. It will also note the names of the client, our advisor and the team members who worked on the project

7. **Year-end Report**

   The final report will provide extensive details on the testing of the prototype and costs involved for the completion of the project. In addition, a reflection on the process of creating our design and lessons learned along the way. Lastly, the report will include suggestions of how this project can be improved.

2. Specifications and Analysis

2.1 Initial Proposed Design:

The initial proposed design included the following:

A low voltage AC input signal will be fed into a rectifier circuit where it will be converted to a DC signal. The signal will then be boosted to a larger voltage of around 3.3 V which will be used to store charge in the supercapacitor. The power supply will then power a 20mA LED and transmit power to other desired areas in the device.

The team has researched potential low-voltage and precision rectifiers that can be used, as well as the supercapacitors that will best fit the needs of the project [1]. Voltage boosters were also sourced, with the goal being a large increase in voltage and very small loss. Below is a schematic of the initial design:

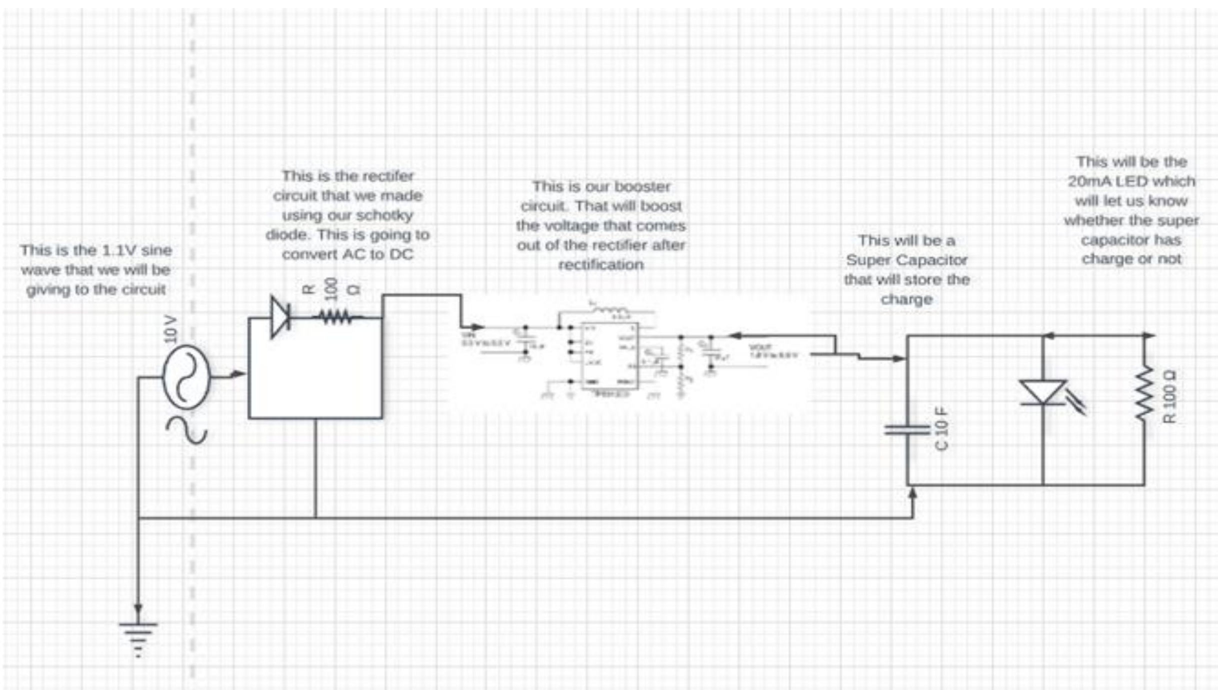


Figure 2.1.1 - Initially Proposed Design Diagram

2.1.1 Final Proposed Design:

After performing various tests on the device, several changes were necessary. The original DC-DC booster module did not perform to specifications, so an alternative part had to be ordered. The Schottky diodes performed adequately and the design now included a full wave rectifier before and after the booster, because the new module that was selected boosted a DC input signal and provided an AC output. The supercapacitors also performed as desired and did not change. In Section 5, the tests that were performed and the component selection process is discussed in more detail.

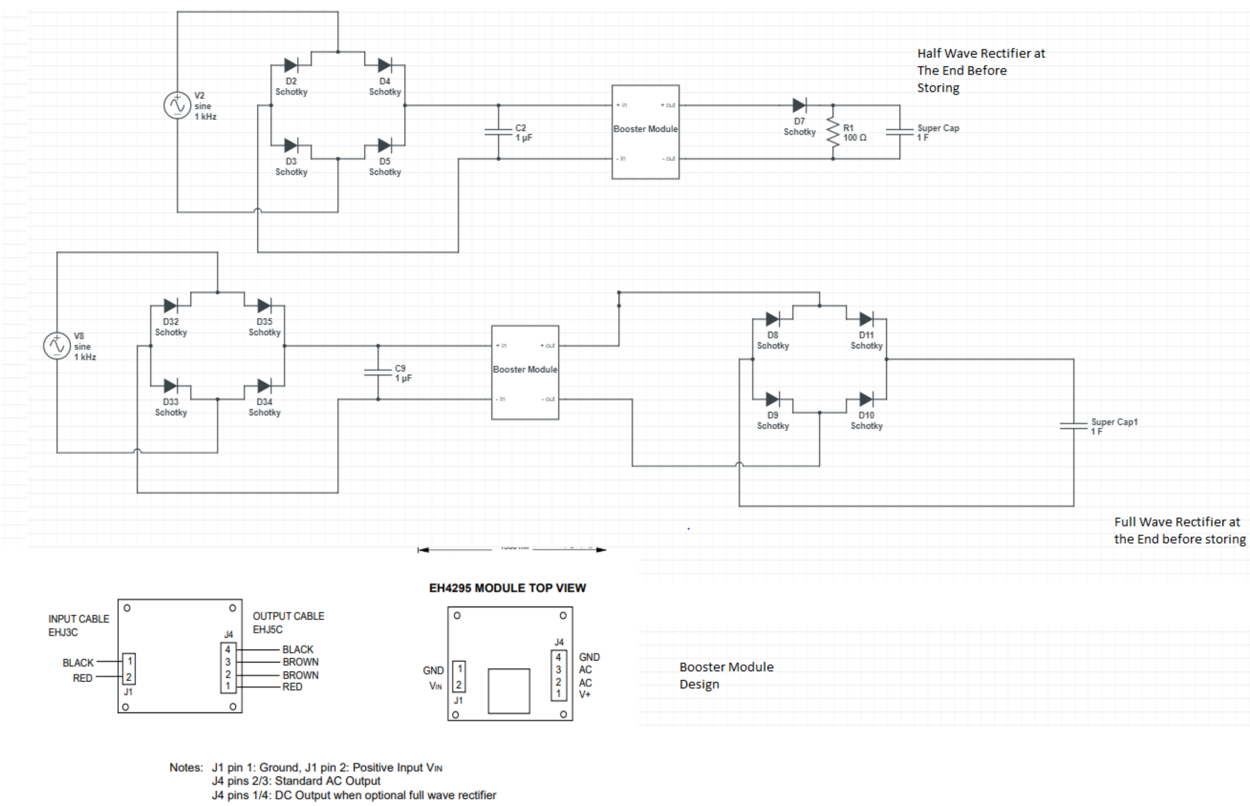


Fig 2.1.2 Final Design.

2.2 Design Analysis

Before we analyzed our entire design based on integrated testing, we analyzed the effects of the individual stages on the system. After modifying the initial design, we analyzed the following. There is a total of four stages for the design of our system: full-wave rectification, boosting, full wave rectification again, and charge storage. Below is a design analysis of each.

The first stage as mentioned in the final design section is the rectification stage. Here the main components are Schottky diodes which feature a low voltage drop. Part of our design analysis is to explore two configurations for this stage: a full-wave and half-wave rectifier. A full-wave rectifier is more advantageous because it utilizes both cycles of the input thus allows for faster charging. The drawback of the full-wave rectifier is that it was expected to have a larger forward voltage drop than the half-wave. After initial testing we determined that the difference in voltage drop for the full-wave versus the half-wave is negligible. Thus, both rectifier stages will be implemented using a full-wave rectifier. This design choice means that the supercapacitor will charge quicker and not limit how low of an input as possible.

The second stage of the design is the booster stage. Unfortunately, the initial booster selected did not perform as expected. Testing for this stage had not produced results that demonstrated it could be used in the final design. During testing the booster was able to boost the voltage significantly. However, the voltage dropped rapidly almost immediately and went back to the initial voltage level. The booster was not able to sustain the voltage at 3V, and the results can be viewed in section 5.

In the final design, a new booster was selected that provided a large enough AC voltage at its output that the signal could be rectified again. This was a newly added third stage in the design. A full wave rectifier was used to rectify the output of the new booster to DC which could then be stored in the supercapacitor.

The last stage of the design is the energy storage stage that consists of a supercapacitor. After testing of this stage, the part ordered worked as expected. No design changes for this stage are anticipated, and the capacitor was also charging as expected.

The greatest strength in the design is the performance of the rectification stage. A primary objective of this project is to see how low of an input can be scraped into a usable DC voltage. The rectification stage potentially allows input voltages around .4-.6 V peak to peak. Initially, the voltage drop was expected to be more significant and thus limit the ability to use a low input. In the new design it still holds true, but the booster can reach up to 4 to 5 V from 0.4 to 0.6 V that is available after rectification.

2.3 Development Process

The development process consisted of continual testing, flexibility with design adjustments, and biweekly meetings with the client and faculty advisor. Members were designated to represent the client's interest by ensuring requirements of the project are met. Other members will be the primary contact for the client and facilitate the technical progress meetings. At these meetings, the team created and prioritized a backlog for the upcoming week then delegated responsibility based on availability. Working with a lot of different hardware in the second semester required careful documentation so that all members knew how each component performed and if any problems were encountered.

2.4 Design Plan

The design plan included four stages: define, ideate, prototype, and testing. The intended purpose behind the first stage was to gather information on energy harvesting, and what solutions already exist. In this stage we met with our client and the stakeholders to help define the problem and understand the constraints given. The information acquired in the first stage facilitated the ideation process. Here we held separate meetings for brainstorming solely with the team and with the faculty advisor. The direction of the project was determined and confirmed with both the advisor and client before prototyping began. Initial prototyping was done on a breadboard and the results would have to be confirmed with the client. If the results would have been unsatisfactory, we would have had to modify the design or find a different approach. In both cases insight about the design and performance limitations could be communicated to our client. Again, the documentation and initial design were finished in the first semester and the finalized design was expected to be accomplished in the second semester.

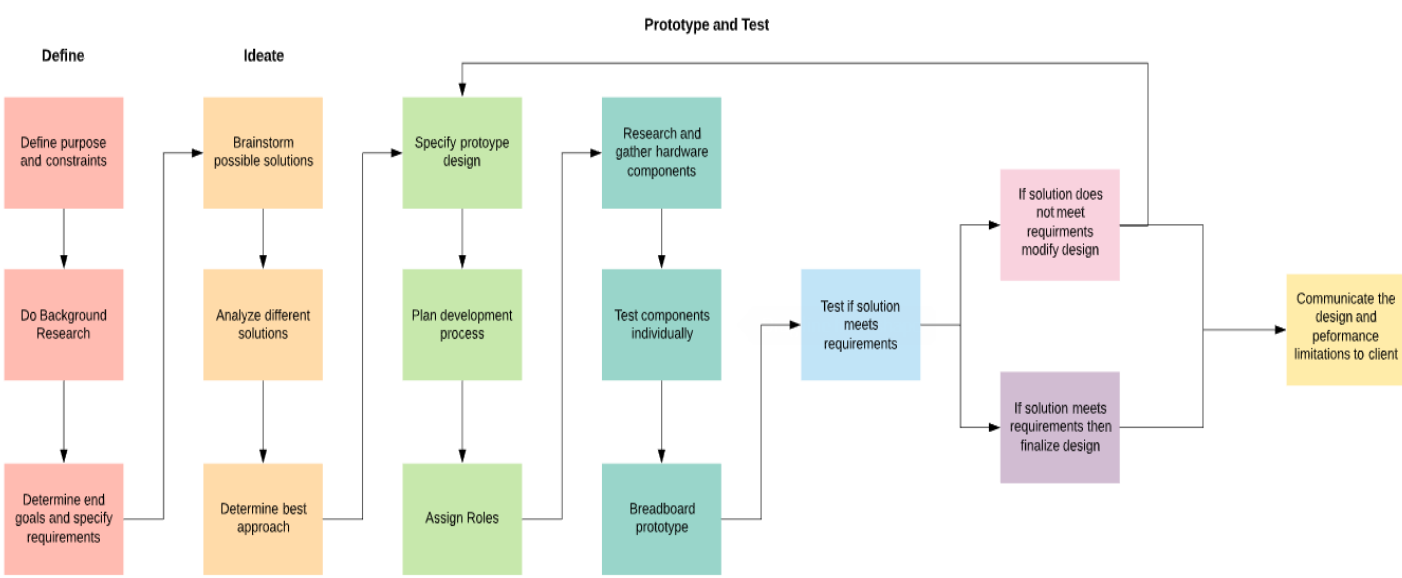


Figure 2.4.1 - Design Plan Diagram

3. Statement of Work

This section of the report will discuss the work that has been performed for the project. It will include research and documents that were referenced for the project, parts that were used, task breakdown, project risk, and milestones and schedules.

3.1 Previous Work and Literature

During the beginning stages of the project, one document that was very beneficial was *Ultra-low Voltage Step-Up Converter and Power Manager.* This detailed a product from Analog Devices that was very similar in functionality to the desired requirements of this project. It utilized several concepts that would be critical for the design, including the following: a low input AC signal, rectification stage, and a boosted DC output. The option of a variable output level selected by the user was also included, which could be a stretch goal for this project.

Although there are many devices in production today that have similar functionality to the module described in this project, the key difference with this project is the extremely low input signal of 1.1 V_{pp}. This is below the threshold of the majority of boosters on the market and as a result, a module with these specific requirements does not yet exist. Additionally, this design includes a supercapacitor as the energy storing element, as opposed to a small battery cell or simply no energy storage element that many devices have.

The following list are the key components selected for this project:

1. **Supercapacitor [2]:**

    Digikey number :1572-1771-ND
    Manufacture number: **DGH105Q5R5**

2. **Schottky Diode [3]:**

    Digikey number: 1655-1922-3-ND;
    Manufacture number: **95SQ015**

3. **DC to AC Voltage Booster [4]:**

    Digikey number: 1014-1207-ND
    Manufacture number: **EH4295**
    Data sheet: http://www.ti.com/lit/ds/symlink/tps61200.pdf

3.2 Technology Considerations

Although voltage boosters and signal rectifiers are currently available on the market, there are not any that satisfy the needs of this project. Most existing boosters are either DC to DC or AC to AC. Additionally, the signal strength desired for this project is below the limits of comparable boosters.

There are also rectifiers available, but again, the low-level input required for this project would render them unusable as there would be no signal left to boost after rectification. Due to the low-input signal that needs to be boosted, a rectifier using Schottky diodes must be designed to limit the amount of signal loss.

Even using Schottky diodes, the design will be using a half wave rectifier as opposed to a full wave model. This is another method to reduce voltage drop in the system but will result in a slower charging time for the supercapacitor at the output of the device.

3.3 Task Decomposition

In order to solve the problem at hand, it helps to decompose it into multiple tasks and to understand interdependence among tasks. The first task was to develop an accurate design to make sure that it can achieve the required output. Use of a booster first is not ideal since most boosters take DC as input to give DC as output or take an AC as input to give AC as an output. This requires the use of a rectifier first before the signal is boosted to the required voltage that would be stored in the supercapacitor. The following is a list of tasks performed for the completion of this project:

1. Researched all parts: the booster, rectifier, supercapacitor, and LED

2. Selected a booster that can take as low of a voltage as possible and then boost it to 3.3V and above

3. Make use of Schottky diodes that only require voltage drops of 0.2 to 0.3 V for them to operate. Use of standard diodes with 0.7 V of drop will incur excessive losses.

4. Selected a supercapacitor that can store a charge of 1 Farad or less. The higher the charge level the longer it will take the supercapacitor to charge.

5. Connected an external input source of 1.1 Vpp to a rectifier to output a DC signal. Then used the DC voltage as an input to the booster so that it could amplify the voltage to 3.3V. Stored that charge into the supercapacitor and then used that to light the LED.

A systematic approach was necessary to ensure all work was done in the correct order and project deadlines were met throughout the process.

3.4 Possible Risks and Risk Management

Risks:

The following are some of the risks that were faced during the project:

1. Booster functionality: amplifies a small voltage (in the range of 0.2 V- 1 V) to 3 V or above.
2. Rectification losses: excessive loss during the rectification stage would render the rest of the device nonfunctional.
3. Energy storage capabilities: The supercapacitors have a large enough capacitance to hold all the charge in the system, but not so large that the system charge time is excessively long.

Risk Management:

These are the methods that were used to mitigate risk within the project:

1. Each of the parts were tested at a component level before implementation in the device, to ensure functionality.
2. If the booster did not function as desired, alternate booster designs were used.
3. Consulting the faculty and client for challenges that are outside the abilities of the members of this team.
4. Schottky diodes have been selected to minimize the voltage drop and resulting losses to the system from the rectification stage.

3.5 Project Proposed Milestones and Evaluation Criteria

Preliminary design schematic:

The initial phase of the project included designing a schematic and running simulations, using software such as PSpice. The simulations verified if the design was acceptable before acquiring parts and moving forward to the next phase.

Identify parts:

After the initial design was simulated, it was presented to the client along with a list of the necessary parts to construct the module.

Breadboard prototype and design schematic update:

Once initial parts were received, a prototype device was constructed. During this phase, changes and alterations that occurred were reflected in the schematic and existing design, as well as an updated list of components.

PCB prototype:

Upon completion of the prototype device, a PCB layout of the model will be designed. After the PCB design is completed it will be ordered. If it does not come completely assembled, any remaining alterations will be done in the ISU lab facilities with the equipment accessible to the team.

Note: Although this was the projected direction for the project, final testing of the breadboard prototype was not able to be completed due the campus shutdown in response to COVID-19. Since testing of the prototype was not finished, the team was unable to move forward to PCB design and build.

Evaluation Criteria:

These are the evaluation criteria that will determine the functionality of the project:

1. Preliminary schematic must reflect desired functionality of the module.
2. Parts used must fit within the project budget.
3. Complete schematic must be updated as the prototype is built.
4. Breadboard prototype should function as desired before creating PCB prototype.
5. PCB prototype must satisfy all requirements stated in the project outline.

3.6 Project Tracking Procedures:

Using the timeline and project milestones, progress was tracked by comparing completion status of the milestones to the corresponding deadlines. In addition, bi-weekly progress reports were posted to the team website. These reports included what was accomplished each week, assigned tasks for the upcoming week(s), and how many hours have been contributed by each member since the last report.

During meetings with the faculty advisor and client, notes were recorded and uploaded to the group messaging platform. This was done to ensure that everyone was aware of their responsibilities for the week. This also ensured that each member of the team was responsible for their tasks. Lastly, all progress was documented in a shared google folder. This included test results, class assignments, and an updated project timeline.

3.7 Expected Results and Validation:

Some of the expected results would be that all parts have been tested and verified as functional before inclusion in the design. If any parts do not perform as necessary, then alternate parts or design methods were selected. The verification of component-level functions helps the troubleshooting process at the system level if problems arise. The result being a functional power-scraping module that boosts and rectifies a low-level AC input signal and stores a larger DC voltage in a supercapacitor. This is a general-purpose module and can be tailored to specific applications at either the input or output stages.

4. Project Timeline, Estimated Resources, and Challenges

Following is the timeline, the roles, and responsibilities of each individual and the estimated resources necessary to complete the project. Challenges faced throughout the project will also be discussed.

4.1 Project Timeline

The team planned to mitigate some of those challenges to bring the final design sufficiently.

	TASK NAME	START DATE	END DATE	WORK DAYS	DAYS Finished	TEAM MEMBER	PERCENT COMPLETE
First Sample Project							
	Team formations & project descriptions	8/26	8/31	6	6	Shahzaib Shahid	100%
	Team expectation and setting roles	9/2	9/7	6	6	Andesen Ande	100%
	Meeting with faculty	9/9	9/13	5	5	Benjamin Yoko	100%
	Design document formation	9/10	9/14			Xiangyu Cao	100%
	Project description & lightning talk	9/16	9/20	5	5	Ahmed Salem	100%
	Pre-liminary design schematic	9/23	9/27	5	5	Jordan Fox	100%
Second Sample Project							
	Assigning project	9/30	10/4	5	5	Shahzaib Shahid	100%
	Search For Parts & meeting with faculty and client	10/7	10/11	5	5	Andesen Ande	100%

	Confirm budget and confirm timeline	10/14	10/16	3	3	Benjamin Yoko	100%
	Meeting with faculty on design options	10/17	10/18	2	2	Xiangyu Cao	100%
	Weekly status report 4, design document version 2 , contact client	10/21	10/24	4	4	Ahmed Salem	100%
	Build a schematic & meeting with faculty	10/25	10/27	3	3	Jordan Fox	100%
Third Sample Project							
	Pre-liminary design schematic, weekly status report # 3, design document expansion	10/28	11/1	5	5	Shahzaib Shahid	100%
	Search For parts, and discuss their specification with third party	11/4	11/8	5	5	Andesen Ande	100%
	Discuss design, search for parts, and confirm budget	11/11	11/13	3	3	Benjamin Yoko	100%
	Confirm timeline and meeting schedule	11/14	11/15	2	2	Xiangyu Cao	100%
	Weekly Status report 4, design document version # 2.	11/18	11/29	12	12	Ahmed Salem	100%
	Get parts, build prototype on breadboards, weekly status report.	12/2	12/6	5	5	Jordan Fox	100%
Fourth Sample Project							
	Build prototype on breadboards, design document V3,	12/9	12/10	2	2	Shahzaib Shahid	100%
	Testing of the breadboard prototype, weekly status report 6	12/10	12/11	2	2	Andesen Ande	100%
	Check For issues and testing For Improvements	12/11	12/13	3	3	Benjamin Yoko	100%

	Design Efficiency Check	12/13	12/14	2	2	Xiangyu Cao	100%
	Final Prototype design and testing., and finalize the design document	12/14	12/15	2	2	Ahmed Salem	100%
	Final presentation for the design.	12/15	12/16	2	2	Jordan Fox	100%
Fifth Sample Project							
	Meeting with faculty and client on alternative solutions	1/30	2/10	12	12	Shahzaib Shahid	100%
	Testing and updating schematics, peer evaluation survey, and weekly status report 1 and 2	2/10	2/18	9	9	Andesen Ande	100%
	Check For issues and testing For Improvements	2/18	2/23	6	6	Benjamin Yoko	100%
	Ordering new parts, and testing them	2/23	2/26	4	4	Xiangyu Cao	100%
	Meeting with advisor to discuss some challenges in boosting and capacitance efficiency	2/26	2/28	3	3	Ahmed Salem	100%
	Unit testing to include testing the individual components such as booster, diode, and capacitor	2/28	3/2	3	3	Jordan Fox	100%
Sixth Sample Project							
	searched for alternative solutions, and updated schematics	3/2	3/5	4	4	Shahzaib Shahid	100%
	Testing of the breadboard prototype, weekly status report 3 and 4	3/5	3/11	7	7	Andesen Ande	100%
	demonstrate the alternative solution is reliable, trustworthy, and successful	3/11	3/15	5	5	Benjamin Yoko	100%

	components efficiency checks, and peer evaluation presentation/video	3/15	3/22	8	8	Xiangyu Cao	100%
	created different type of modules for integrating testing and testing each module's effect on the entire system.	3/22	3/24	3	3	Ahmed Salem	100%
	Integrating testing where booster, diode and capacitor are integrated together as one system. Also, evaluated the faults due to the interaction between integrated units, and discussed the results with clients and advisor	3/24	3/25	2	2	Jordan Fox	100%
Seventh Sample Project							
	Build prototype on breadboards, design document V3,	3/25	3/27	3	3	Shahzaib Shahid	100%
	Testing of the breadboard prototype, weekly status report 5	3/27	3/29	3	3	Andesen Ande	100%
	Check For issues and testing For Improvements	3/29	3/30	2	2	Benjamin Yoko	100%
	Design Efficiency Check	3/30	4/1	3	3	Xiangyu Cao	100%
	Final Prototype design and testing., and finalize the design document	4/1	4/3	3	3	Ahmed Salem	100%
	System testing where testing the level of completion of an integrated system. Also, evaluated the project specification requirement with system's compliance to include the capacitance, diode and booster efficiency	4/3	4/5	3	3	Jordan Fox	100%
Eighth Sample Project							
	Facilitate the reuse of the component testing cases, and improve traceability between lab testing and schematics	4/5	4/9	5	5	Shahzaib Shahid	100%

	testing data analysis, weekly status report 6	4/9	4/12	4	4	Andesen Ande	100%
	Adjusted Deliverables	4/12	4/14	3	3	Benjamin Yoko	100%
	Acceptance testing to evaluate system's compliance with client requirements and assess whether it is acceptable to collect , rectify, boost and finally deliver the required current and voltage to power the indicator during a specific period of time.	4/14	4/18	5	5	Xiangyu Cao	100%
	finalize the design document , poster, and pear evaluation report	4/18	4/20	3	3	Ahmed Salem	100%
	Final presentation completion	4/20	4/22	3	3	Jordan Fox	100%

Figure 4.1.1 - Timeline and Task Breakdown

The proposed timeline was part of the agreement to make sure the work was to be done as was planned. The timeline had many advantages, including keeping everyone on the same page, defining the roles and responsibility for each team member, and holding team members accountable for their work.

Even though the new changes had to be considered toward the end of the second semester, the overall timeline allowed the team to be on the same page and adhere to the project requirements.

4.2 Feasibility Assessment

The objective of the project was to create a circuit that took in the low input signal, boost, and stored that signal for later use. The client requested research on the limitations from a design and components standpoint. Initially, a few different design approaches were considered, such as using an IC transformer to boost the input signal before rectification. The biggest challenge was minimizing losses in the circuit while operating at an extremely low voltage. The team incorporated a new model to provide a useful insight into the system and component integration.

4.3 Personnel Effort Requirements

This table represents the main tasks that were necessary to complete the project. Each primary responsibility is listed, described, and given an estimated time of completion. Justifications for each time estimate are given but completed before any work.

Task	***Description***	***Approx. Completion Time***
Research Power Scraping Module	***Research key topics: rectification, supercapacitors, DC-DC boosters.***	***5 hrs. This task includes all team members gathering information online.***
Create an initial design of circuit	***Outline objectives given by the client. Brainstorm different designs and research components as a team. Assess design with the client and faculty advisor.***	***15 hrs. Will require separate meetings between the team members, faculty advisor, and client.***
Select and order components of the design	***Browse the Digi-key website and other resources for components for the prototype circuit.***	***10 hrs. The collective time for each member to thoroughly research parts and agree on each other's selection.***
Component Testing	***Once the parts are received, use lab instruments to test if parts perform according to the part description.***	***15 hrs. We anticipate testing the booster module may take more time than other components because we are less familiar with it.***
Integration Testing	***Connect circuit components each stage at a time and test the performance***	***15 hrs. Integration testing anticipated to take at least as long as the time required for testing individual components***
System testing	***Testing the fully integrated applications, including external factors to check how rectifier, booster, capacitor, and LED are interacting with one another and with the system as a whole.***	***25 hrs. The system integration was a collaborative work between the team members, client, and advisor.***
Acceptance testing	***Testing different elements and approaches that have been proposed. We used different designs to simulate the component testing and the system as a whole to allow us to have a much closer look and finally get everyone acceptance. During this stage, we had a closer collaboration between team members to provide a clear and unambiguous contract between our team on hand and the customer and client on the other side.***	***15 hrs. The accepting testing was very challenging due to the circumstances of COVID-19. We put our thoughts together as a team to develop a similar finish project, as we have planned earlier. The project is mainly based on lab equipment even though all the challenges, we were capable of overcoming those challenges and delivering the finished project most desirably.***

Table 4.3.1 - Task Breakdown for Project

4.3.1 Roles and Responsibilities:

The following are some of the roles and responsibilities that each one of the team members had to do this year. These documented responsibilities ensured that each member is held accountable for the duties that the member did not finish.

Names	***Roles & Responsibility***	***Tasks***
Shahzaib Shahid	***Team leader***	***Team formations & project descriptions, Team expectation and setting roles, Design document formation, Project description & lightning talk, Pre-liminary design schematic, Design document review, Build prototype on breadboards.***
Andesen Ande	***Report Manager***	***Testing of the breadboard prototype, Search For Parts & meeting with faculty and clients, Design Efficiency Check, Design document review, Searched for alternative solutions.***
Benjamin Yoko	***Test Engineer***	***Update schematics, checking components efficiency, created different type of modules for testing, Integrating testing, Testing each module effect on the entire system, Evaluated the faults due to the interaction between integrated units, Build prototype on breadboards.***
Xiangyu Cao	***Chief Engineer***	***Confirm budget and confirm timeline, Check For issues and testing For Improvements, Design Efficiency Check, Final Prototype design and testing, System testing, Peer evaluation report, Facilitate the reuse of the component testing cases***
Ahmed Salem	***Test Engineer***	***Check For issues and testing For Improvements, Adjusted Deliverables, assigning projects, testing of the breadboard prototype, improve traceability between lab testing and schematics, Designing poster***
Jordan Fox	***Design engineer***	***Testing data analysis, Acceptance testing, Finalize the design document, Final presentation completion, Build a schematic & meeting with faculty.***

Figure 4.3.1 - Roles and Responsibilities of Team Members

4.4 Other ResourceRequirements

In this section, the primary and secondary resources that were used in the design are discussed.

Primary Resources Needed:

- Breadboard, and wires
- Supercapacitor - around five devices
- Schottky Diode - around ten devices
- DC-DC booster – around three devices
- Power Supply, oscilloscope and multimeter provided by Iowa State University lab
- Scope of Work (SOW) provided by the client.
- Products specifications provided by the supplier.
- Notes provided by the clients.
- Notes provided by the professor.

Secondary Resources Needed:

- Textbooks, Book Reviews, and Research Papers.
- Iowa State Online Library.

4.5 FinancialRequirements

The total budget for the completion of the project is less than $400, as expected. This amount was a conservative figure that accounted for both the prototyping and PCB fabrication costs for the circuit. Below is the budget table that accounts for all materials that were not provided by Iowa State University.

Part Name	Seller	Part Number	Amount Ordered	Total Cost per part
Supercapacitor	Digi-Key	1572-1771-ND	5	$14.35
Schottky Diode	Digi-Key	1655-1922-3-ND	10	$5.02
DC-DC Booster	Digi-Key	1568-1155-ND	3	$47.85
Schottky diode	Digi-Key	1655-1922-1-ND	20	$13

Part Name	Seller	Part Number	Amount Ordered	Total Cost per part
MICROPOWER LOW VOLTAGE BOOSTER	Digi-Key	1014-1208-ND	2	$128.5
MICROPOWER LOW VOLTAGE BOOSTER	Digi-Key	1014-1207-ND	1	$64.25
CABLE OUTPUT FOR EH42 MODULE	Digi-Key	1014-1206-ND	3	$22.53
			Total Cost	$295.95

Table 4.5.1 - Budget for components to be ordered

5. Testing and Implementation

In this section, information regarding the testing is presented. This includes equipment testing, individual component testing, and system-level testing.

5.1 Interface Specifications

For testing of the prototype circuit, lab instruments will be used to determine that each individual circuit component worked as expected. Once the team confirmed that each component worked separately, the implementation process started as the first stage. The plan was to test and observe how each individual component behaved when interfaced with another. Once the entire circuit performed as desired on the breadboard, extensive testing was done to build the final design, conduct testing and verification of its working over the course of the remaining academic year. The team tested different inputs and measured for every hour of scraping how long could the system drive a 20 mA LED to understand the performance and design limitations and expectations.

5.2 Hardware and Software

The hardware used for testing the circuit included a breadboard, multimeter, oscilloscope, and function generator. Tektronix 3021B function generator is a device that produces a time-varying voltage signal that is used as the input for the circuit. Agilent DSO-X-2024A digital oscilloscope is a device that takes voltage measurements rapidly and plots voltage as a function of time. The oscilloscope is used to observe the input-output relation to confirm the diode is rectifying as expected. The main purchased parts are EH4295 micropower low voltage booster manufactured by Advanced Linear Devices Inc;

Schottky Diode 95SQ015 manufactured by SMC Diode Solutions. Initial design included the use of a PRT-10255 voltage booster manufactured by SparkFun Electronics. The supercapacitor was used as a source of storage for the charge produced.

5.3 Functional Testing

Functionality tests were run often throughout the development process to ensure that the team was adhering to the client's expectations as well as be able to quickly identify what specifically was the problem. The team implemented three phases of testing: unit, integration, and system. This is a methodical approach often used in a software development however the principles of this method apply to the hardware development process.

The first phase was unit testing which consisted of evaluating individual circuit components. All unit test processes are detailed in section 5.5; this section will briefly discuss the purpose and performance expectations. The design as stated previously consists of three main components. The first unit test was for the Schottky diodes. Here the team conducted two separate unit tests for two different configurations to gather information about the voltage drop. The results of this unit test aided the team in making a design choice as well as shaped the expectations for the next phase of testing. The second unit test was for the supercapacitors. Here nominal values were given from the manufacturer about the capacitance. In practice these values were not ideal, and thus needed to be measured for true capacitance values and labeled. This was done to track if the components were within tolerance and so that the team could understand the results of later testing phases in conjunction with the results from this phase. The last unit test was performed on the booster module to ensure that it boosted voltage within the advertised range of .3-5.5 V. For the design's application, the team considered the lower part of the range, mainly from 0.5-0.8V.

The second phase was integration testing which consisted of evaluating circuit performance after adding parts sequentially. The team performed two separate integration tests. The first integration test was to connect the rectifier output to the booster module input. The output of the rectifier stage was a DC voltage however it must be assessed if the ripple voltage was small enough to not distort the output. If the smoothing capacitor value was correct, then this should not have been an issue. The team also checked to see what the maximum and minimum output of these two stages were. The second integration test consisted of using lab generated signals as input for the booster and connecting the supercapacitor. This test was for sanity check to see if the two components were behaving as expected.

Lastly, the team performed a full system integration test where all three components were connected and evaluated. Here the input of 1.1 V peak and peak was used and then it was decremented by .05 or .1 V and the output was evaluated. Probes from the oscilloscope were used at the connection points on the circuit to confirm results were consistent with expectations and the system output was evaluated. We measured for every hour of power scraping how long could the system drive a 20 mA LED. All functional requirements as outlined from the client were considered during this phase of testing.

5.4 Non-Functional testing

Efficiency Testing:

There are three stages of the system that can improve the efficiency of the module.

1. **Rectification Stage:**

   The final design now indicates that the full wave rectifier with the smoothing capacitor gave the best output signal to the booster, but if the system can maintain the output stability of the full wave rectifier with half wave rectifier, it can potentially improve the efficiency of the system [6].

2. **Voltage Boosting Stage:**

   The voltage booster purchased had an efficiency of around 90% which is sufficient, but there might be room for improvement with a different module.

3. **Output:**

   When releasing the power from the super capacitor, leakage current can be reduced to make full use of the energy collected. This can increase the efficiency of the system, in terms of outputting energy.

Usability and Compatibility:

Since the desired outcome of the device is a relatively simple concept, take a small AC input and turn it into a usable DC output, there are a variety of applications it could be used for. As such, the usability and compatibility of the project go hand in hand. The use case for the device is any larger circuit that has small, miscellaneous AC voltages that could be applied to a specific purpose. For compatibility, it was necessary to ensure that the device can effectively power a small DC component (a microcontroller being the simplest example) without burning out the device. This may require simple modifications regulating the power output, depending on the application. Testing for these conditions will require a prototype device to determine that it can actually receive the small AC input, and then boost, convert, and charge/power another device. This testing took place during the second semester of the design project.

5.5 Process

In this section the components used for the project and the various test circuits are shown and discussed.

Rectifier Testing:

The following is the schematic of the halfwave rectifier. The purpose of this testing is to accurately record the behavior of a single diode and the amount of rectification we can achieve with a single diode. The advantage of a halfwave rectifier is its output voltage is higher due to the number of diodes we use, which is one. It can potentially reduce the difficulty of the voltage booster stage of the system. The input testing signal is 1.1V p-p sine wave at 1k Hz frequency. The diode is 95SQ015 Schottky diode which has an ultra-low forward voltage drop at about 0.35V. Following is a schematic of the half wave rectifier circuit. The testing was done with different loads with resistor values ranging from 33 to 10K.

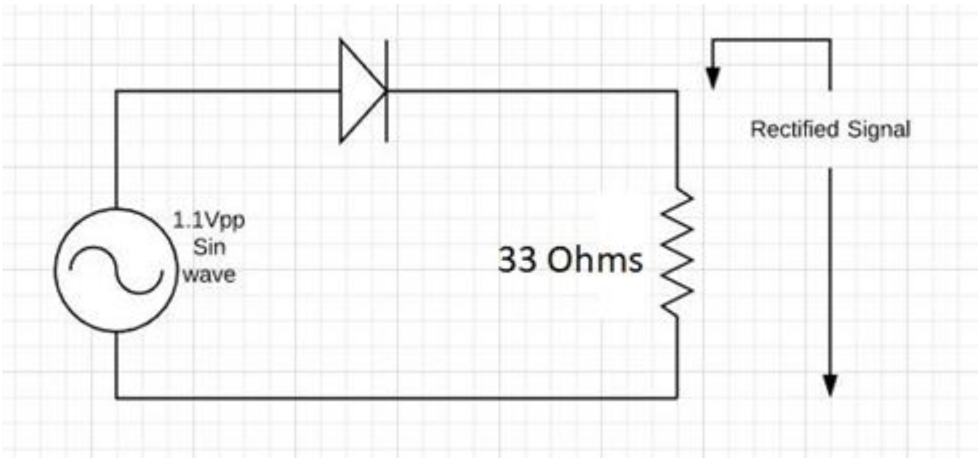


Figure 5.5.1 Half Wave Rectifier Schematic

The following is the schematic of the full wave rectifier design that was also tested to see which one is better for the design. The input testing signal is 1.1Vp-p sine wave at 1kHz frequency. The same diode is being used as in the half wave rectifier circuit. The only difference is that there are four diodes as opposed to one. The resistor is a 10k resistor. The expected waveform on the output end is the absolute value of the sin wave. However, the input signal and output signal do not share the same ground, so it is not possible to present them on the same screen.

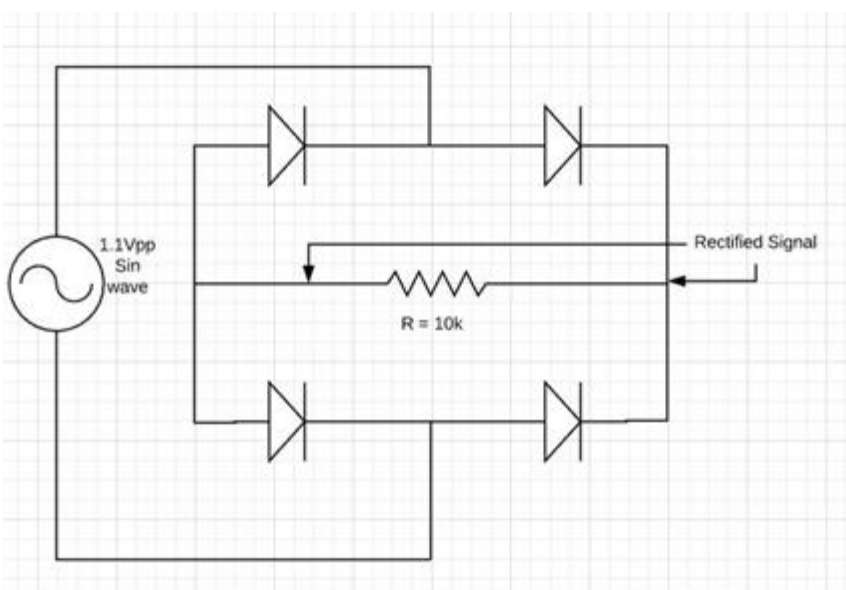


Figure 5.5.2 Full Wave Rectifier Schematic

The following is a schematic of another full wave bridge rectifier design, using the same rectifier and voltage source. However, a 10uF capacitor was added. The advantage of this design is the capacitor can smooth out the waveform to make it closer to the actual DC signal. The expected waveform on the output end is the absolute value of the sin wave. Below is a schematic of the design:

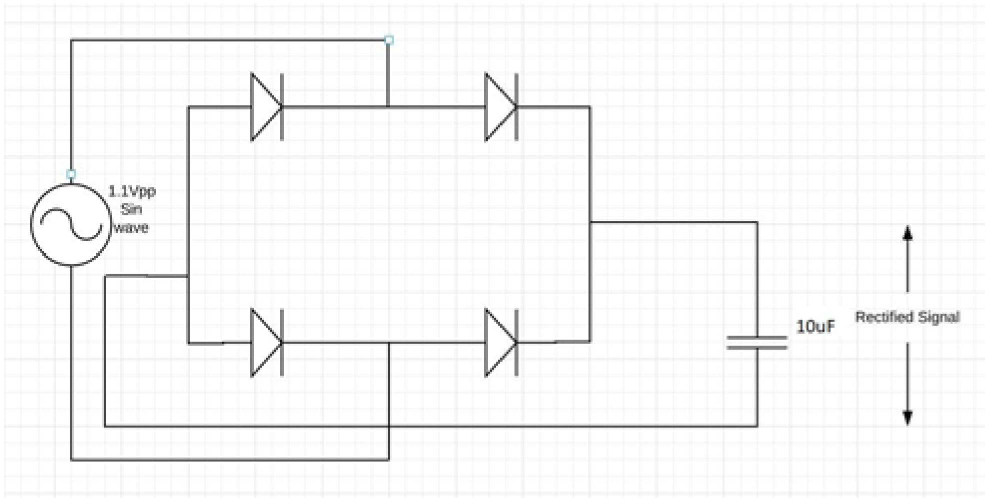


Figure 5.5.3 Full Wave Rectifier Schematic With Smoothing Cap

Booster Testing:

The following is a schematic of the voltage booster testing circuit. The booster came in a prototype board with all the components needed so it could be tested directly with the protection circuit. The input provided was 0.3V DC, and a 10k protection resistor was included with the parasitic capacitor to prevent the analog circuit from interfering with the digital circuit.

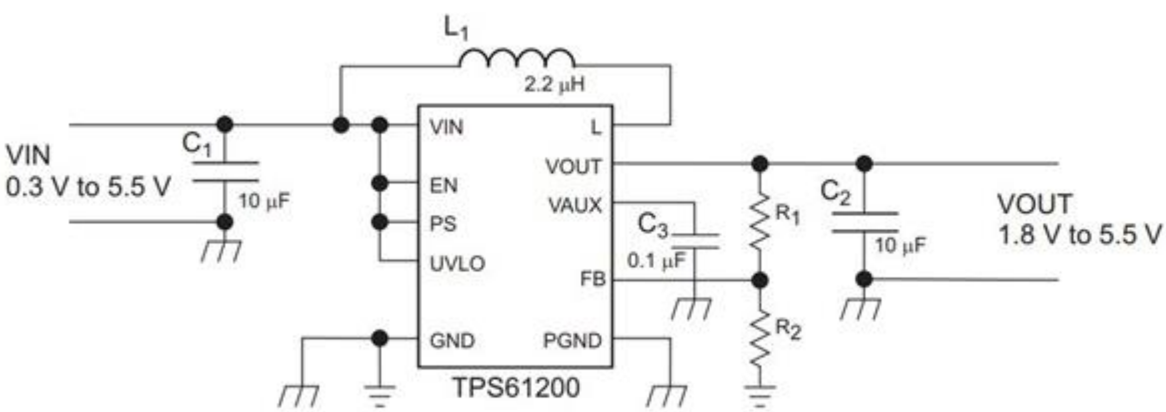


Figure 5.5.4 Booster Testing Schematic From Data Sheet

The booster was hooked up with a 0.3V DC voltage from a power source and the grounds were connected. A 10K resistor was also added in parallel as a protection resistor to avoid burning out the booster. The following schematic shows how the circuit was hooked up onto a breadboard:

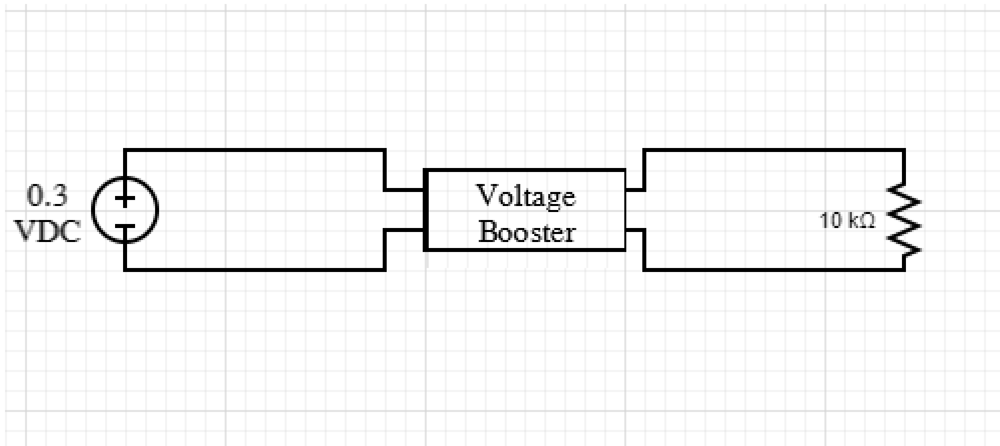


Figure 5.5.5 Booster Testing Schematic

After initial testing of the booster, the setup was reconfigured for an additional round of testing. This time, a 100 Ω resistor was placed in series with a red LED to act as the load of booster output. A DC voltage was applied as the input at varying levels, and a voltmeter was attached over the entire output to measure the boosted voltage. The results of this test are discussed in section 5.6 of the report.

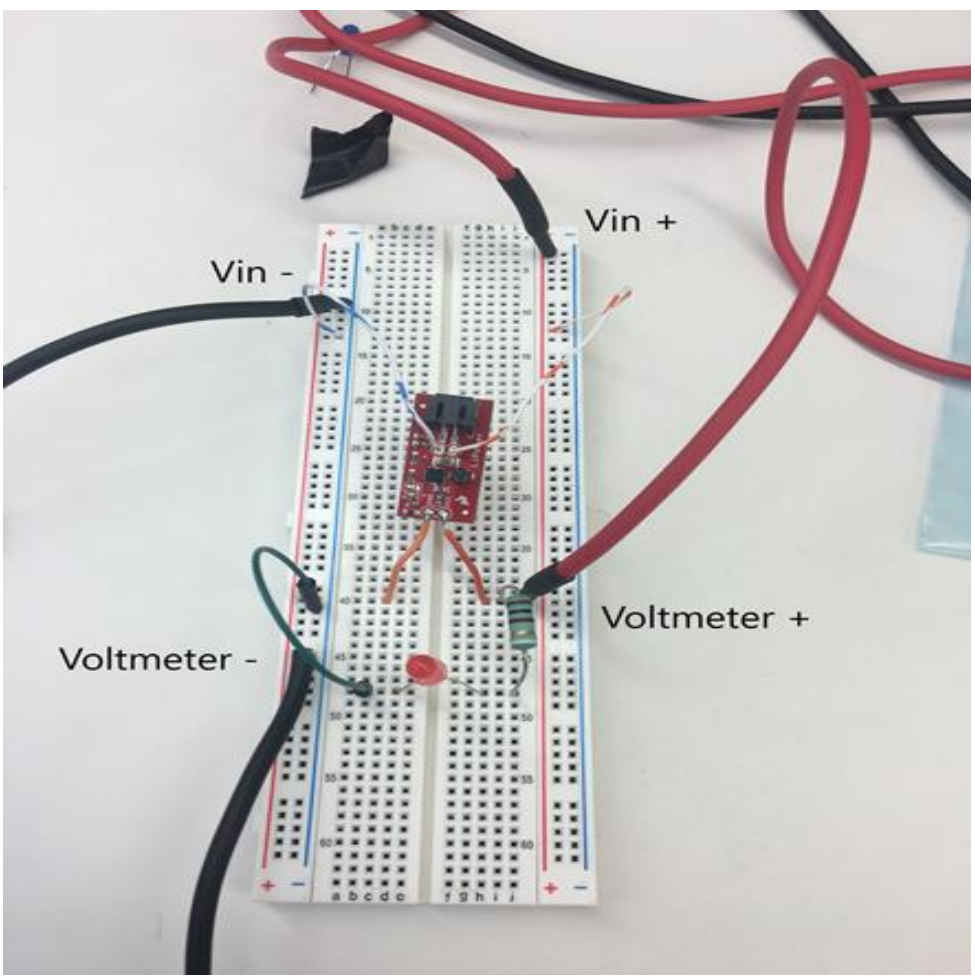
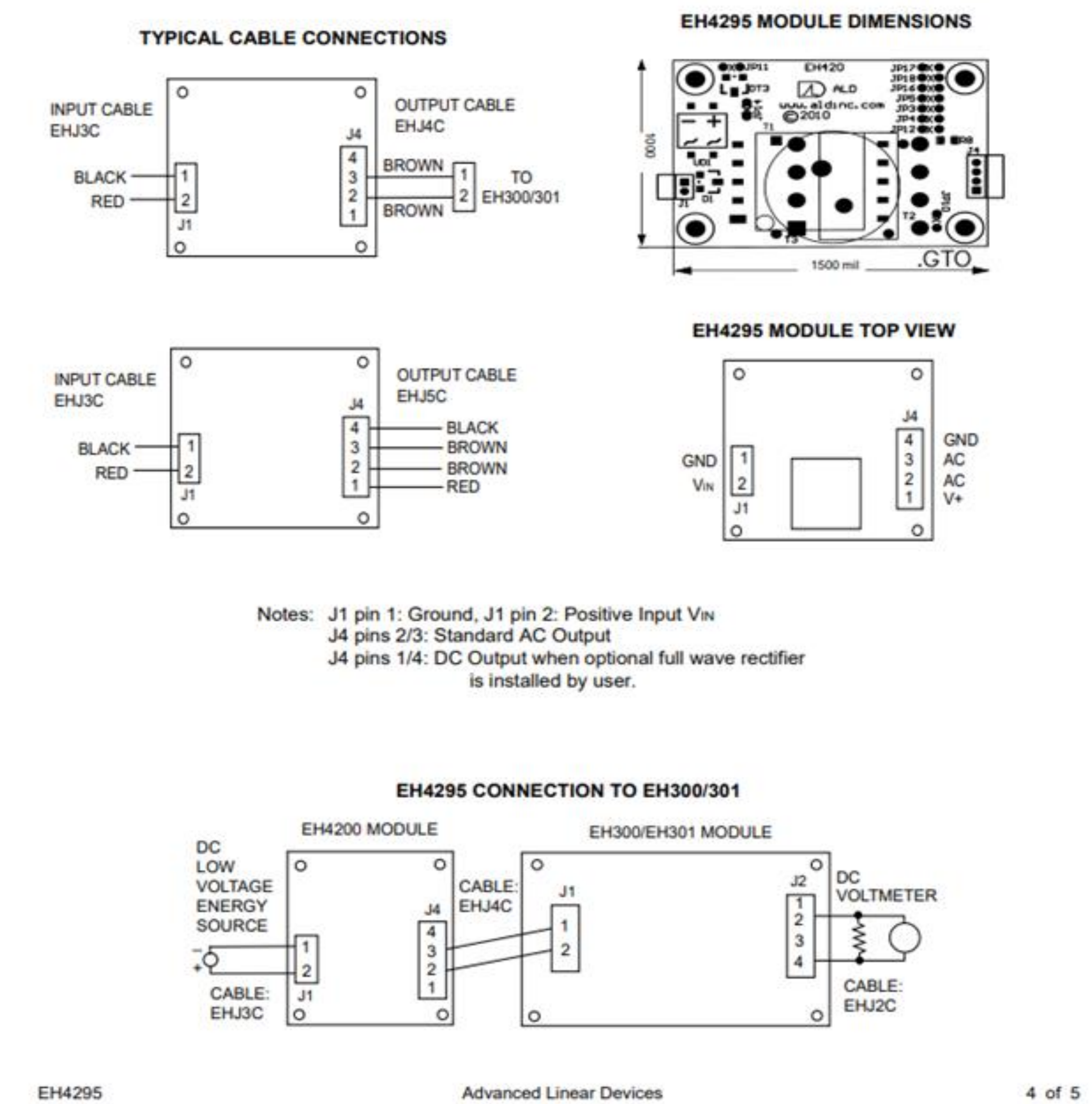


Figure 5.5.6 Breadboard setup for booster testing

Note: the ground output of the booster (lower left corner of chip) is completely isolated and does not connect to the ground of the input. When this lead was connected to the grounding rail it appeared to short out the entire output and there was no voltage over the resistor or LED.

Booster Testing 2:



Based on the Schematic provided in the datasheet of EH4295 low voltage booster, separate tests were done using the unaltered AC output of the booster, as well as attaching the Schottky rectifier to the output of the booster.

Super Capacitor Testing:

Functional Test - 1 Farad Supercapacitors:

One of the critical components to be used in the device is a 1 Farad supercapacitor. The team ordered five of these components, but before integrating them into the circuit, the characteristics needed to be verified. To test the capacitance, the following RC test circuit was constructed:

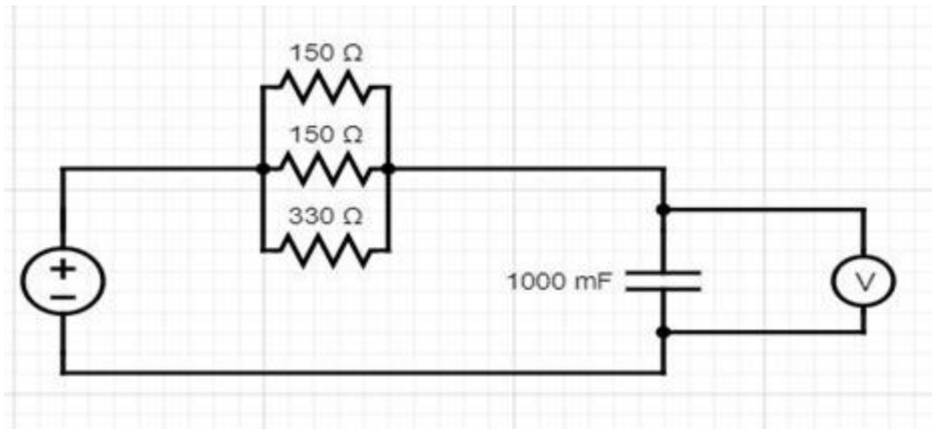


Figure 5.5.7 Supercapacitor Testing Schematic

Since the capacitors had such large capacitance value, they exceeded the limitations of the measuring equipment in the lab and had to be verified by measuring the voltage and time constant to calculate the capacitance value. The voltage supplied was 3 VDC for the input. A digital multimeter was attached across the capacitor to read the voltage value and monitor it over time. To do the test, a team member started a stopwatch at the exact moment the output from the power supply was turned on. The time was noted once the capacitor reached a voltage of 63.2% of the input voltage (in this case 1.896 VDC). Using this time value, in seconds, and the equivalent resistance of the parallel resistors, the capacitance of each capacitor was calculated and compared with its rated value.

A summary of data is provided in the following table:

Input Voltage	3 VDC
63.2 % Value	1.896 VDC
Calculated R_{EQ}	61.11 Ω
Measured R_{EQ}	65 Ω

Table 5.5.1 - Supercapacitor Testing Setup Information

An image of the physical test circuit used for testing is shown below:

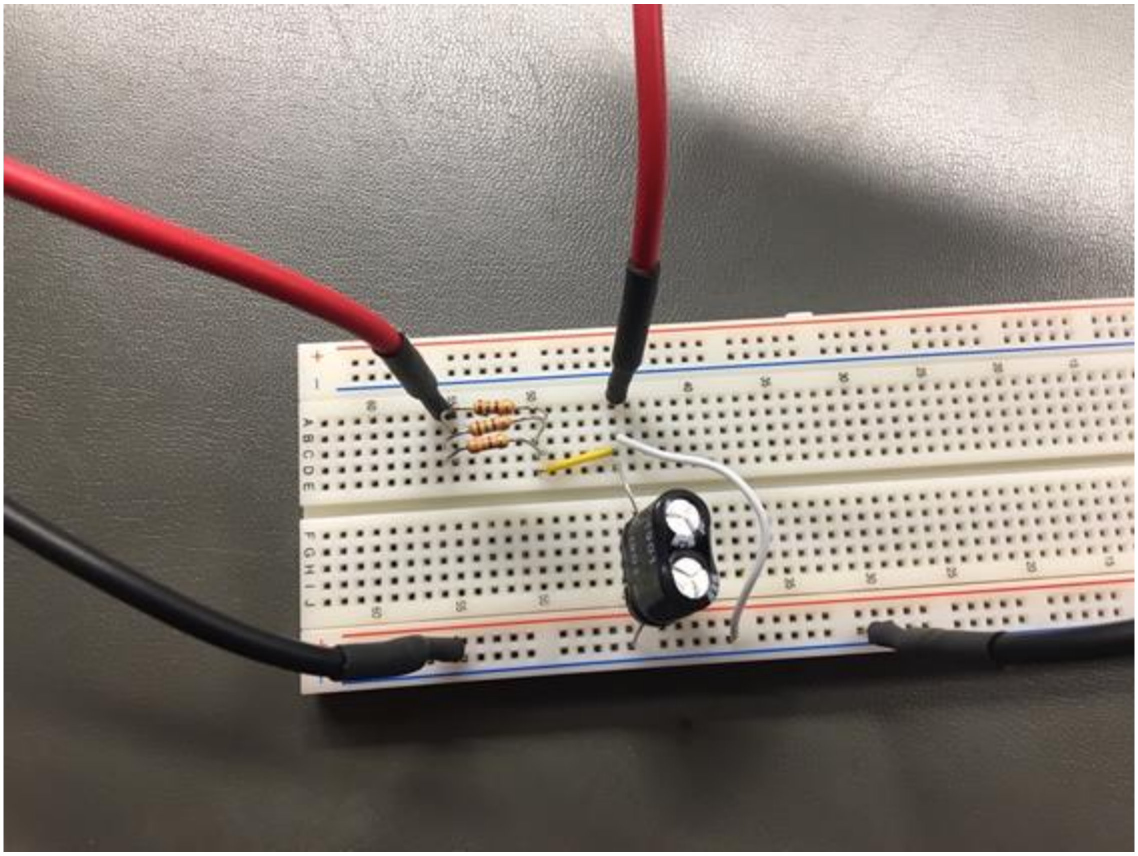


Figure 5.5.8 Supercapacitor Testing Circuit

The white jumper wire was used to short the capacitor to ensure it was fully discharged at the start of each test. It was removed simultaneously as the power supply output was turned on.

The results of the capacitor testing can be found in the following section (5.6)

5.6 Results:

Following are the results that the team obtained for all of the components that were tested, the way these parts were hooked up has already been shown in the section

Half Wave Rectifier Testing Result:

For the single diode testing experiment the team used the 1kHz 1.1Vpp sine wave input signal with loads ranging from 22ohms to 10k ohms. The results are listed below. In conclusion, the rectification ability and the forward voltage drop of a single diode depends on the load value.

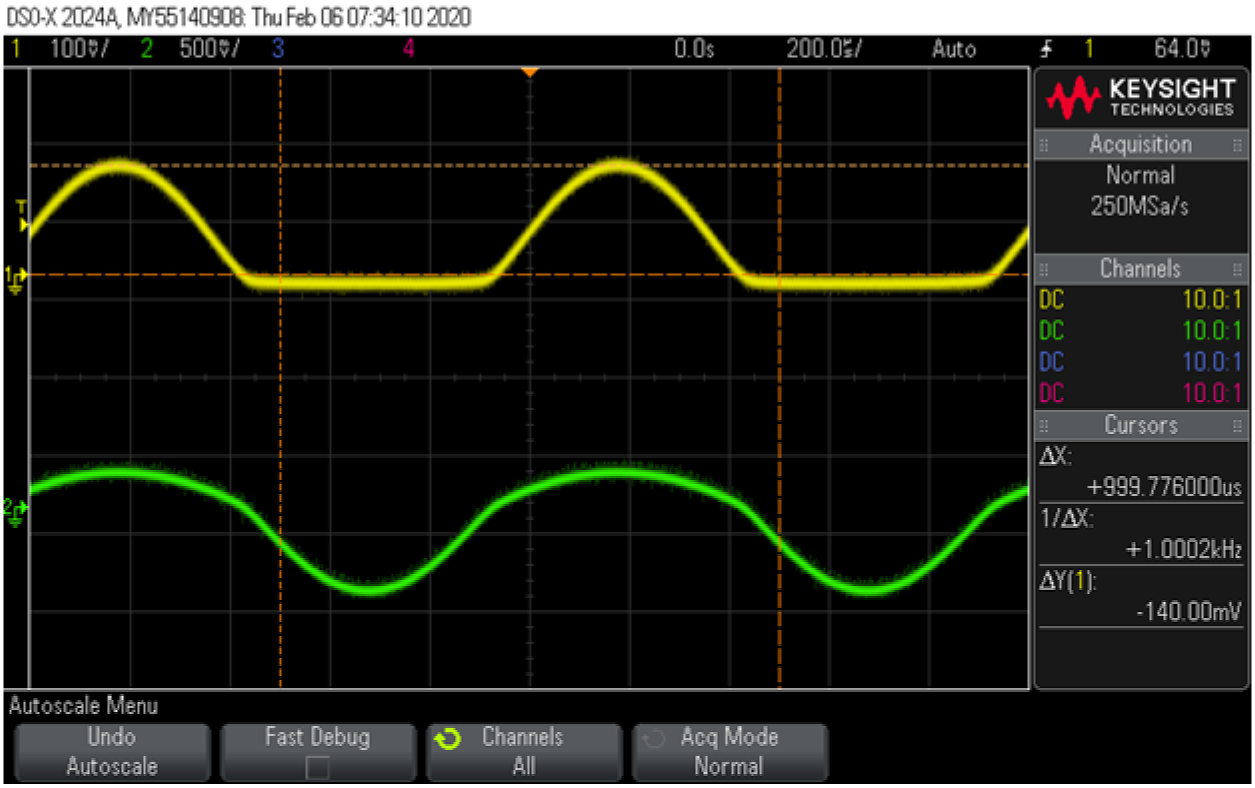


Figure 5.6.1 Half-wave Rectifier Test Output 1 22ohms load

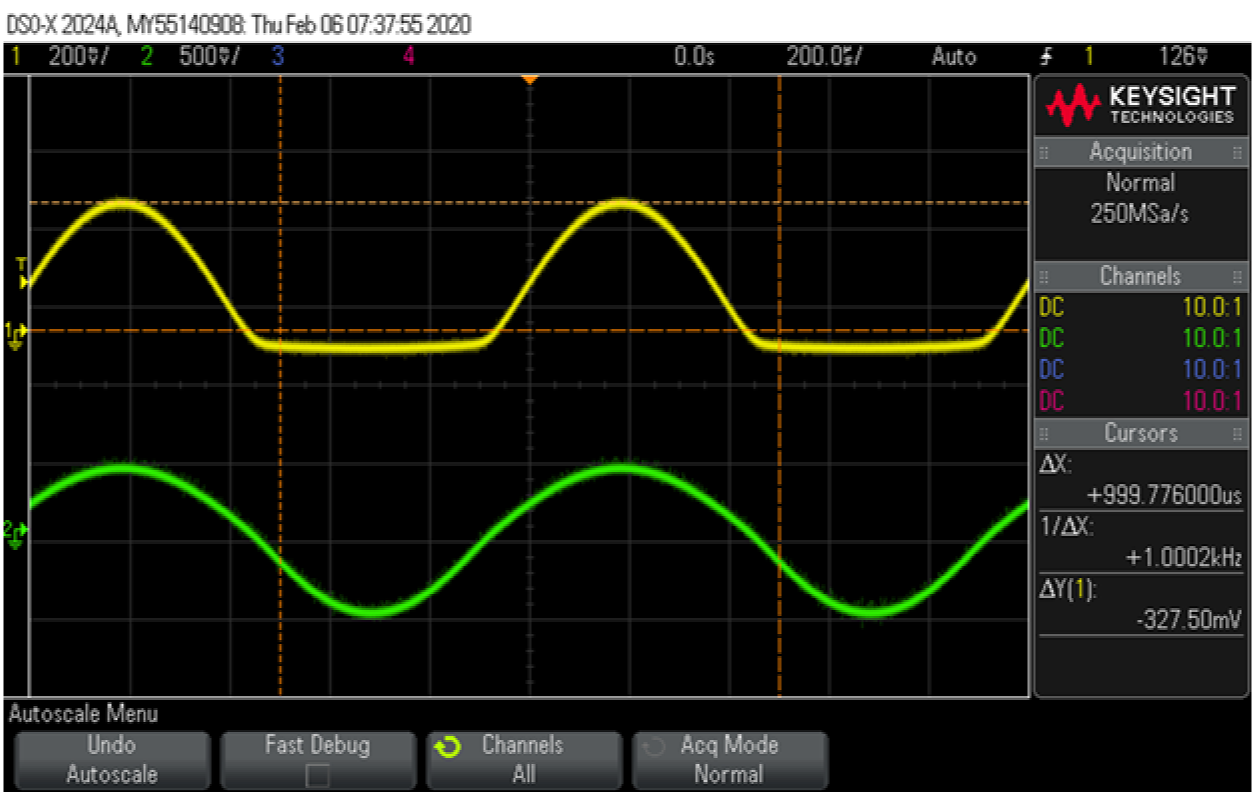


Figure 5.6.2 Half-wave Rectifier Test Output 2 100ohms load

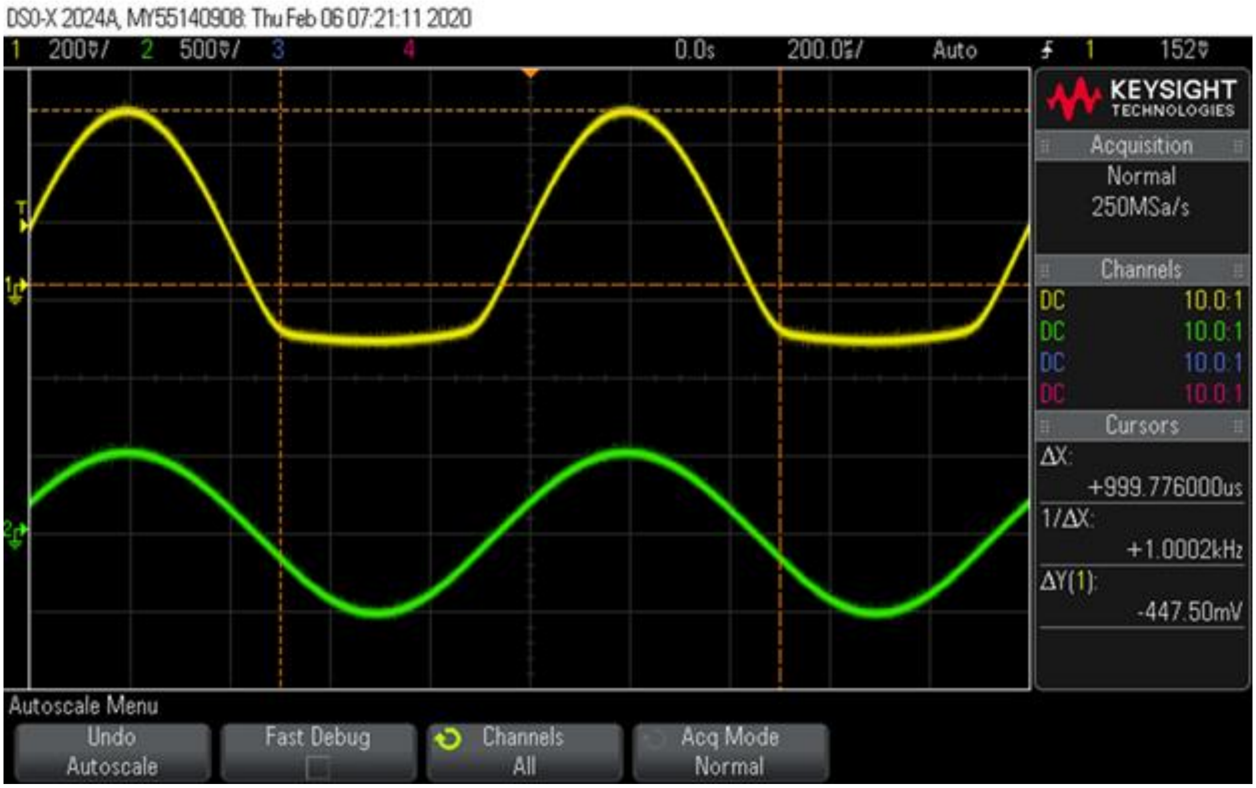


Figure 5.6.3 Half-wave Rectifier Test Output 3 330ohms load

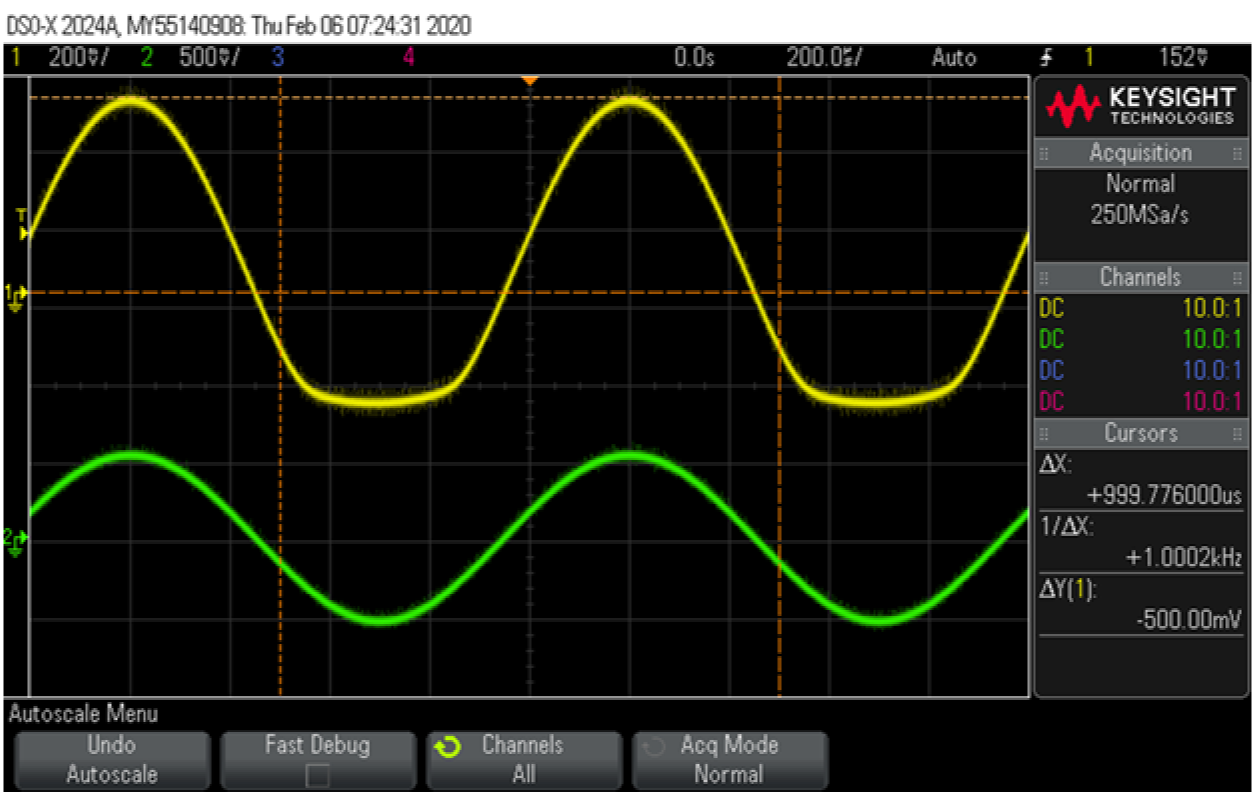


Figure 5.6.4 Half-wave Rectifier Test Output 4 680ohms load

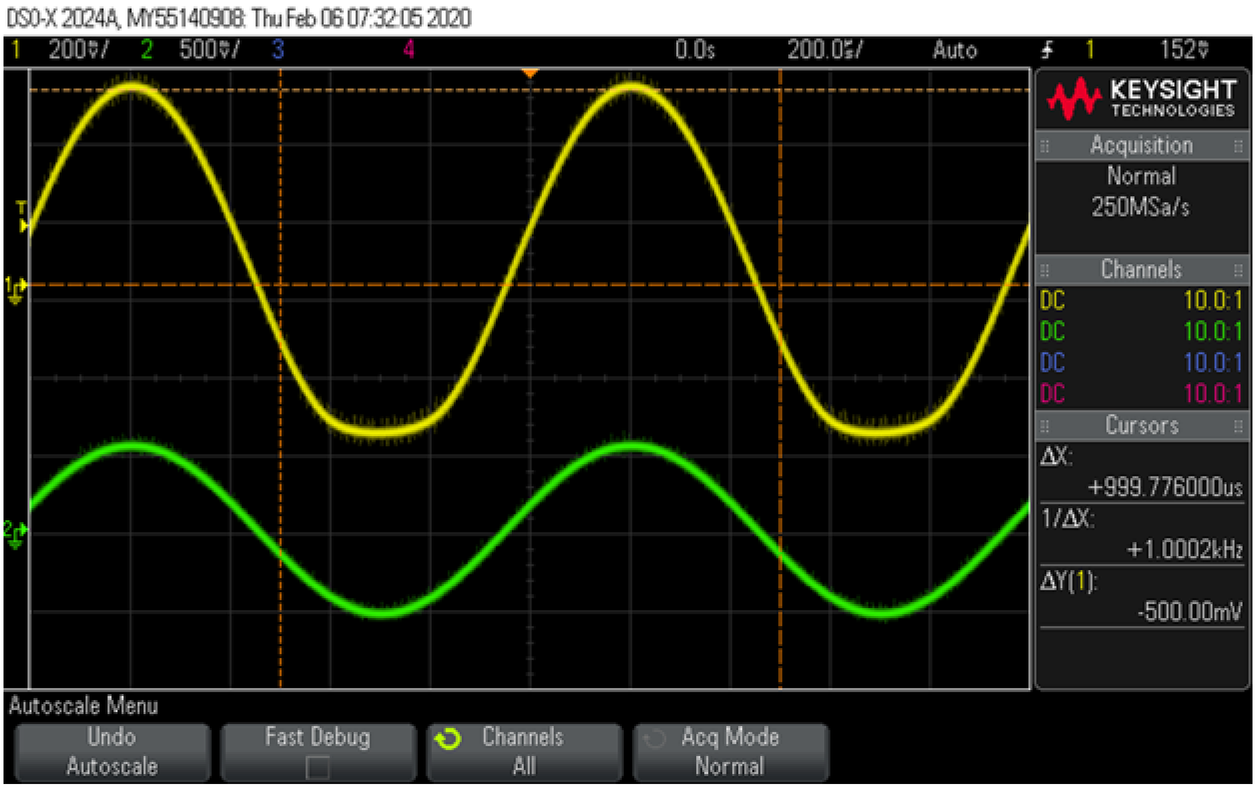


Figure 5.6.5 Half-wave Rectifier Test Output 5 1000ohms load

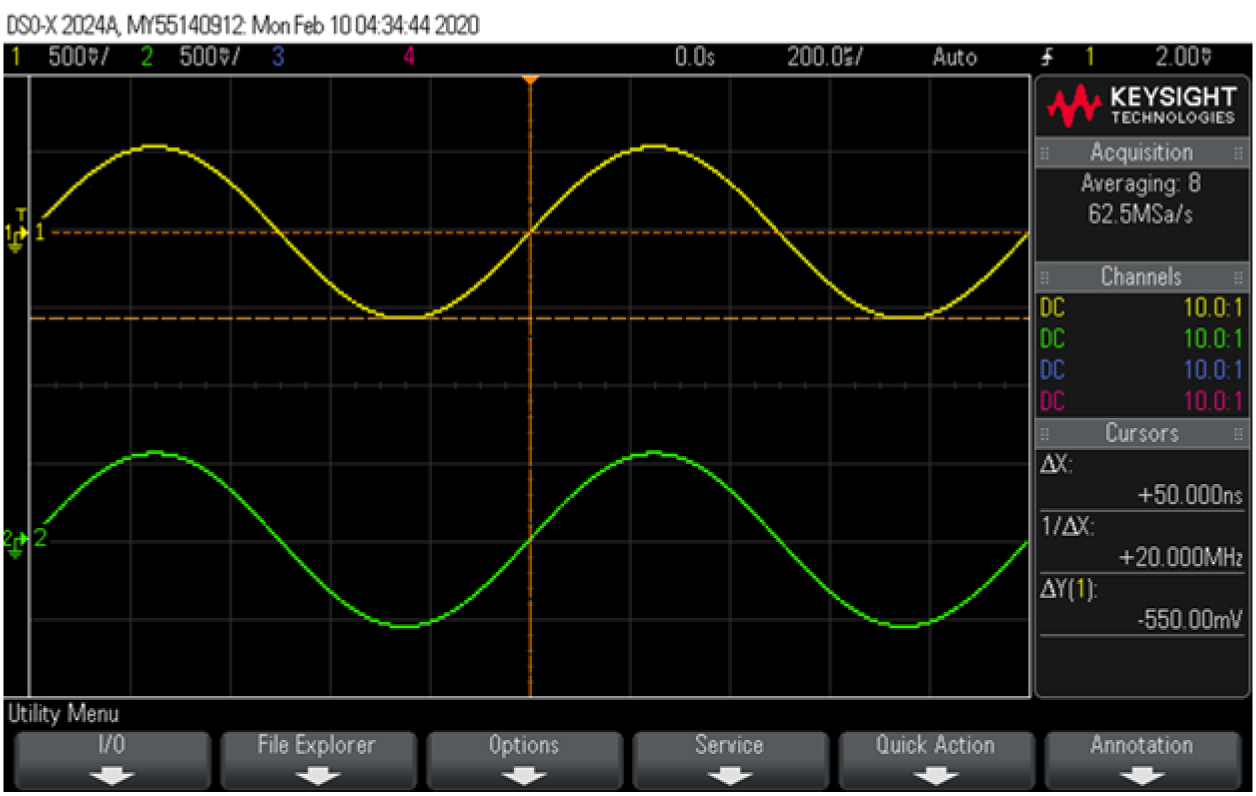


Figure 5.6.6 Half-wave Rectifier Test Output 6 10Kohms load (stop the rectification)

Conclusion: from the above results the output end of a single diode rectifier varies a lot with the load value which is a property that the team does not expect to see. Before the team could fully understand the function and the reason why the Schottky diodes were behaving like they were tested, the team decided not to use any type of single diode as rectification measures which, in the energy harvesting module, might cause system failures.

Full Wave Rectifier Testing Result:

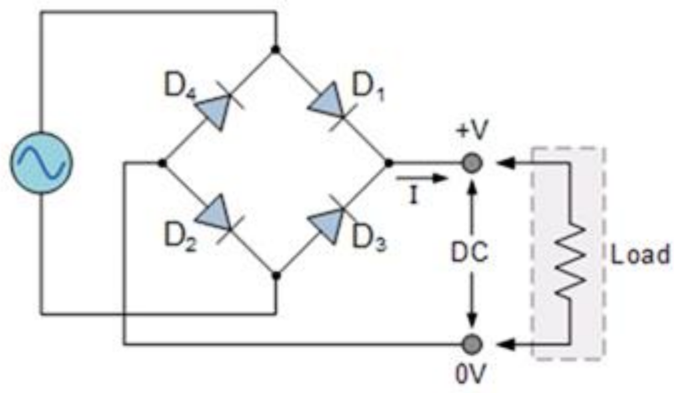


Figure 5.6.7 Full Wave Rectifier Testing circuit

For the full wave rectifier with resistor testing experiment the team verified the ability of the module to rectify the signal in a manner that is compatible with the rest of the circuit. The input signal is 1.1Vpp 1kHz sine wave consistent with the previous testing with half wave rectifier.

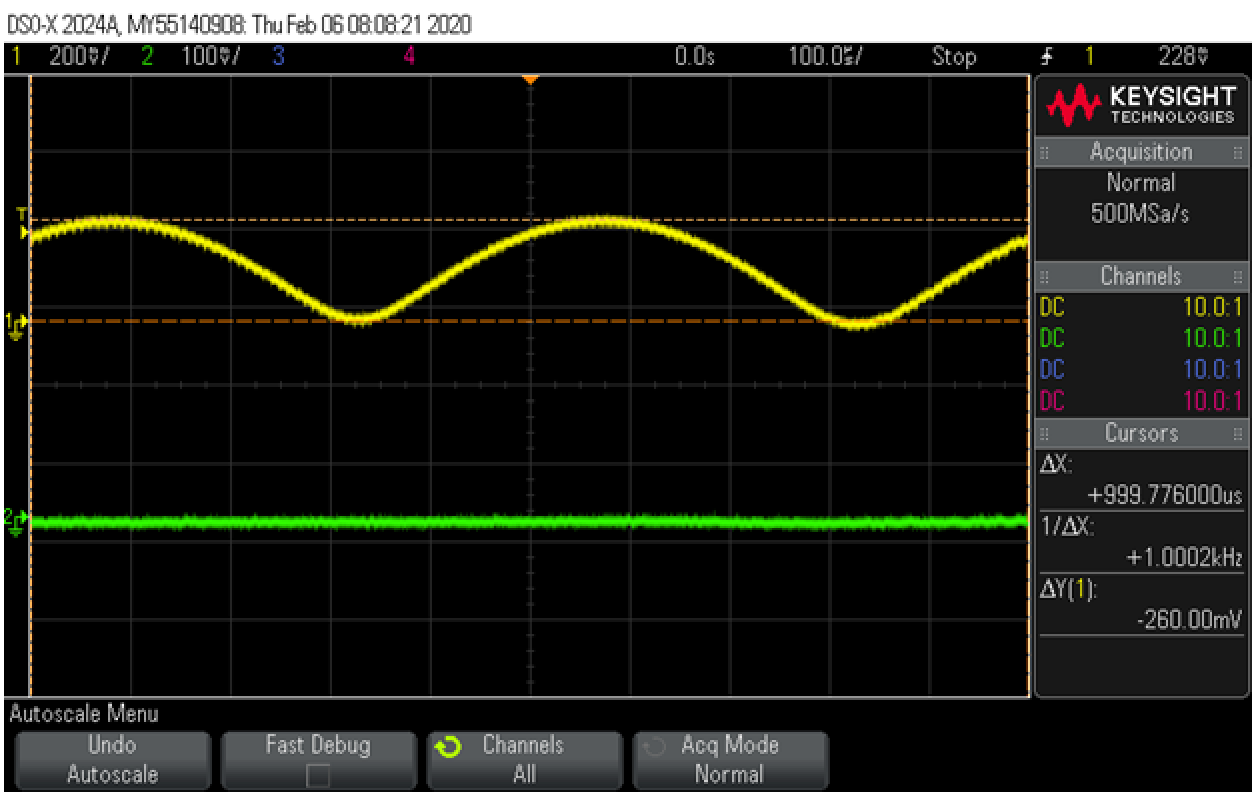


Figure 5.6.8 Full Wave Rectifier Testing Output 1 100 ohms load

Figure 5.6.9 Full Wave Rectifier Testing Output 2 330 ohms load

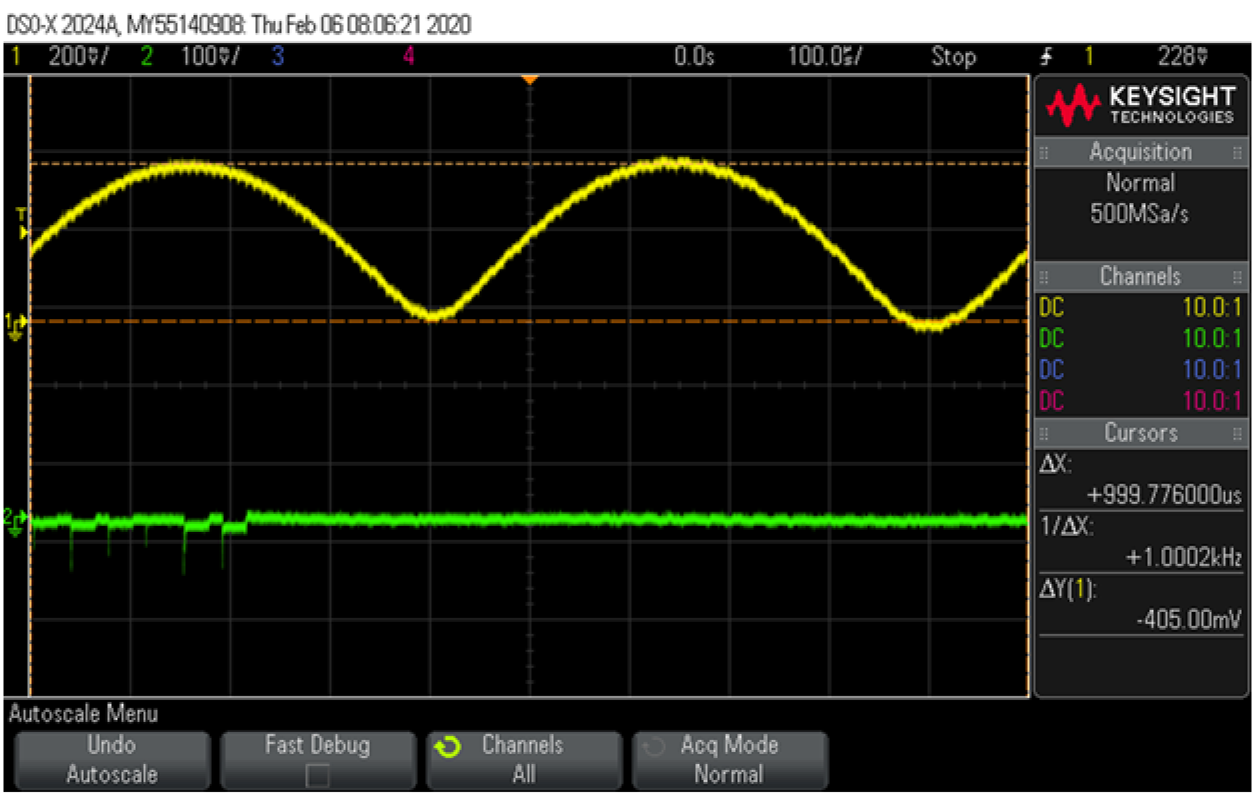


Figure 5.6.10 Full Wave Rectifier Testing Output 3 680 ohms load

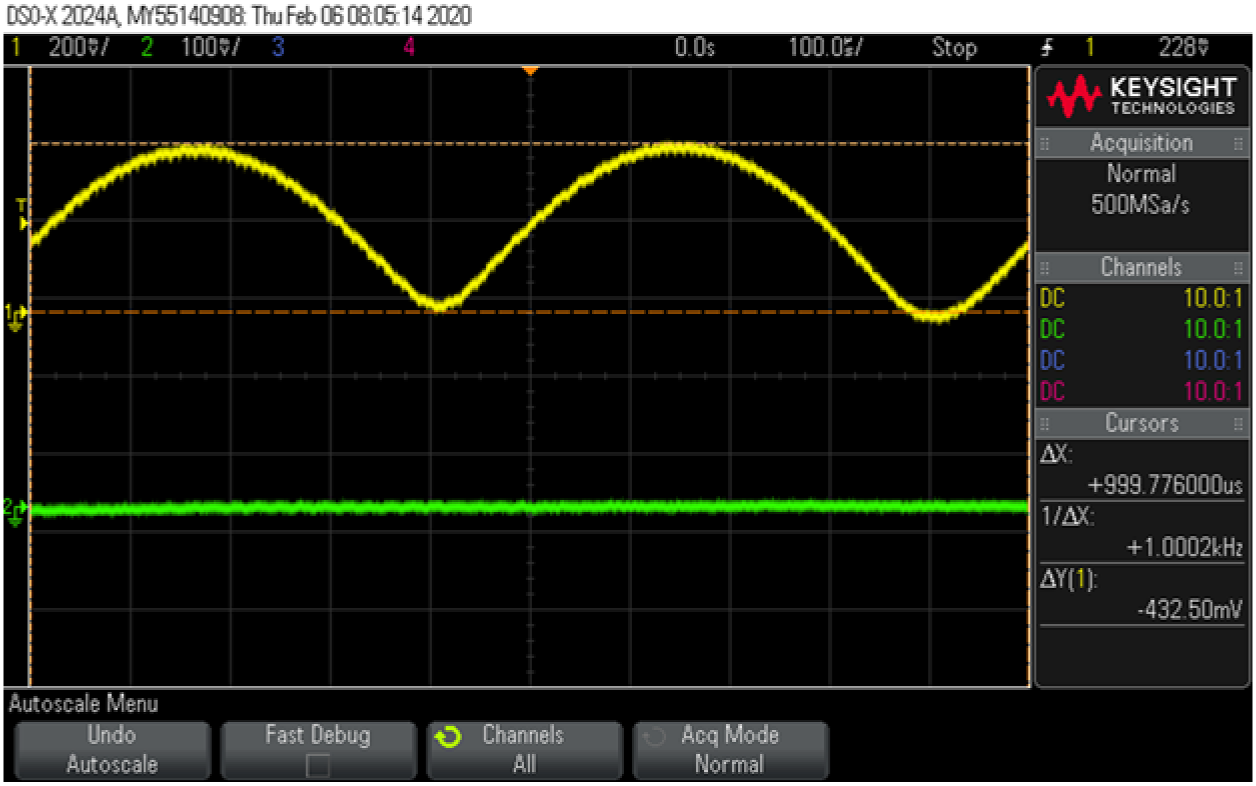


Figure 5.6.11 Full Wave Rectifier Testing Output 4 1000 ohms load

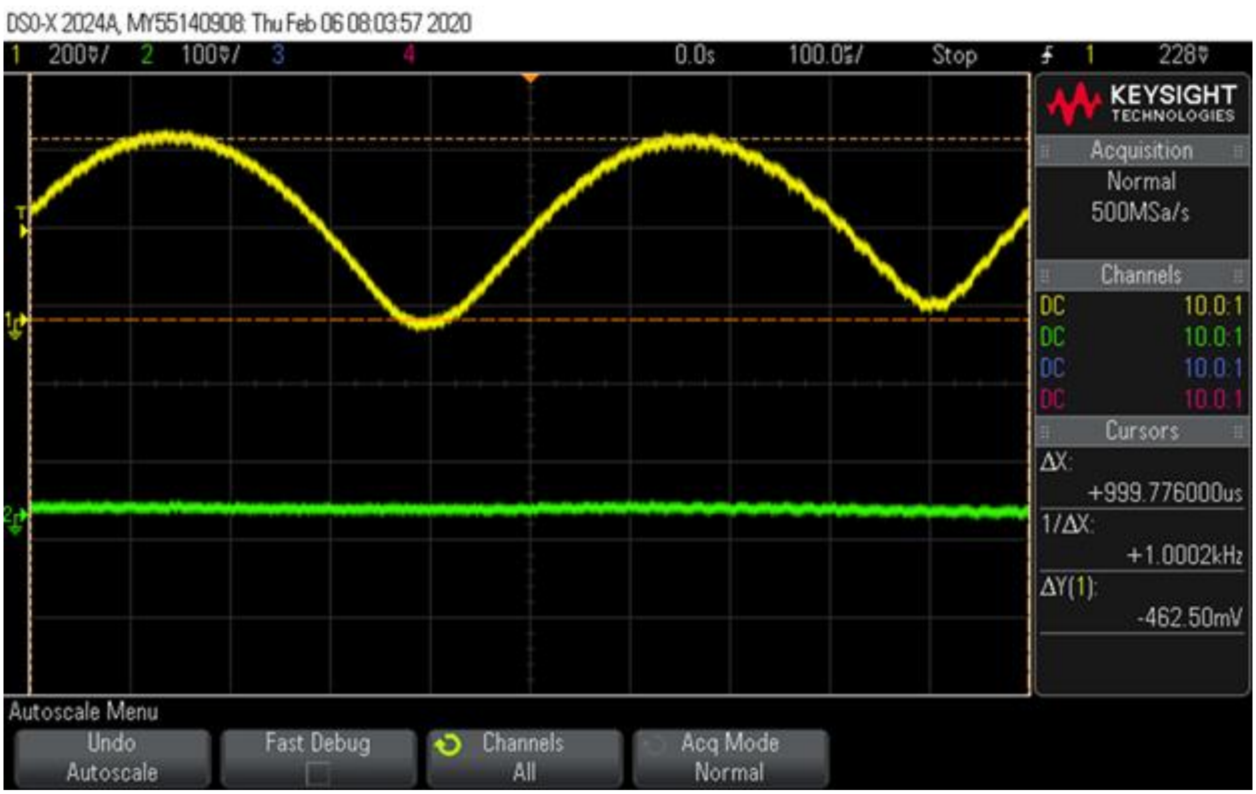


Figure 5.6.12 Full Wave Rectifier Testing Output 5 10K ohms load

Conclusion: The result of a full wave rectifier without a smoothing capacitor was partly successful. We verified that the output voltage is about 450mV at peak which is acceptable for the voltage booster to boost. However, the voltage booster is not able to accept highly unstable signals like above, therefore a smoothing method must be applied.

Full Wave Rectifier with smoothing Capacitor Testing Result:

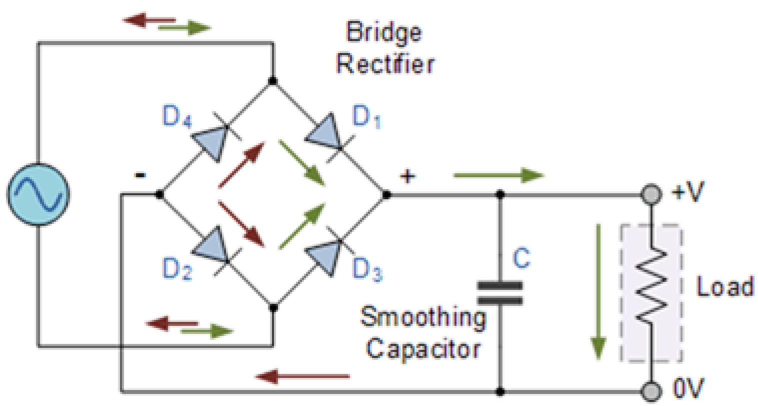


Figure 5.6.13 Full Wave Rectifier Testing with smoothing capacitor

For the full wave rectifier with smoothing capacitor testing experiment the team verified the ability of the module to rectify the signal that is stable and robust enough to power the voltage booster stage. The input signal is 1.1Vpp 1kHz sine wave consistent with the previous testing with half wave rectifier.

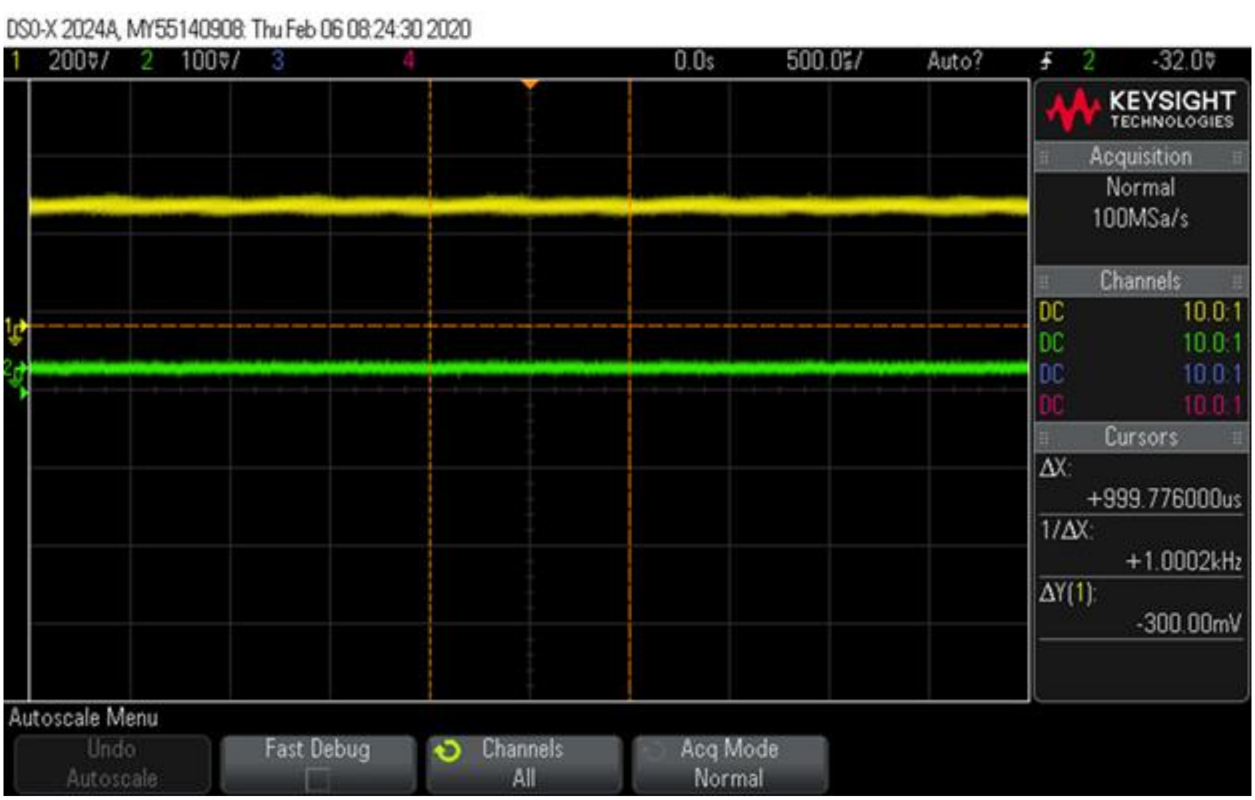


Figure 5.6.13 Full Wave Rectifier Testing with smoothing capacitor 1K ohms load 20uF smoothing cap

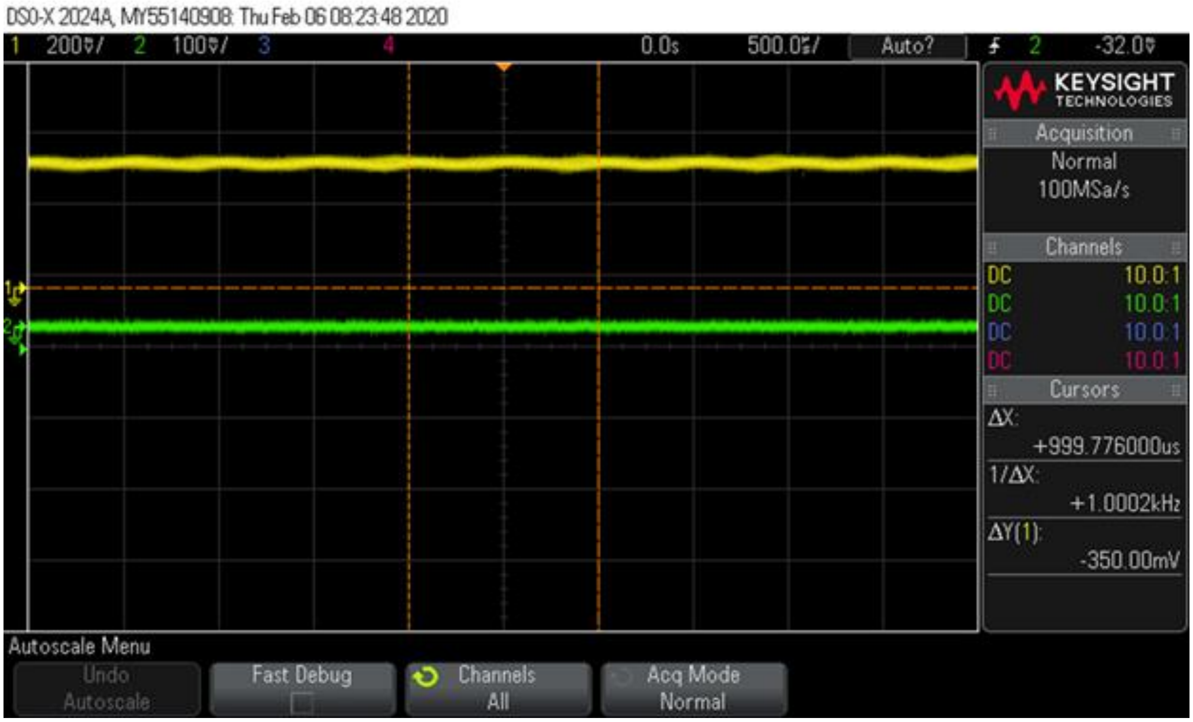


Figure 5.6.14 Full Wave Rectifier Testing with smoothing capacitor 10K ohms load 20uF smoothing cap

Conclusion: The result of the full-wave rectifier with smoothing capacitor was successful. We verified that the output voltage is about 350mV which is acceptable for the voltage booster to boost and the voltage is much more stable compared to the half wave rectifier and the full wave rectifier without the smoothing capacitor.

Super Capacitor Testing Result:

Capacitor	Measured Time Constant (seconds)	Calculated Capacitance (Farads), C=**τ**/R	% Error
1	62.67	0.964	3.6
2	63.72	0.98	2
3	60.1	0.925	7.5
4	64.67	0.995	0.5
5	64.1	0.986	1.4

Table 5.6.1 - Capacitor Measurement Results

From these testing results the team determined that the capacitors would be acceptable for use in the design. Although there is some variation in the values, this can be accounted for due to the inexact nature of the test. Manually applying the output and tracking with a stopwatch while observing the voltmeter is not ideal like using an LCR meter or some form of automated test, which was not available to us. However, since all of the capacitors behaved as expected during the test, the team does not anticipate this will cause any issues.

Voltage Booster Testing Result (PRT-10255):

The result didn't meet the design expectations since the output was not stable. Right after the input is given the output voltage instantly jumps to 2.4V as expected but it keeps declining, all the way below to 1V. We were anticipating two possible causes:

1. Damage to the device when soldering the test leads on.
2. The input signal polarity is critical, and a reversed input may have been applied during initial testing, damaging the device.

Some other testing showed that the output only stabilizes at specific points in the testing. For example, with a 100 ohms resistor and a 1.1V DC voltage we saw that the output did boost to 2.6V. However, changing the input to 1 V with the same setup results in the output decaying again. The table below contains the input and output voltages where the booster exhibited stable behavior.

Measurement	Voltage	Output Boost
1	1.1	2.6
2	1.2	2.78
3	1.3	3
4	1.4	3.27
5	1.5	3.5
6	1.6	3.75 - 4 (between these values)
7	1.7	Starts Decaying again

Table 5.6.2 - Voltage Values from Booster Testing

After much testing the team found that this module was not working as expected and a new module was needed to meet our design requirements.

Voltage Booster Testing Result (EH4295):

The purpose of this experiment was to verify the ability of the module to boost DC voltage and to record the property of its output waveform for the design of potential adjusting stage. The input signal is a DC signal of 0.35V and at the output end there is a 10K ohms resistor as a placeholder for the load. The switch to this voltage booster module was so that it can utilize an input signal of as low of a voltage as 0.3V, an important distinction since the max voltage the rectifier was able to provide was 0.35V.

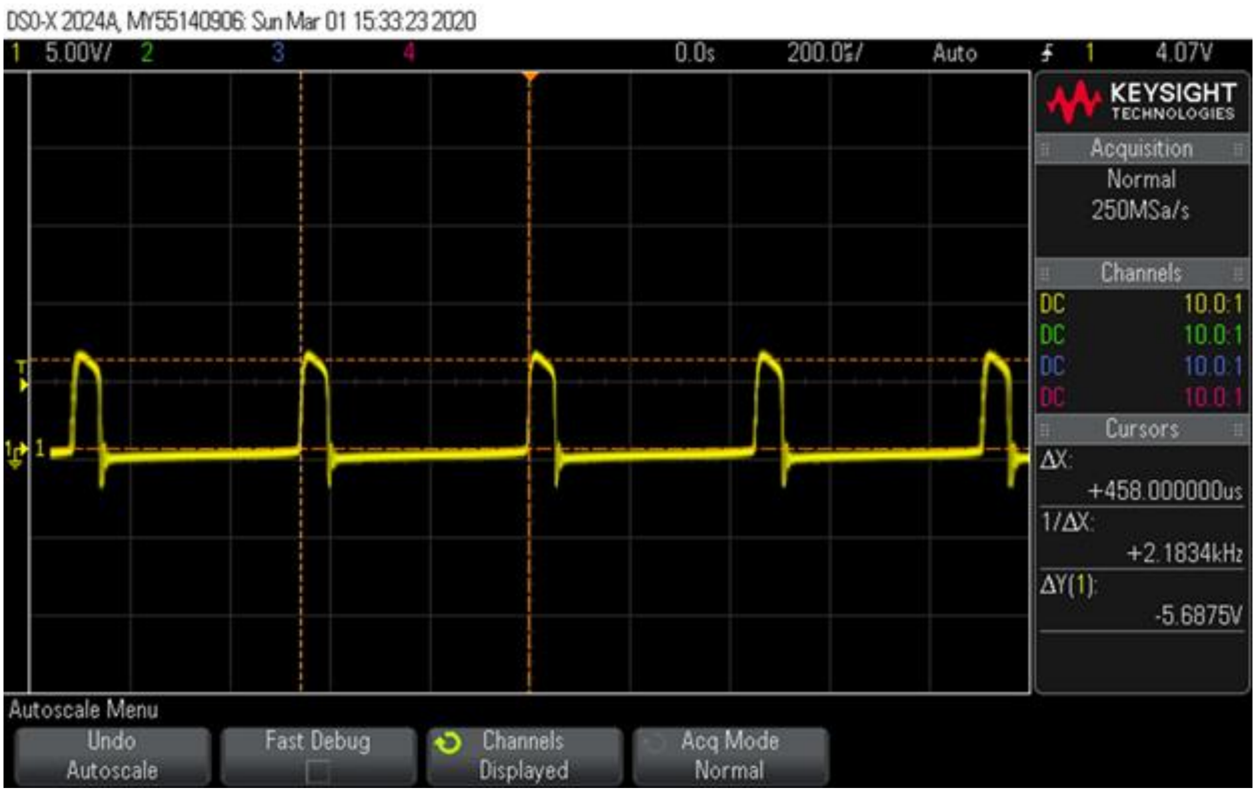


Figure 5.6.15 direct measurement of voltage booster with 0.35V input

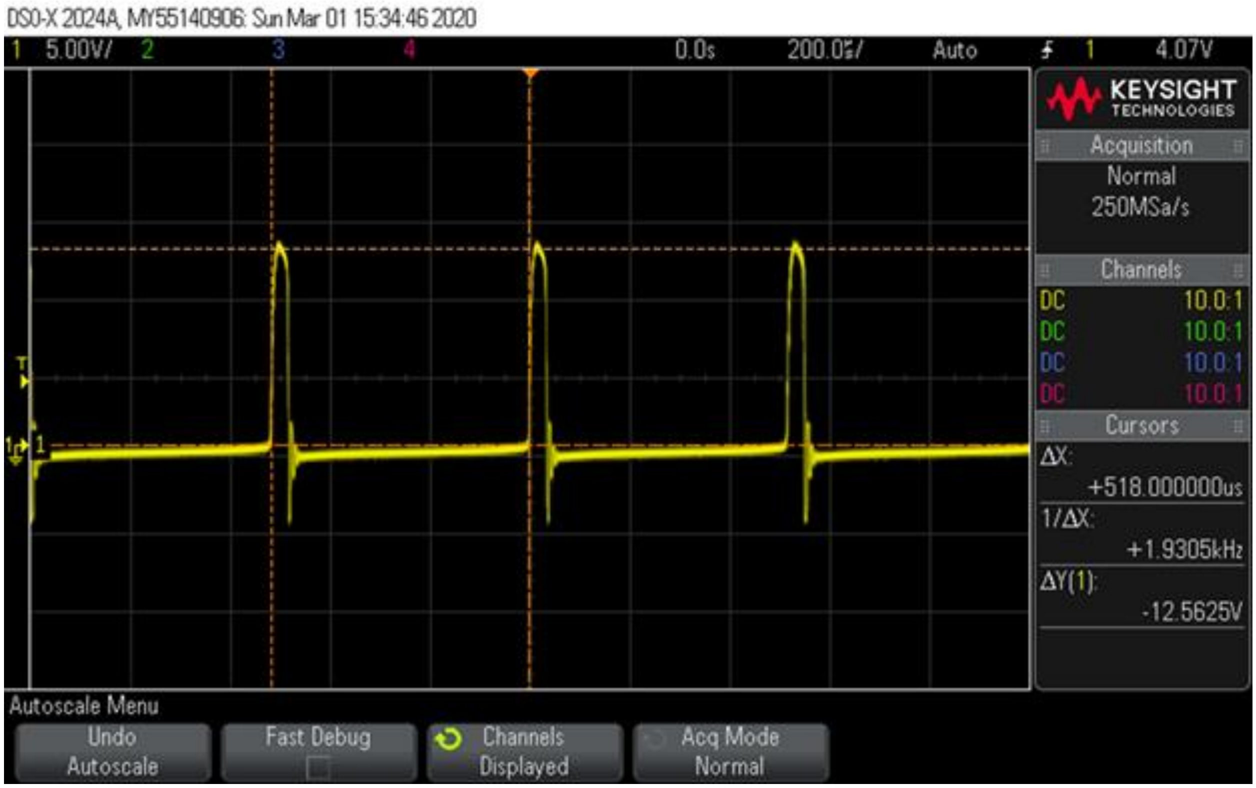


Figure 5.6.16 direct measurement of voltage booster with 0.5V input

Conclusion: The output waveform is usable in terms of charging the capacitor. It can be seen that the booster is making the DC signal oscillate and uses the transformer to boost the signal. According to the datasheet, the efficiency of this booster can be as high as 90 percent which is sufficient for the module. It should also be noted that the duty cycle of this power stage is short. So, this puts an efficacy problem in place. Also, the team noticed that when the booster made the DC signal oscillate, the negative part of the signal was wasted, which can be problematic. An additional rectifier stage is needed before the super capacitor. This led to some efficiency problems and the charging speed was also affected, but these problems were not as bad as expected.

Whole System Testing Result:

The system is set up as below. The input is a sine wave 1.1Vpp 1kHz as required, and voltage across the supercapacitor is measured. Meanwhile, during the experiment the output of the rectifier and the voltage booster is also monitored to detect the potential malfunction of the subsystems.

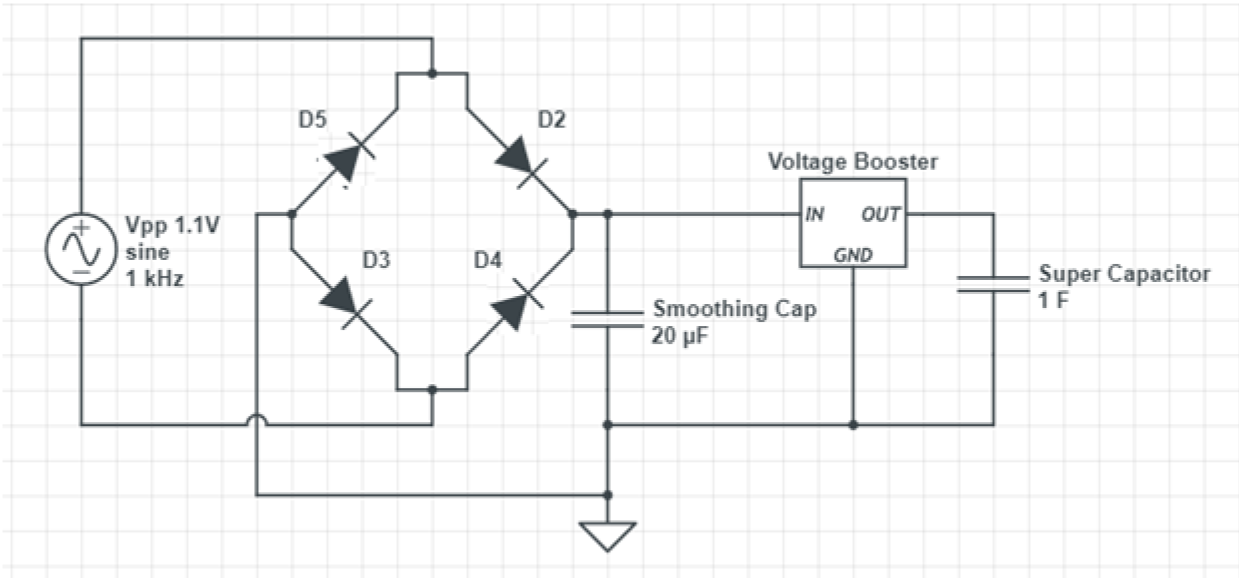
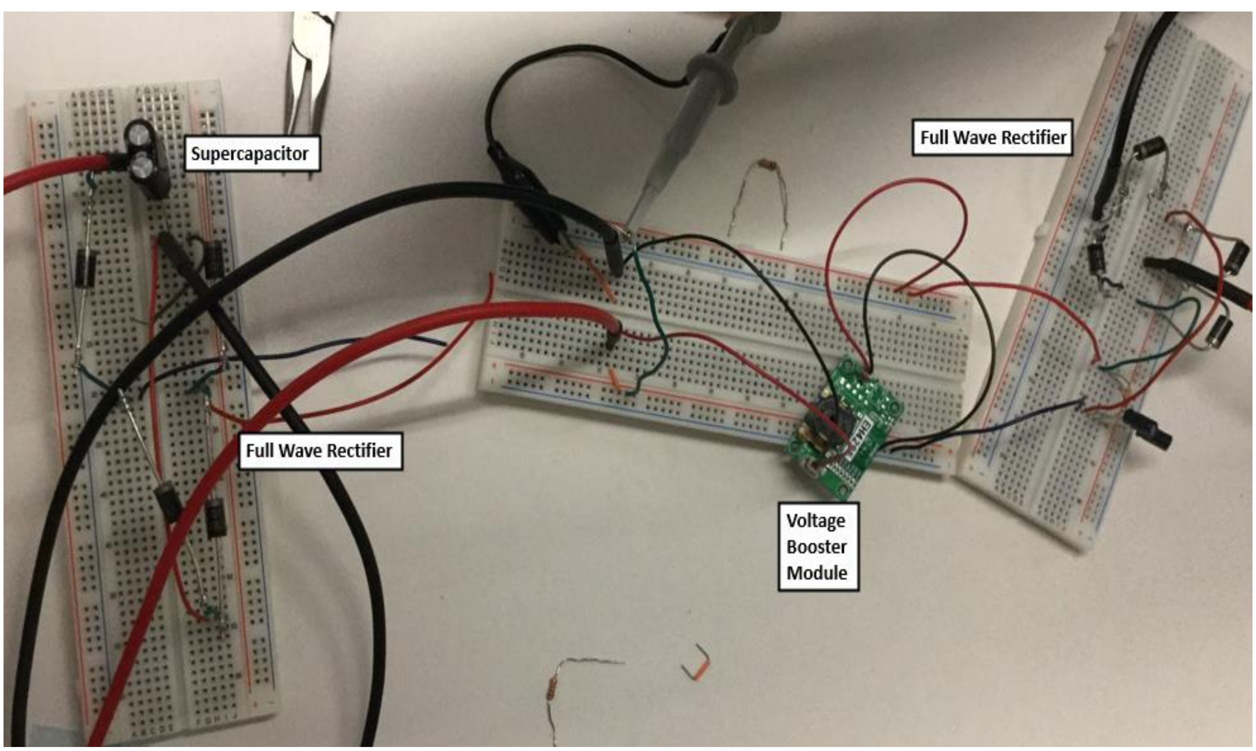


Figure 5.6.17 Whole System Testing Schematic

The Voltage across the capacitor indicates that it is charging. The charging rate can be calculated according to the plot below.

Prototype Implementation on Breadboard:



The Table below shows the time vs voltage values. How much voltage did the system charge the supercapacitor at a specific time.

Time(minutes)	Voltage(V)	Time(minutes)	Voltage(V)
1	0.041	11	0.297
2	0.126	12	0.299
3	0.18	13	0.299
4	0.22	14	0.3
5	0.25	15	0.3
6	0.27	16	0.3
7	0.28	17	0.3
8	0.285	18	0.301
9	0.29	19	0.301
10	0.294	20	0.301

Table 5.6 t-V Measurements table

Graphical Representation:

The following graph shows the graphical representation of the above table. The x axis represents the time in minutes and the y-axis represents the voltage in Volts.

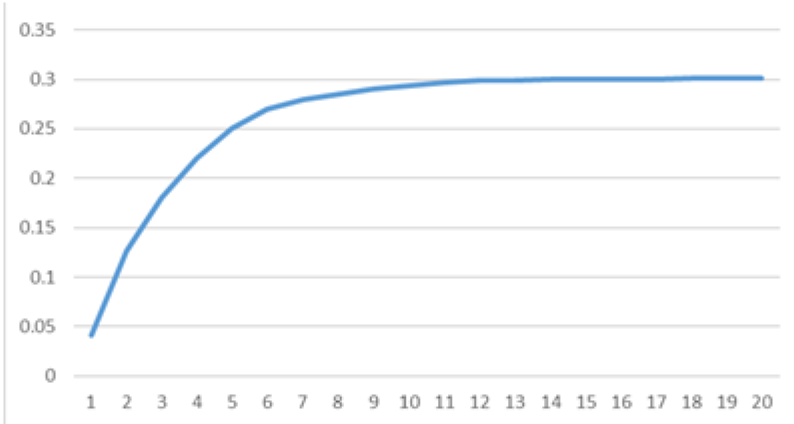


Figure 5.6.17 Whole System Testing Results Plotted in Excel

According to the hand recording of the voltages across the capacitor, it was verified to be charging, although slower than expected. Further testing would have helped finish the project but unforeseen circumstances cut the testing short.

6. Closing Material

6.1 CONCLUSION

A significant amount of work has been accomplished throughout the year on this project. From receiving the initial problem statement, additional clarification was needed from the client to determine what the expectations and deliverables were. After meeting with Honeywell (the client), it was determined that the desired power scraping module would receive a low input AC signal (1.1 V-P-P), convert the signal to DC, and then boost the signal to a higher voltage where it will charge a supercapacitor and then power a device of the client's choosing.

Having a clear outline of what project was, the team began designing the various stages of the power scraping module and sourcing the components to be used. After the components were obtained, a test plan for each component was developed to verify their functionality. The supercapacitors and Schottky diodes passed the initial acceptance testing, but the booster modules have been the source of much confusion. Throughout testing and consulting with the team faculty advisor, the boosters have been unpredictable and inconsistent. After communicating with the manufacturer of the booster, it was discovered that the strange behavior is likely a result of insufficient current. It is believed that the booster will work as expected if used in the conditions specified by its manufacturer. Due to the COVID-19 pandemic, this idea cannot be tested, and it remains unknown whether the booster can be used to create a power scraping module.

There are a wide variety of applications that can benefit from the use of a power scraping device, including GPS or battery-free remote sensors for HVAC control, and building automation, structural monitoring, and industrial control. To be able to create a device that would have such a high demand and large number of uses was very satisfying.

6.2 REFERENCES

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