Microcontroller-based Capacitor Discharge Circuit with Configurable Setpoints

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2.1 - Project Motivation and Background

Throughout the power industry, capacitors and capacitor banks are used in a wide variety of applications. At its simplest level, a capacitor bank is a group of capacitors, connected in either series or parallel or with a combination of both, that are designed to store electrical energy for later uses. [1] This is evident when capacitors are utilized for power factor correction, where local capacitor banks supply reactive power to inductive loads, such as motors. In doing so, real power output, system efficiency, and system capacity can be increased. [2] Additionally, capacitors can aid in smoothing out voltage and power fluctuations in a system. This becomes especially important within renewable integration since most renewable energy sources produce nonconstant power over the course of a day. During brief changes in production, capacitors can help the system ride through power fluctuations. Finally, capacitors can act as key components in filtering out unwanted frequencies for a system. This helps aid overall power quality and also becomes very useful for communication systems. One such example in the power industry would be the use of power line carrier communication which takes advantage of already existing high voltage powerlines as a medium to send control signals between substations. In such systems, capacitors are utilized as filters to protect substation equipment from damage associated with higher frequency signals.

While capacitor banks provide a variety of advantages and useful applications within a power system, disadvantages can come with the process of charging and discharging the bank itself. A capacitor bank can hold a high and hazardous amount of residual voltage after it is disconnected from a power system. [3] This can pose a safety risk to any workers present near the bank due to the potential for electric shock. Additionally, reconnecting a capacitor bank into a power system while residual voltage is present can be problematic as higher than expected inrush currents can occur. This can lead to equipment breakdown as well as potential tripping within relays. Within parallel capacitors further inrush issues can be caused if one capacitor bank is already charged and another parallel bank that is not fully charged is connected on the same parallel bus. The voltage difference between the first bank and the second bank produces high currents that go back and forth between the two banks, which places immense stress on the system. [4]

The standard solution within the power industry to these issues would be to employ bleeding resistors at the terminals of a capacitor bank to safely discharge the circuit. The resistors can be in a switching topology, or permanently connected, although the latter choice would result in power loss and potential overheating. NextEra Energy, an American energy company specializing in energy utility and efficiency, wanted to pursue a switching resistor-based capacitor discharge tool to safely discharge high voltage capacitor banks that are utilized in conjunction with PVS980 inverters. More specifically, NextEra wanted a tool that could be utilized in a laboratory setting where, after undergoing certain testing, capacitor banks can be brought in and easily discharged. As a result, this senior design project was formed to explore potential solutions and provide NextEra with a design that can safely discharge their capacitor banks while also meeting various constraints and requirements. Due to the dangers of high voltages, however, NextEra has agreed to allow the team to develop a prototype of the system that will only be tested at low voltage and that can then be potentially scaled to higher voltages in the future.

2.2 - Existing Products and Projects

This project's product classification would fall under the umbrella of Photovoltaic Rapid Shutdown Systems or PVRSS, which are a group of products used to safely disconnect the photovoltaic panels from their inverter and swiftly drain the power stored in the system. Use cases for PVRSS range from residential solar installations to multi-Megawatt photovoltaic fields used by electric utilities.

One of the major considerations when installing a photovoltaic array is the safety of maintenance personnel for routine inspections and first responders in emergency situations, and the National Electric Code has a section addressing the standards that products of the category must adhere to, under NEC Section 690.12: Rapid Shutdown of PV Systems on Buildings [5]. Because the PVS980 inverter this project is working with is designed to be a modular system, it requires the installation of a PVRSS to meet the standard. Below are a few examples of products that are either modules in a PVRSS system or have such a system integrated into the product.

2.2.1 - Beny BFS-A1

A current product that fulfills a similar purpose is the Beny BFS-A1, which is a "rapid shutdown switch for connection to PV panel arrays to achieve compliance with 2020 NEC 690.12" [6]. This product shuts down panels and dissipates energy stored in its connected inverter. While the function of this device is similar to this project's motivation, it appears to be designed for smaller scales, such as a residential installation that would have a far smaller capacitance to discharge than the scope of this project.

The main selling point of the BFS-A1 is its simplicity of installation and per-module shutoff for lower-power systems. Because this product is designed to be installed onto the back of a photovoltaic module and control its output to the inverter, it is optimal for smaller installations such as a residential solar array. However, one of the main downsides of the BFS-A1 would be that it only disconnects the photovoltaic panel from its inverter, rather than discharging the capacitors in the inverter.

2.2.2 - EG4 18kPV

On the residential-scale inverter side, the 18kPV inverter by EG4 electronics is designed to be installed on a house and provide supplemental power while the solar panels are active. The 18kPV "includes a rapid shutdown system that complies with 2017 and 2020 NEC 690.12" that can be connected to an E-stop button and activated if emergency personnel need to cut power to the home [7].While the 18kPV does have a rapid shutdown feature that complies with the past two iterations of NEC 690.12, its main drawback is the fact that its discharge system is only designed to work at the scale of a residential solar installation, with a maximum input of 21kW at 600V. As such, the PVRSS in the 18kPV would not be able to work at the utility-scale requirements specified for this project.

2.2.3 - SMA Sunny TriPower CORE1

While the Sunny TriPower CORE1 from SMA Solar Technology is smaller than the inverter in this project, with a maximum output power of 62.5kW on its highest specification model (compared to the minimum specification model PVS980 capable of output in the multi-Megawatt range). CORE1 does include a self-discharge feature that is activated with its PVRSS. The CORE1 does not include capacitance on its datasheet, it has a maximum voltage of 1000V when it starts discharging, which is lower than the 1200V maximum for the scope of this project [8].The primary use case of the CORE1 is for integrating a commercial-scale roof or parking lot solar array into a building's electrical systems. As such, the CORE1 is designed to have plenty of safety and convenience features, including self-discharge in emergency situations, without the customer having to make any further modifications. Where it falls short is its scale, as the CORE1 is intended to be installed on a building to augment the power consumption, versus the utility scale needs presented by the PVS980's utility-scale use case.

2.2.4 - Summary

As far as current projects and commercially available products go, there are standalone devices that operate at lower voltages, and there are smaller inverter systems that offer features like the purpose of this project, albeit already integrated with the system being sold and therefore not scalable to the requirements. There do not appear to be any products that operate at these high voltages available as an individual module rather than already being integrated into a larger inverter system, which presents an opportunity to innovate a new solution.

2.3 - Goals and Objectives

Based on the background of the project, along with inspiration from existing products, the following goals and objectives were outlined by the team. It is worth noting that goals are defined as broad, high-level aspirations for our project. Objectives, on the other hand, are specific, measurable outcomes that work towards the set goals. They also provide a foundation for further developing system requirements and specifications. Both goals and objectives can be further broken down into three categories: basic, advanced, and stretch. Basic goals/objectives will be a required part of the design implementation, often being dictated directly by NextEra. Advanced goals/objectives include scope that is not directly specified but could be beneficial to include in the final design. Stretch goals/objectives can also be beneficial to the final design but are out of scope for the project due to the time or complexity required to implement them.

2.3.1 - Goals

Below are basic goals outlined for this project, which all are derived based on requirements coming directly from NextEra:

- The discharge tool shall be safe and reliable.
- The discharge tool shall fully discharge the capacitor quickly.
- The discharge tool shall visibly indicate the discharge stages to the user.
- The discharge states shall be configurable based on specific voltage setpoints.
- The overall design shall be scalable to higher voltages.

Below are advanced goals outlined for this project produced by the team, which will be in scope for the project:

- The discharge tool shall communicate the real time voltage of the capacitor to the user.
- The discharge tool shall communicate the total elapsed discharge time to the user.
- The discharge tool shall monitor thermal conditions for potential overheating.

Below are stretch goals for this project that will likely be out of scope for the design:

- The discharge tool shall log/store measured data over time for future access and/or analysis.
- The discharge tool shall telemeter data to, and allow controllability via, a remote station.

2.3.2 - Objectives

Below are basic objectives outlined for this project, which are all derived from information provided by NextEra:

- The discharge tool shall fully discharge a 1650uF capacitor in less than 30 seconds.
- The initial voltage across the capacitor to be discharged shall be 12V, but the system must be scalable to an initial voltage of 1200V.
- The discharge tool shall include four configurable logic alarms to activate at specified voltages.
- One of the four logic alarms shall be activated when the voltage is <0.1V for low voltage testing, and <10V when the system is scaled to high voltage
- The discharge tool shall utilize relays and a microcontroller to control the discharge process.
- The discharge tool shall utilize resistive networks for the discharge process.
- Device should be able to provide a visual indication of the discharge state.
- The discharge tool shall be powered by a 24V DC source.
- A bill of materials for high voltage scalability shall be provided alongside relevant high voltage calculations.

Below are advanced objectives produced by the team:

- The discharge tool shall display capacitor voltage measurements with an error tolerance of 5%
- The discharge tool shall display total elapsed discharge time with an error tolerance of 5%
- The discharge tool shall display internal device temperature in degrees Celsius with an error tolerance of 5%
- The prototype should be able to display a response time within 500 ms

Below are stretch objectives that will likely be out of scope for the design:

- The discharge tool shall be able to record up to 30 seconds of data while discharging
- The discharge tool shall be able to log real time data over USB

2.4 - Specifications

This project seeks to address the main issue of not having a safe and reliable system for discharging large capacitors used in electrical power inverters. The team will design a prototype system that is, to the best of our ability, rated for HV input, but it will be tested at a scaled lower voltage. We will then run simulations and calculations to compare our low voltage prototype with a theorized high voltage performance, discussing the differences in notable areas.

The engineering specifications listed below were selected to inform the user and operators of the general system and specific component capabilities. The most important specifications are for the system to have a less than 30 second discharge rate, 3 discharge stages, and a scaled safe threshold voltage indication of less than 0.1V. These define the heart of the system and its purpose. The additional information provided is given to show the operator this prototype's specific capabilities and use case based on our design and internal component selection. However, these specifications also serve the purpose of summarizing our design, allowing for future modifications and development based on our prototype.The overall system and component specifications are listed below, with specifications that the team feels can be demoed to reviewers highlighted in yellow:

Table 1: Specifications

Parameter	Specification
Capacitor Discharge System Specifications	
Input Capacitance	1650 µF ± 10 %
Input Capacitor Voltage (LV)	12 V ± 15 %
Input Capacitor Voltage (HV)	1200 V ± 15 %
Discharge Time from Full to Safe	≤ 30 seconds
Number of Discharge Stages	3
Stage 2 Voltage Setpoint Range (LV)	8 V to 6 V
Stage 2 Voltage Setpoint Range (HV)	800 V to 600 V
Stage 3 Voltage Setpoint Range (LV)	4 V to 2 V
Stage 3 Voltage Setpoint Range (HV)	400 V to 200 V
Discharge System Temperature	< 120 ˚C
Voltage Measurement Accuracy	± 5 %
Voltage/Current Sampling Rate	25 – 50 Hz
Temperature Measurement Accuracy	± 10 %
Safe Indication Threshold (LV)	< 0.1 V
Safe Indication Threshold (HV)	< 10 V
Power Consumption	5 – 35 W
System Area	≤ 24 inches by 36 inches
Unit Cost	< $1200
Component Specifications	
Microcontroller	
Clock Frequency	≥ 160 MHz
Number of GPIO pins	≥ 15
Logic Rail Voltage	3.3 V
Relays	
Coil Voltage	≤ 24 V
Contact Switching Voltage	≥ 1200V DC
Resistors	
Type	Chassis-mount Power
Power Rating	25 – 100 W

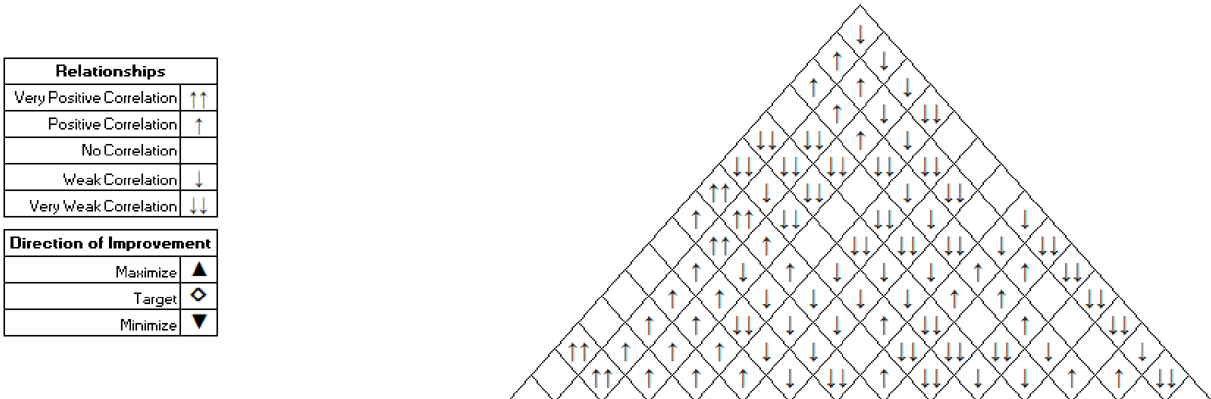
In addition to engineering requirements, it is important that the design be marketable and satisfactory to the sponsor. Based on the sponsor’s input and the design use case and hard specifications, we have come up with a list of marketing requirements we will try to maximize.

Table 2: Marketing Requirements

Marketing Requirements	
Parameter	Description
Safety	The system should prevent accidental HV exposure with safety systems, E-stop, and only show safe voltage level when system is truly below the threshold
Ease of Use	A new user and technician should be able to setup the discharge with minimal training and be confident in their operation
Affordability	The system should be affordable and be worth implementing for companies.
Reliability	The system should be robust and be able to complete many discharge cycles throughout its lifetime without needing replacement
Ease of Maintenance	The system should be easily serviceable if it needs repairs
Configurability	The system should be compatible with any reasonable voltage level configured or set by the operator during use
Deployability/Portability	The system should be manageable in size and weight and easily integrable into existing systems if permanent installation is desired

2.5 - House of Quality

The House of Quality (HOQ) is a common diagram format used in engineering design plans to show the connections and correlations between engineering and market/sponsor/client requirements as well as the desired direction or target for each of these requirements. Using the requirements previously discussed in the previous section, we filled out the table accordingly. The tradeoffs between engineering requirements are listed in the "roof" (upper triangle) portion of the house. The direction of desirability shows whether it is best to increase, decrease, or hit a specific requirement. The inner arrows show the strength and the type of correlation between engineering and marketing requirements.



Column #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Customer Requirements (Explicit and Implicit) / Engineering Requirements	Direction of Desirability	Input Capacitance	Input Capacitor Voltage (LV & HV Models)	Discharge Time from Full to Safe	Number of Discharge States	Stage 2 Voltage Range (LV & HV Models)	Stage 3 Voltage Range (LV & HV Models)	Safe Indication Threshold (LV & HV Models)	Discharge System Temperature	Resistor Power Rating	Voltage Measurement Accuracy	Voltage Sampling Rate	Temperature Measurement Accuracy	Power Consumption	System Size	cost
Direction of Desirability		◇	▲	▼	◇	◇	◇	◇	▼	▲	▲	▲	▲	▼	▼	▼
Safety	▲	↓	↓↓	↑		↑	↑	↑↑	↓↓	↑↑	↑↑	↑	↑↑			↓
Ease of Use	▲		↓	↑	↓	↓	↓	↑	↓				↑	↓	↑	↓
Affordability	▲	↓	↓↓		↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓	↓	↓	↑↑
Reliability	▲		↓	↓	↓	↓	↓	↓	↓↓	↑			↑			↓
Ease of Maintenance	▲		↓		↓↓	↓	↓	↓	↓	↑			↓		↑	↓
Configurability	▲	↓	↓		↑↑	↑↑	↑↑	↑		↑	↑	↑	↑	↑		↓
Deployability/Portability	▲	↓	↓↓		↓				↓						↓↓	↓
Target		1650uF +/- 20%	12V / 1200V +/- 15%	<= 30 seconds	3	8-6V / 800-600V	4-2V / 400-200V	<0.1V / <10V	<120 C	25-100W	+/- 5%	25-50Hz	+/- 10%	5-35W	<24" x 36"	<$1200

Figure 1: House of Quality

2.6 - Features and Functionality

2.6.1 - Hardware Features and Functionality

The previously defined objectives and goals dictate our system's target features and operation. The system can be broken into a few main subsystems: computing and I/O, power delivery, sensing and isolation, and staged capacitor discharge. Each group member has claimed the main responsibility for one of these subsystems.

Computing includes the microcontroller and user I/O. There will be input devices (buttons, rotary encoder/dial, etc.) on the outside of the device to allow users to set the voltages of the various discharge stages. A screen display will showcase the discharge-to-safe time, current voltage and temperature level, and the user settings. The screen's various settings will be navigable by the previously mentioned input devices. The microcontroller is responsible for gathering the voltage and temperature data and switching the relay stages on according to the user's defined set points. Included on the device will be 4 indicator lights showing the current discharge state and when the safe voltage threshold has been reached.

The power delivery subsystem includes the external power supply input and the various regulators for all the different internal voltage rails. We will be using an external 24 V DC source for our system. Internal voltage regulators will split that into various voltage levels, such as 3.3 V and 5 V rails, to be used for various components.

The sensing isolation subsystem includes all the various sensors and devices that measure the data and report it to the microcontroller. This includes the main voltage sensor, the temperature sensor, and their conversion to digital signals with the onboard ADC. The ADC will feed the microcontroller with the data gathered from the sensors. The sensor data will be used to control the current discharge state by driving relays from the MCU control signal and other relay driving circuitry. Isolating the low voltage circuitry needed to sense, process, and make control decisions for the system from potential high voltage connections is also crucial for safety.

The staged capacitor discharge subsystem includes the resistor stages activated by relays, the sequence and calculations for the discharge cycle, and how to safely contain the high voltage connections on an external chassis for isolation purposes. The various resistance values of the discharge stages will be based on the input capacitance, the voltage setpoints, and an optimal discharge speed. The customizable voltage setpoints will determine the points at which the rate of discharge can safely change.

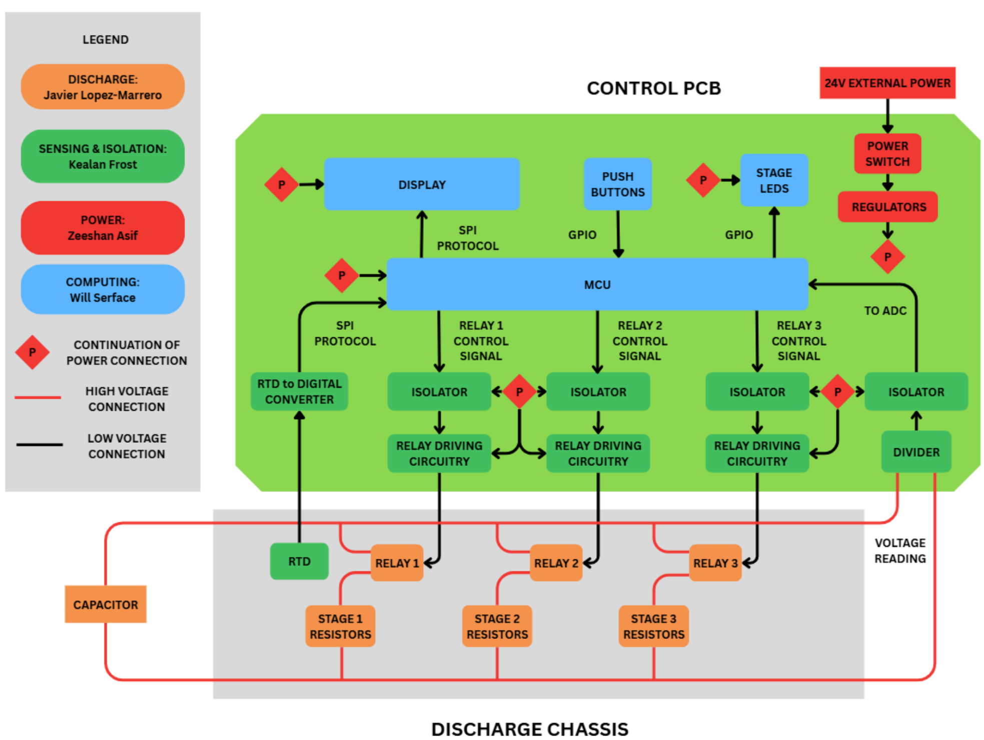


Figure 2: Hardware Diagram

2.6.2 - Software Features and Functionality

The software for this project has a few main principles provided by our sponsor, NextEra, that can be divided into the categories of configuration, control & communication. As this code will be running on a microcontroller, it will perform the initial I/O setup and other configuration before starting its main loop, which will continue until the microcontroller is reset or powered off.

2.6.2.1 Configuration

Part of the project objectives provided by NextEra include four configurable logic alarms based on voltage thresholds. After the initial input and output configuration is run, the software will accept these thresholds as input, either from a user or another source. Once these thresholds have been read into the program, they will be saved until the program is reconfigured.

2.6.2.2 Control

Once the program enters its control loop, it will wait until it receives a signal to start the staged discharge. The scaled voltage will be read through the ADC on each iteration of the control loop, which then will be used to determine the corresponding discharge stage by comparing it to the configured voltage thresholds. The program will then output the corresponding logic alarm and activate the three relays in the optimal dissipation for each given discharge stage. Finally, when the voltage has dropped below the final alarm's threshold, the program will activate the logic high output to indicate that the capacitors have been discharged to a safe voltage.

2.6.2.3 Communication

Even before the staged discharge control loop has been started, the program will monitor the voltage through the ADC. After the alarm configuration is complete, the program then displays its state to the user. Starting before the program receives the signal to discharge, it will indicate that it is idle. Once the staged discharge sequence is started, the program will show its current state, and which alarm is activated. Finally, along with the logic high output, the program will also display an indication of safe voltage when the discharge sequence has been completed.

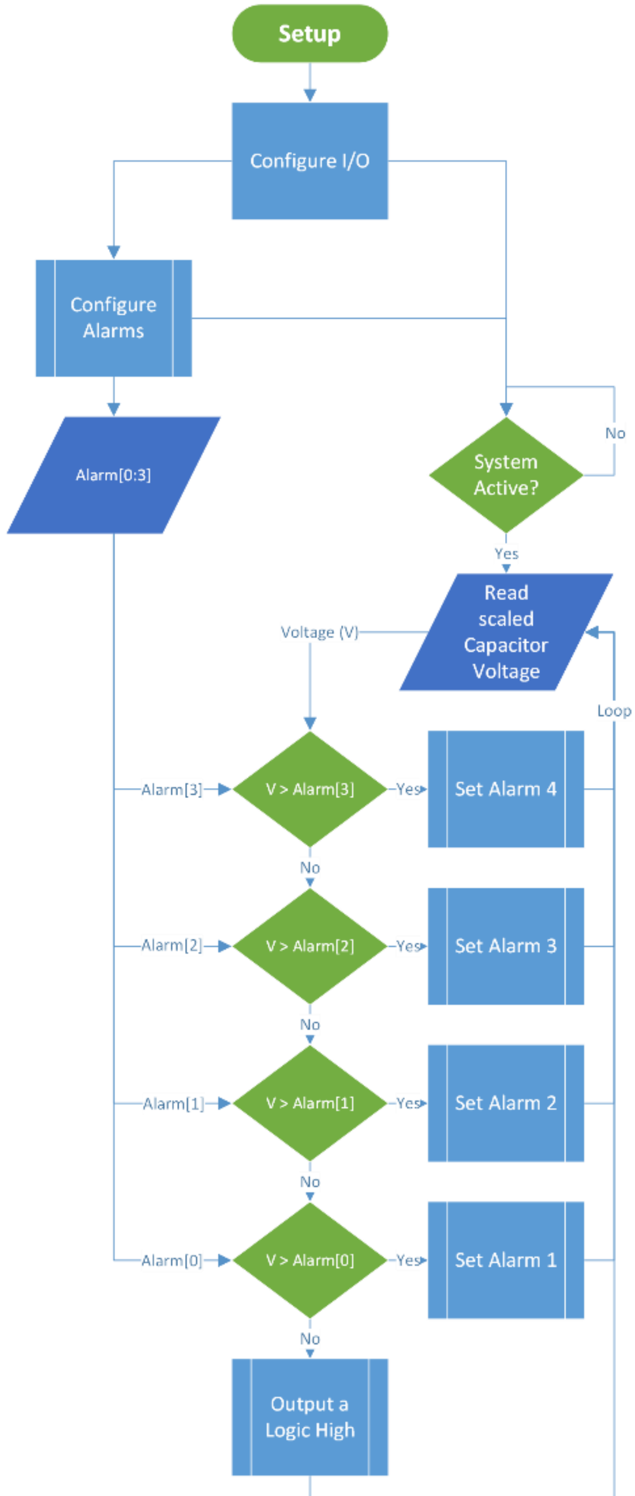


Figure 3: Initial Software Flowchart

Chapter 3: Research and Investigation

3.1 - Resistor Technology

Resistors are an especially crucial component for the scope of this project. The heart of the project depends on bleeding resistors that are dissipating energy from the capacitor over time, but resistors also form the backbone for the low voltage portion of the system as well. A resistor divider network will help monitor the voltage across the capacitor, and resistors will be necessary for much of the low voltage circuitry. As a result of all these uses, it becomes especially important to understand different resistor technologies and select components on a use case basis. It does not make sense, for example, for a pull up resistor to be the exact same make/model as a bleeding resistor. So, to support this effort, the following technologies were researched and explored to understand their capabilities for potential use in the final system.

3.1.1 - Carbon Composition Resistors

Carbon composition is one of the oldest resistor manufacturing technologies dating back to the early 1900s. The manufacturing process involves making the entire resistor body out of a mixture of carbon particles and an insulator such as ceramic. The mixture is then held together with a binder such as resin. Since the carbon particles are conductive, the final resistance value is determined by the concentration of carbon in the final mixture. More carbon results in a higher conductivity and lower overall resistance. Once the mixture is baked, a protective coating is applied over the body, which can then also be painted over with resistor color codes. [9]

The manufacturing process of carbon composition resistors does provide some unique benefits to the final product. Because the resistive element comprises the entire body of the resistor, there is more volume to conduct current, and as a result, conduct heat. The solid body is also noninductive by nature. On the surface, this makes carbon composition resistors good for handling high pulses of energy. As will be discussed later on, however, some instability issues prevent the technology from fully taking advantage of this [10]. In addition to handling high energy pulses, the manufacturing process for these resistors makes it easy to create high resistance values in a cheap manner.

Over the years, carbon composition resistors have largely been replaced by other resistor technology types. This was mainly fueled by issues that are derived from the way they are made. Firstly, the technology does not create very tight tolerances for resistor values in general (usually around 10%). Additionally, the mixture of different materials creates instability in the resistor body. This instability causes conditions like temperature, humidity, long use, and overvoltage to alter the resistance value quite a bit. Depending on the environment, a shelf life of one year could see the resistance value change by as much as 5% [9]. Finally, different materials in the resistor body also contribute to the resistor being more noisy than other technologies [11]. Altogether, these factors made carbon composition resistors unsuitable for high precision applications and newer technologies have largely taken over most of the resistor market by offering better performance.

3.1.2 - Film Resistors

Film resistors are a broad category of resistor technology that encompasses a large portion of the through hole resistor market. They represent a step up in performance in almost every category compared to carbon composition resistors. At their core, film resistors are comprised of an insulating substrate (usually ceramic) and a conductive material that is then deposited around the substrate. This conductive material can be carbon, a metal, or a metal oxide. Once deposited, the conductive material is then cut in a helical pattern which helps control the overall resistance value. Utilizing a higher pitch for the cut results in a larger area and shorter distance in the resistor for current to flow which corresponds to a smaller resistance value. A lower pitch results in the opposite and creates higher resistance value. Once the cuts are made, a mold is typically applied over the resistor body for protection [12].

Due to a controlled and precise cutting process, film resistors are available in resistances ranging from as low as 1 ohm to as high as several megaohms. Tolerances also become tighter compared to carbon composition resistors, with typical values being 2, 5, and 10%. Of the different types of film resistors, carbon film is considered as a good general-purpose technology when high precision is not required. Metal film offers higher performance in multiple categories over carbon film for only a small price increase. These resistors generally have typical tolerances of 1% but can have a tolerance of as low as 0.1%. Additionally, their temperature coefficient is lower than carbon film and they produce less noise. All of these factors make them a much more precise resistor technology when compared to carbon film. Finally, metal oxide resistors are the best of the three when it comes to power rating, voltage rating, overload capability, and thermal performance [10]. Their noise, however, is comparable to that of a carbon film resistor and they may be less precise than metal film resistors at higher power ratings [11]. Another trait worth noting for all of these film resistors, is that they will naturally have parasitic inductance and capacitance associated with them. So, depending on the application, these effects may need to be taken into account.

3.1.3 - Thick and Thin Film

When it comes to SMD packaging, thick and thin film resistors are the dominant technology. Unlike other film resistors, the manufacturing process of thick and thin film resistors is much more planar. This involves a resistive layer of material being either sputtered (a method of vacuum deposition) or screen printed onto a ceramic base. The amount of resistive material determines the resistance value once photoetching or laser trimming is used to calibrate the resistance value. For thin film resistors, the thickness of the resistive material is typically less than one micron. Thick film resistors, as the name suggests, have much thicker resistive material, typically measuring anywhere between 1 and 100 microns. [13]

The main advantage of thin/thick film resistors would be their size. In an SMD package, these resistors can be smaller a tenth of an inch and follow very standardized sizing codes. Both also offer tight tolerance on their resistance values, but to varying degrees. Thick film resistors offer tolerances between 1% and 5% while thin film offer much tighter values between 0.01% and 1%. In addition to this, thin film resistors also have lower temperature coefficients, lower noise, and lower parasitic capacitance and inductance when compared to their thick film counterpart and also when compared to other resistor technologies in general. However, this usually comes at a higher cost as thick film resistors are typically cheaper since they are easier to make and are designed to be more general purpose oriented.

Having so many benefits within a very small package, however, does come with its downsides. Power handling in general will be less when compared to technologies like metal-oxide film and wire wound, although special packages designed to be incorporated with heatsinks to allow for higher wattage use are available. They can also be more sensitive to moisture and the potential effects of ESD. [10]

3.1.4 - Wire wound Resistors

Wire wound resistors are another technology that date back to the early 1900s. Unlike carbon composition resistors, however, wire wound resistors still see a fair amount of use today. The technology is comprised of wire with high resistivity which is wrapped around a non-conductive core. Based on a variety of variables, such as the resistivity of the wire, the size of the wire, and the length of the wrapping, the resistance value can be tuned. By using very thin wire with low resistivity, low power and low resistance can be achieved. For higher power applications, thicker wire with special coatings and insulation are used and the resistor itself can be encased in a metal-finned chassis to help with heat dissipation. [14]

Due to their simplicity, wire wound resistors can be produced accurately at low resistances for precision applications. This makes them a popular choice for fuse applications. On the other end of the spectrum, they can also exhibit the highest power ratings out of all available resistor technologies. This often comes at the cost, however, of being bulky and requiring a dedicated heat sink to utilize the full power rating. Another disadvantage that wire wound resistors have is that their construction is essentially that of a conventional inductor. This means they have higher parasitic inductance than other resistor types. Specific winding patterns, however, have been developed to minimize this effect, although these resistors still typically have the poorest frequency performance. [10] [15]

3.1.5 - Technology Comparison and Selection

The following table compares some key parameters between all the discussed resistor types:

Table 3: Comparison of Various Resistor Technologies

	Carbon Composition	**Carbon Film**	**Metal Film**	**Metal Oxide Film**	**Thick Film**	**Thin Film**	**Wirewound**
Typically Used Package	Through Hole	Through Hole	Through Hole	Through Hole	SMD	SMD	Through Hole or Chassis Mount
Typical Resistance Range	Ω to MΩ	Ω to MΩ	mΩ to MΩ	Ω to MΩ	mΩ to MΩ	mΩ to MΩ	mΩ to MΩ
Typical Tolerances	5 to 20%	2 to 10%	0.1 to 5%	0.1 to 5%	0.1 to 5%	0.01 to 5%	0.1 to 5%
Typical Temp. Coefficient	+2000 to -1400 ppm/°C	±400 to -1500 ppm/°C	±10 to ±100 ppm/°C	±200 to ±350 ppm/°C	±100 to ±400 ppm/°C	±10 to ±50 ppm/°C	-80 to 900 ppm/°C
Typical Power Ratings	1/4 to 1W	1/8 to 2 W	1/8 to 2 W	1/2 to 7 W*	1/20 to 3.5 W*	1/20 to 2/5 W	1/2 to 50W*
Relative Noise/Parasitics	Noisiest	Moderate Noise	Low Noise	Low Noise	Moderate Noise	Low Noise	Low Noise High inductance
Relative Cost	Low	Low	Moderate	Moderate	Lowest	Moderate	Highest
Typical Applications	Legacy Electronics Absorbing High Energy Pulses	General Purpose/Low Cost Electronics	Precision Analog, Audio, and Measurement	Power Surge and Overvoltage absorbtion	General Purpose SMD	High Precision SMD	High Power Dividers/Bleeders
Notes:	*Specialty products/packaging may provide higher wattage (Ex: chassis mount, package design, heatsink use, etc.)						

For the scope of this senior design project, there are two main uses for resistors: high power dissipation and integration of low voltage electronics (sensor circuits, regulator circuits, etc.). Since these uses differ drastically, the choice of resistor technology used for them should also be different. Based on the available technologies, wire wound resistors seem to be the most suitable for high power applications such as the discharge circuits bleeder resistors. They offer the highest base power ratings while also providing a good range of typical resistance value with sufficient tolerance. For low voltage applications, thick and thin film resistors seem to be best suited since they are very widely available at low costs with a variety of resistance values. They also offer great tolerance, little noise, and low TCR.

3.2 - Resistor Component Selection

In terms of wire wound resistors utilized for high power/voltage applications, a large part of the market consists of aluminum housed, chassis mounted resistors. There are, however, other unique options that don't fit that category as well. Below are some options from various market leaders followed by specific comparisons of individual products:

3.2.1 - TE Type HS Series

TE connectivity offers a wide range of passive electronics products within their portfolio. This includes high power wire wound resistors, most notably through the type HS series. This series includes power resistors that range from 5 W to 500 W, which is marketed as the largest range for a single product series on the market. The resistance value range for this series is also large, but specifics differ depending on the specified power rating. Additionally, these resistors are suitable for use in pulse and high voltage applications. This includes but is not limited to, braking and balancing resistors, electric machinery use, and, most importantly, capacitor charging and discharging. Depending on the specific power rating specified, various mounting options are available. Lower power options utilize two mounting holes, while resistors with rated power above 50 W utilize four mounting holes. Additionally, the standard terminal for these resistors is a solder lug suitable for soldering wire or securing ring terminals.

3.2.2 - Arcol HS Series

Arcol is a known quality manufacturer of power resistors based in the United Kingdom. As of 2015, they were purchased by Ohmite, another leader in resistive technology. Their HS series of power resistors has many similarities with those produced by TE connectivity. They are specifically wound to maximize high pulse capability and are marketed as having a high power to volume ratio. As a series, when compared to TE, the available power range is less, only running from 10W to 300W. The resistance range for various power ratings is still large and many of the mechanical aspects in terms of housing and terminal style is similar to TE. The only major difference mechanically is the use of six mounting holes instead of four for higher power ratings.

3.2.3 - Ohmite 270 Series

As mentioned before, Ohmite is another major player when it comes to resistive technologies. Their acquisition of Arcol added a strong aluminum chassis power resistor product line to their portfolio, but they also offer other wire wound resistor packages. A notable one is their 270 series of vitreous enamel coated wire wounds. This kind of packaging offers the benefit of not needing to be mounted specifically to a heatsink and providing a flame-resistant coating. The downside is typically taking up more space and being more costly. With that being said, the 270 series offers wattage ratings from 12 to 1000W and include a hollow core for various types of mounting hardware (through bolt, spring-type brackets, etc.). A wide range of resistances are available and the included lug terminals are suitable for soldering or bolt connection.

3.2.4 - StackPole KAL and Bournes UAL Series

Circling back to aluminum chassis mount resistors, StackPole Electronics and Bournes Incorporated also provide many resistive products of this type. In fact, their KAL and UAL product lines have many similarities between them. They both offer a much smaller range of power ratings, maxing out at 50W. Additionally, their construction/mechanical attributes are nearly identical within a smaller package compared to TE and Arcol options. Both are also marketed for good pulse handling capabilities. The only downside is that limited power ratings also limits the potential working voltage of this series, which will be a crucial parameter for the high voltage applications of this project.

3.2.5 - Comparison and Selection

Of the discussed product series, the most suitable model was selected from each one in order to determine the best option for this project's application. Based on preliminary design work, one of the key component parameters will be the resistors voltage handling capabilities, which is also related to its power handling capability. Additionally, it is worth noting that the rated power for most of these resistors assumes a fairly idealized and well designed heatsink. In order to avoid fully depending on heatsink design for the performance of the discharge resistors, it is more conservative to utilize the free air power rating of these resistors for design calculations. As a result, voltage capability and free air power will be the most important parameters for comparison. For similar performance, cost will ultimately be the deciding factor.

Table 4: Comparison of Power Resistor Options

	TE HSC100 Series	Arcol HS100 Series	StackPole KAL Series	Bournes UAL50 Series	Ohmite 270 L50 Series
Max Rated Power	100W	100W	50W	50W	50W
Max Free Air Power	50W	30W	20W	20W	N/A
Withstand Voltage	1900V DC	1900V DC	3000 VAC	3500 VAC	1625 V DC
Tolerance	5%	5%	5%	5%	5%
Range of Values	5Ω to 100kΩ	1Ω to 70kΩ	0.05Ω to 75kΩ	0.01Ω to 250kΩ	0.38Ω to 260kΩ
Length	3.44 in	3.46 in	2.78 in	2.72 in	4 in
Cost	$17.83	$14.54	$6.44	$8.47	$24.15

Based on the comparison, the highest free air power is between the TE and Ohmite option. Since the TE option offers a higher withstand voltage for a lower price while also being about half an inch smaller, it is a better choice for this application. The Arcol HS100 series could be a good secondary option since it has the second lowest free air power with the same withstanding voltage. In summary, however, the discharge resistor selection will be the TE HSC100 series.

3.3 - Relay Technology

Another key component of this project are the relays, which switch on the various stages of the discharge process. They are also one of the main isolation points between the low voltage portion of the system and the high voltage capacitor, allowing the microcontroller to dictate the discharge order while not coming into direct contact with high voltage. The following research looks at different relay technologies that are currently available in order to have a complete understanding of each one's strengths and weaknesses. From there, a reasonable selection for the projects scope can be made.

3.3.1 - Electromechanical Relays

Electromechanical relays are the oldest type of relay technology with their use dating back to the 1800s in telegraph systems. Despite their age, they still see much use today in a variety of applications such as industrial control and automotive electrical systems. In its simplest form, the key parts of an electromechanical relay consist of a coil, an armature, and a set of contacts. When current from a control signal flows through the coil on one side of the relay, a magnetic field is produced which attracts the metal armature. When the armature moves towards the coil, a set of contacts come together to connect a circuit on the opposite side of the relay. When current stops flowing through the coil and the magnetic field dissipates, a spring returns the armature to its original position and causes the contacts to break the circuit. [16]

Based on the basic construction of an electromechanical relay, alongside the 200 years that the technology has had to develop, a number of advantages become clear. Firstly, this relay type is rugged and many years of technological development have made them quite reliable. The electrical life for electromechanical relays are often in the hundreds of thousands of switching cycles, and it is not uncommon for lightly loaded relays to reach a million switching cycles before failing [17]. Additionally, electromechanical relays have become very general purpose and unique types exist for a variety of applications. These include signal relays, power relays, contactors, etc. [18] The coil-armature system in these relays also provides true galvanic isolation between the control circuit and the load circuit which is critical for high voltage applications.

There are, however, some drawbacks to such a rugged technology. The mechanical nature of this relay type does make them larger than other relay technologies. Additionally, when the contacts break the load circuit there is a possibility for arcing to occur between them. Over time, this arcing can create residue on the contact surfaces which can increase resistance in the load circuit and, if severe enough, can cause electrical failure of the relay. In fact, power limitations of these relay models typically are derived by how much arcing the contacts can handle before they weld together and fail. Even when arcing is not factor, the switching of the contacts themselves can be both physically and electrically noisy, which could affect sensitive circuitry if not considered. Moving away from the contacts on the load side, the coil on the control side can also provide some issues. Essentially acting as an inductor, the coil can add unwanted inductance to a circuit and its switching behavior can lead to transient effects. To account for these effects, driving/protective circuitry is typically required around the coil to effectively switch the relay on and off.

3.3.2 - Reed Relays

Reed relays are a newer technology when compared to electromechanical relays, with their earliest uses dating back to the 1930s Reed relays are also mechanical in nature, but their construction and properties differ enough from conventional electromechanical relays to warrant dedicated research. Rather than having a dedicated armature and contacts, reed relays utilize strips of flexible ferromagnetic metal which are hermetically in a glass tube. In the presence of a magnetic field, the metal strips will be attracted towards each other and make electrical contact. In order to make such a scheme controllable, a coil of wire is wrapped around or near the glass tube, which generates the necessary magnetic field to close the contacts when current flows through it. [19]

This difference in construction for a reed relay does provide unique benefits. The most obvious one is that since the contacts are sealed off from the environment, they are less susceptible to degradation and oxidation that can come from factors such as humidity. Such protection translates to increased electrical life and thus more switching cycles before failure. The isolation of the contacts can also make reed relays able to be more easily designed to sustain high voltages as well. The tradeoff for this is that the lightness and flexibility of the contacts makes their current carrying capacity significantly less than conventional electromechanical relays. And yet, that same lightness and flexibility also provides generally higher switching speeds alongside less switching noise. [19]

Due to the mechanical nature of the reed relay, some disadvantages that are shared with general electromechanical relays remain and may even be amplified. Arcing, for example, is still a phenomenon that occurs and can be more of issue due to the delicate nature of the contacts. In fact, most of the power ratings for such reed relays will be limited by contact arcing and risk of the contacts welding together when they connect the load. Additionally, the main driver for the relay is still a magnetic coil that will act as an inductor on the control side circuit, bringing unwanted transients. Driving/protection circuitry would still be required to adequately control the coil voltage.

3.3.3 - Solid State Relays

Solid state relays represent a large advancement in relay technology and offer a completely different way of controlled switching when compared to their mechanical counterparts. Solid state relays rely completely on semiconductor devices for switching and isolation. While specific details and schemes may differ, in general solid-state relays utilize an LED on its control side. When the LED is biased by a control signal, photons will be detected on the other side of the relay by a photodiode. The photodiode then activates an electric switch, typically some kind of MOSFET, which closes the connection for the load circuit to operate. So, rather than the magnetic field providing a medium for galvanic isolation between the control and load side, in solid state relays light is what helps provide the galvanic isolation [16].

Utilizing semiconductor devices in lieu of mechanical parts does provide solid state relays with a number of advantages. No mechanical contacts results in zero arcing and no forms of mechanical failure, which translates to longer operational life. The switching speed for semiconductor devices is also much faster than any mechanical switching and provides very little noise. The lack of a inductive coil on the control side also means that driving/protection circuitry is not needed. It may even be possible to drive the control signal directly from a microcontroller pine. Taking advantage of current semiconductor manufacturing techniques also allows for solid state relays to come in very small packages [20].

Some unique downsides of using semiconductor devices are also present. One downside that was not present in prior relay technologies has to do with leakage current. Even when the load side of the relay is in its off state, leakage current will still flow through the MOSFET and into the rest of the load circuit. Despite it being in the order of microamps, this does mean that load circuit isn't as fully disconnected as it is with electromechanical relays. Additionally, semiconductor devices can be more susceptible to being damaged from transients and overvoltage in addition to potentially being sensitive to noise. Lastly, most solid-state relays are made for low power applications, but there are a number of AC high-power options on the market that utilize silicon carbide MOSFETS/IGBTS in order to safely switch high voltages [20].

3.3.4 - Contactors

At this point, it is worth noting that another category of electromechanical relays exists when operating voltages and currents get high enough. These relays are known as contactors, and they are essentially electromechanical relays that are built to be larger, more robust, and better equipped to handle the arcing that can occur when switching high power loads. Where the line is drawn to differentiate a relay from a contactor can differ depending on the source, but generally contactors are defined as having a carry current of more than 10 amps.

As a result of their construction, contactors are often designed to be mounted onto a chassis or electrical panel as opposed to integrating directly onto a PCB, although some rare PCB options do exist. This makes them more expensive when compared to other relay options. The increased size can also require a greater coil current to drive the switching action for the same coil voltage when compared to smaller relays. Despite all of these differences and potential downsides, when its comes to effectively switching under high power conditions, contactors are the industry standard.

3.3.5 - Technology Comparison and Selection

The following table compares some key parameters between all the discussed relay types:

Table 5: Comparison of Various Relay Technologies

	Electromechanical	Reed	Solid State	Contactors
Typical Switching Voltage	V to kV	V to kV	V to kV	KV
Typical Load Current	mA to 30A	mA to 3A	mA	A
Typical Switching Speed	ms	ms	µs to ms	ms
Switching Characterstics	Noise Bouncing Arcing	Less Noise Less Bouncing Arcing	Off State Leakage Current	More Noise Bouncing Possible Arc Supression
Typical On Resistance	mΩ	mΩ	mΩ to Ω	mΩ
Typical Lifetime (In Switching Cycles)	10^4 to 10^7	10^6 to 10^7	10^7 to 10^9	~10^6
Relative Cost	Low to Moderate	Moderate	Moderate to High	High

For this senior design project, the discharge system will be seeing high voltage (1200V) but the current coming from the capacitor is not expected to exceed half an amp. Despite this much lower current, the overall switching power will still be very high. Switching 1200V at even 0.1A results in a switching power of 120W, which can bring heavy arcing at the relay contacts. Most standard electromechanical and reed relays aren't rated for this high of switching power, and those that are will see a substantially reduced lifetime by operating near their maximum capabilities. Higher power solid state relays are typically rated for AC voltages, and those designed for high DC voltages are typically more expensive than equivalent contactors. As a result, contactors were chosen as the relay technology for this project, even if the majority of the options on the market may be over required specifications.

3.4 - Relay Component Selection

Navigating the contactor market for this project did prove to be challenging. As stated before, many options on the market have far higher capabilities than what are needed for this project. As a result of that, the cost also increases. Some options, however, were found that were not extremely unreasonable when it came to cost versus performance.

3.4.1 - TE ECP40B Series

TE connectivity offers a contactor option that is designed for use in 1500V DC systems. These include applications such as EV charging, battery storage, and solar inverter systems. Like most the contactors that will be discussed, its 40A current rating is much higher than this project's system would ever need, but it is a lower cost option at $66. In terms of packaging, this contactor is chassis mounted and utilizes M3 screw holes for the main contacts. The coil wires are a fixed length, and would likely need some form of extension for use in this project. Additionally, both 12 and 24V coil voltages are available.

3.4.2 - Sensata-Gigavac P125 Series

Sensata-Gigavac provides a 30A contactor option that is also utilized in charging and solar applications. The reduced current, however, also brings a reduced operating voltage of 1200V. While this does match the operating voltage of this project's system, it does not leave any potential margin. The cost also ends up being higher for this option at 91$. This is likely due to the products packaging. Compared to the TE option, this product is smaller and designed to be incorporated on a larger PCB as opposed to a separate chassis. This PCB mounting comes in the form of M4 and M3 studs for the power and coil contacts respectively. Integrating a product with these terminals onto a PCB for this senior design project may prove challenging.

3.4.3 - Sensata-Gigavac P115 Series

Another option from Sensata-Gigavac provides a more traditional chassis mount design. In terms of performance, the P115 matches or outdoes the other options in many categories. The max switching voltage is 1500V and the current carrying capacity is 50A. Being part of the same minitactor series as the P125, it also retains a smaller packaging despite being chassis mounted. Unlike the TE option, both the main contacts and the coil contacts are stud terminals of either M3 or M4 sizing. Coil options include both 12 and 24V.

Table 6: Comparison of Contactor Options

	TE ECP40B	Sensata-Gigavac P125BDA	Sensata-Gigavac P115CDA
Max Contact Voltage	1500 V	1200V	1500 V
Max Carry Current	40 A	30 A	50A
Max Operate Time	30 ms	25 ms	25 ms
Max Release Time	10 ms	8 ms	8 ms
Nominal Coil Voltage	24 V	24 V	24 V
Nominal Coil Current	125 mA	85 mA	85 mA
Coil Power	3 W	2 W	2 W
Coil Resistance	192Ω	280Ω	280Ω
Mechanical Life	500,000 cycles	1,000,000 cycles	1,000,000 cycles
Cost	$66.03	$91.00	$108.36

3.4.4 - Comparison and Selection

In terms of the P125, both the ECP40 and the P115 provide better contact voltage performance with margin for the expected voltage levels of this project. When comparing just the ECP40 and the P115, it is clear that the P115 has slightly better operate and release times and requires one less watt of power to operate the coil. The mechanical life is also double that of the ECP40. The real question, however, is whether this better performance really justifies the cost. In normal circumstances, probably not, but part availability is also worth considering. In this regard, the P115 is much more widely available and should not experience potential stocking issues, so it will be the contactor selected for this project.

3.5 - Wire Technology

As discussed previously, the high voltage nature of this project requires carefully designed isolation and the use of chassis mounted components to handle the expected power dissipation. As a result, the use of suitable wire is required to connect the various resistors and relays, along with interfacing with the external capacitor and control PCB. The following research seeks to establish a better understanding of wire technology, specifically when it comes to material, current carrying capacity, and insulation. From this information, a more informed decision can be made as to not over or under spec the selection of wire for the project.

3.5.1 - Conductor Material

The backbone of any wire is the material of the conductor itself. The conductor must excel in three key parameters: conductivity, malleability, and cost. Today, copper is the baseline for conductor performance in these three categories, and alternatives to copper are directly compared to it for evaluating their own performance. Some common alternatives to bare copper that were further studied include tinned copper, and aluminum.

Starting with bare annealed copper, it has a conductivity of 5.8×10^7 siemens per meter at 20 degrees Celsius [21]. As implied before, this conductivity is used as a baseline for comparing the conductivities of other metals. This is done through the International Annealed Copper Standard, which gives this conductivity a value of 100%, and gives all other metals' conductivities a value relative to it. There are few materials with higher conductivity to copper, and those that do typically have a much higher cost. Additionally, bare copper is very workable, available, and has a high thermal conductivity as well, which prevents overheating.

Tinned copper has one added feature to traditional copper. Rather than the copper core of the wire being left bare, it is covered in a thin layer tin for protection. The tin prevents potential oxidation of the copper core, which can decrease electrical performance. Additionally, this protection can make the wire have better solderability since the reduction of copper oxides allows for better heating of the material with a soldering iron and the tin enhances solder flow and adhesion [22]. Surprisingly, the tin coating also has a very negligible effect on overall conductivity and final wire pricing.

Moving away from copper-based technologies, aluminum is the only other metal that is used in the same amounts as copper. This is mainly due to cost and weight. Aluminum is significantly cheaper than copper and is much lighter. This becomes evident in their cost per kilogram, with copper costing between $8-10/kg and aluminum only costing between $2-3/kg. An important caveat, however, is that aluminum only has about 61% the conductivity of aluminum [23]. Practically this implies that for the same load carrying capacity, you would need an aluminum conductor that's nearly double the size of its copper counterpart. Additionally, aluminum can be harder to solder, and can be more prone to corrosion compared to copper. So, the cost and weight savings become very beneficial when considering large infrastructure projects such as those undertaken by electric utilities.

3.5.2 - Effects of Insulation and Wire Guage on Ampacity and Voltage Rating

A wires ampacity is defined as the conductor's current carrying limit. The main limiting factor when it comes to a wires ampacity is heat. If too much current runs through an improperly rated wire, then an excess of heat is generated which will end up burning the wire. This heat is a manifestation of the power dissipated in the conductor, which is equal to I^2R, where I is the current and R is the resistance, according to Ohm's Law. Additionally, the resistance of the wire can be expressed as a function of conductivity via the equation $\frac{L}{\sigma A}$, where L is the length of the conductor, A is its cross-sectional area, and sigma is its conductivity. Based on this logic, there are really two ways to increase a conductors current carrying capacity for a fixed current: Either decrease the resistance to minimize power dissipation, or improve the insulation to better handle the subsequent heat. First, various common insulation technologies will be discussed with their effects on temperature and voltage ratings. Then, wire gauges will be briefly discussed along with ampacity charts.

Wire insulation typically falls into one of two categories of polymer plastics: thermoplastics and thermosets. Thermosets are materials that can be molded and strengthened when heated, but once reheated they do not melt, rather they tend to char, and cannot be remolded. Thermoplastics, on the other hand, can be remolded, will melt when exposed to heat, and remain quite flexible after setting [24]. The most popular thermoset insulation is cross-linked polyethylene (XLPE), while the most popular thermoplastic insulation is polyvinyl chloride (PVC). [25] Other options include silicone rubber insulation (a thermoset) and polytetrafluoroethylene (PTFE) (a thermoplastic). The key parameters when it comes to comparing these materials are their dielectric strength, and maximum operating temperatures. Dielectric strength directly determine the voltage rating of the wire and is measured per millimeter of insulation. The insulation temperature capability also effects ampacity as will be discussed soon. Typically, thermoset type insulation will have better temperature performance and can be made to be more flame retardant since it doesn't melt. This is more suitable for cases of failure in high voltage applications. Dielectric strength can be more variable across specific insulation types, with options in both thermosets and thermoplastics having suitable performance for high voltages [26].

Moving away from insulation, the gauge of a wire is also an important factor. A wire's gauge is nothing more than a representation of its diameter. Gauges that are associated with a larger diameter have more cross-sectional area, which decreases the overall resistance of a wire. This can then increase ampacity. Combining this with the temperature rating of a wire that is based on its insulation can be used to derive the ampacity of the wire. In fact, multiple sources of ampacity tables are available for reference to make design decisions based on a wires gauge and temperature rating. [27]

3.5.3 - Technology Comparison and Selection

The following table summarizes and compares key parameters between wire conductors and insulation types:

Table 7: Conductor Technology Comparison

	Bare Copper	Tinned Copper	Aluminum
IASC Conductivity	100%	100%	62%
Typical Operating Temperature	150 C	150 C	90 C
Relative Corrosion Resistance	Medium	High	Low without external compound
Relative Solderability	Medium	High	Low
Relative Cost	Low	Low	Lowest

Table 8: Insulation Technology Comparison

	PVC	XLPE	PTFE	Silicone
Material Type	Thermoplastic	Thermoset	Thermoplastic	Thermoset
Typical Dielectric Strength	~15kV/mm	~20kV/mm	~50kV/mm	~20kV/mm
Relative Flexibility	Low to Medium	Medium	High	High
Typical Temperature Ranges	-55 to 105 C	-40 to 130 C	-70 to 260 C	-65 to 150 C
Relative Cost	Low	Medium	High	Medium

In terms of conductor material, all of the specified conductors are low cost, so pure performance becomes the deciding factor. Tinned copper retains all of the benefits of bare copper plus includes additional corrosion resistance and makes any potential soldering easier. As a result, tinned copper will be selected as the conductor material.

In terms of insulation, there needs to be a balance between dielectric strength and cost. Additionally, the wire itself should be fairly flexible in order to make potential chassis wiring and routing easier. For the majority of the wire market when it comes to 1200V or higher ratings, XLPE or Silicone Rubber is utilized because they strike a balance between the these requirements. For this project, silicone rubber insulation will be selected due to its better flexibility and temperature performance for roughly the same cost as XLPE.

3.6 - Wire Selection

In terms of wire options from different manufacturers, once the conductor, insulation, and wire gauge are all selected, their properties are all essentially identical. The only difference is the rated voltage, but all three options are above 1200V needed for this project. So the selection will essentially come down purely to cost.

Table 9: Comparison of Wire Options

	CNC Tech Wire	Rowe Lead Wire	McMaster-Carr Wire
Insulation	Silicone Rubber	Silicone Rubber	Silicone Rubber
Conductor	Tinned Copper	Tinned Copper	Tinned Copper
Gauge	22 AWG	22 AWG	22 AWG
Rated Voltage	3kV	5kV	10kV
Rated Temperature	150 C	150 C	150 C
Estimated Ampacity	~ 9 A	~ 9 A	~ 9 A
Cost Per Foot	$0.30	$0.82	$5.64
Minimum Required Feet to Purchase	500	25	1

When considering cost for wire, an important factor besides the cost per foot is the minimum amount of feet required to be purchase at once from the manufacturer. Since this project is not expected to utilize large wire lengths, the Rowe Lead Wire ends up being the most economical choice for the application. As a result, it will be the selected wire for this project.

3.7 - Voltage Sensing Technology

Voltage sensing/measurement is what allows a microcontroller or other computing chip to control a system. Some microcontrollers have voltage measurement capabilities built in, but some may not or might be lacking in terms of sampling rate, accuracy, or voltage range. To account for this, one can select dedicated voltage measurement ICs or systems that help translate the analog signal into a readable signal by the MCU. In this section we review and contrast a variety of voltage sensing and supporting technologies to determine what would be the best fit for our system.

Our system needs high speed, low-latency, and accurate voltage measuring capability to operate effectively. The capacitor discharge tool switches between discharge resistor stages and sends logic outputs depending on the active voltage reading. One of our stretch goals is to also track the voltage discharge curve and plot it after the cycle is complete. To achieve these levels of operation, we need our voltage measurement system to meet a few criteria. It must be able to read the voltage level of our capacitor, ranging from 1200-0 V with an accuracy of ± 5 %. It needs to be sampled at a rate of at least 25 Hz. It needs to be compatible with voltage isolation procedures to adhere to safety principles for this project.

3.7.1 - Input Scaling and Networks

The capacitor/input voltage we are trying to measure is very high, ranging from 1200-0 V. This is beyond the range supported by typical voltage measurement ICs. We can use scaling networks on the input to be able to reduce the voltage down and measure it with traditional voltage measurement ICs.

For DC or very slow time varying signals, we can use a simple resistor voltage divider with the input to our voltage measurement IC connected across the lower value resistor. It is important to note the tradeoff between high versus low value resistors for this. Low value resistors will draw excess current and give off excess heat, while high value resistors can be noisy and throw off a voltage measurement. Also, when attaching a voltage measurement IC to the lower resistor in a network, the input impedance/resistance of the IC can throw off the voltage divider ratio. The effect is minimal if the input impedance of the measurement IC is much larger than the lower resistor. If the IC does not have a high input impedance, a voltage follower circuit can be used to copy the voltage seen by the lower resistor to the measurement IC without loading that portion of the circuit.

For AC or fast-moving transient portions of a circuit, a capacitor voltage divider network can be used at the input of a measurement IC. Sometimes capacitor and resistor divider networks are used together to divide both the AC and DC portions of signals together for measurement. Similar concerns show up here. The specific frequency or transient speed you can measure will be determined by the size of your capacitors.

Special resistors are needed for our resistor voltage divider network. Inside this voltage divider chain, the individual voltages across the resistors may be very high. Some resistor technologies are prone to varying resistances based on applied voltage. This is characterized by the VCR (voltage coefficient of resistance) of the specific resistors. The resistors should also have a matching TCR (temperature coefficient of resistance). This means that their resistance changes the same given the same temperature change. Resistors can also come in pre-packaged network ICs, which are thermally bonded to help keep their resistance ratio stable. However, these packages are often not rated for HV.

In addition to the voltage divider, we can add additional input-side components to our measurement ICs to increase performance. Often, TVS (transient voltage suppression) diodes are added to the input lines to prevent high voltage transients or spikes from damaging or overloading a measurement IC. These can clamp the input lines both above and below certain set voltages.

Some voltage measurement ICs use internal resistor and capacitor divider networks. These are constantly switching and cause a dynamic complex input impedance to be seen. To account for this, one can use a voltage follower circuit or series resistor and parallel capacitor at the input.

3.7.2 - Comparators

Comparators are logic level devices that compare an analog input to a reference and then output high or low depending on if the analog input is above or below the reference. You can combine two comparators together to make a window comparator, a device that can check if an input is within a set voltage range. Comparators are very fast and reliable. However, they are not useful for measuring voltages. They are useful for determining if voltages are above, below, or within a certain range.

Comparators can be fixed with a given voltage reference and specific values of resistors, but there are a variety of techniques that can be used to make a variable voltage comparator. The voltage reference pin can be the output from a DAC. You can also use digital potentiometers to adjust the resistor ratio values.

While comparators are not useful for voltage measurements, they can serve as a backup or safety measurement. A system can implement both an ADC and a comparator for voltage measurements. When trying to determine if the system is in a safe condition, the ADC and comparator's voltage can be read. If both don't show safe, the system can show warning. This could make for a good, easy to integrate solution to having a backup for safe voltage measurement.

3.7.3 - Voltage to Frequency and Voltage to Time Converters

There are a variety of voltage measurement tools that read an analog voltage level and output a frequency/time varied digital signal. There are three main kinds of conversion. The first is outputting a single pulse train with frequency of the pulses proportional to the voltage input. The second is outputting an extended/longer period pulse proportional to the voltage input. The third is adjusting the duty cycle of a fixed frequency output proportional to the voltage input.

The benefit of these converters are their isolation requirements and their cost/compatibility with existing hardware. These converters only use a single digital line output. That means only a single optocoupler is needed for each voltage measurement to be properly isolated from the LV portion of the board. These types of ICs are also often cheaper/simpler than full ADC ICs. The conversion of the digital pulses into a voltage reading can be done by most microcontrollers.

3.7.4 - ADC Architectures

A standard way of measuring voltage level is by using an ADC IC. These take in an analog level and convert the output to a bitstream or digitally encoded piece of data. There are many kinds of ADC IC architectures, each having their own benefits and drawbacks.

The most basic ADC architecture is the successive approximation register (SAR) ADC. It uses a resistor or capacitor divider internally and a binary search against a reference voltage to get the voltage input equivalent. They usually have low latency. They can have a complicated input impedance due to the sample and hold nature and the capacitive divider, so the data sheet needs to be consulted for input circuitry. These usually have resolutions on the order of 12-18 bits and are in the kilosamples per second range.

Another common ADC architecture is the delta-sigma converter. This oversamples the voltage input. It then uses a low pass filter to cancel out the noise and a decimator to convert into a readable digital output. It then takes this average and outputs it as a digital signal into your controller. These converters have average sampling rate and high resolution. They also provide internal isolation because of the delta-sigma modulator. However, the decimation filter introduces a latency in the signal measurement.

The integrating ADC switches an integrating op amp between the voltage input and a known positive and/or negative reference voltage. The run-up time and the run-down time of the integrator are proportional to the input voltage. A comparator device detects the zero-crossing line of the integrating op amp, and a timer measures the run-down time. These times together allow you to find the voltage input. This architecture has good absolute accuracy, but they do have low sampling rates.

Pipeline ADCs have very high sampling rates at the expense of resolution. These perform the analog to digital conversion in stages. Each stage uses a tiny DAC to generate an amount to subtract from the input. The difference is passed onto the next stage where this process repeats until the sum of the DACs equals the input voltage. These ADCs have a longer latency between the input and the measurement. They are also more complicated. Their benefit is in their very high sampling rate.

3.7.5 - Voltage Sensing Technology Comparison and Selection

Knowing the above, we compared the comparators, voltage-to-frequency/time, SAR ADC, and delta-sigma ADC technologies together to determine if there was a best fit for our situation Below is a table comparing the technologies.

Table 10: Voltage Sensing Technology Comparison

Technology	Resolution	Sampling Rate	Latency	Setup Overhead	Cost
Comparator	N/A (or very low)	N/A (very fast)	Very low	Low (op amp setup)	Low
Voltage-to-frequency/time	10-14 bits	10-1000 sps	Low-medium	Medium (IC + MCU timer + filter)	Medium
SAR ADC	10-16 bits	1-1000 ksps	Low	Low (single IC /in MCU)	Very Low
Delta-Sigma ADC	16-24 bits	1-100 ksps	Medium-high	Low-Medium (internal clock vs MCU conversion)	Low

Based on the comparison we selected the SAR ADC. Specifically, we are using the SAR ADC located inside of the STM32. This choice best matches our latency, sampling rate, and accuracy requirements while also keeping the design simple and the board power low. The SAR can use an external reference that we supply, so we can make sure it is plenty accurate enough to be used.

3.8 - Voltage Sensing Component Selection

3.9 - Temperature Sensing Technology

Temperature sensing is what allows our microcontroller to read the current state and control the system. Some microcontrollers do have temperature sensing built in that can measure the temperature of the individual IC or PCB. This only measures local temperatures to the MCU. To measure the temperature of a remote system or location, we can select a remote temperature sensor that communicates the information to our MCU. In this section we will be going over various types of remote temperature sensing technologies, how they work, and which one would work best for our application.

Our system needs low-latency and accurate temperature measurement capability to operate effectively. The capacitor discharge tool switches on/off resistor stages, dissipating the energy stored in the capacitor as heat in the resistors. The resistors are power resistors meant for high energy throughput. They were also sized such that the peak wattage in them stays below their continuous wattage rating. These aluminum cased resistors will sit on top of an aluminum plate, thermally bonded to the plate, to add thermal mass and dissipate extra heat. One of our goals in this project is to discharge the capacitor safely. If there is a situation where a discharge event creates a very high temperature, this can melt/deform plastics and melt the insulation on wires creating shorts in the system. This could lead to rapid discharges and unsafe situations for the operators of the tool. To ensure that the system stays below a certain temperature, we need to first read the temperature and then if the temperature increases too much, open the contactors to stop the flow of current. To be able to do this effectively, we need to be able to read the temperature within the range of 0-150 degrees Celsius with a +/- 5% accuracy tolerance. The poling rate should be as fast as possible to ensure that the system can be shut off as quickly as possible. However, the thermal resistance of the plate and the resistors housing and the connection to the thermal probe means that our temperature measurement may lag or change slowly with the current discharge state.

RTDs (Resistance Temperature Detectors) are precision resistors that have a positive temperature coefficient (their resistance increases as temperature increases). RTDs are made of components with repeatable temperature and resistance profiles. The RTD element is fed a known current value. The voltage across the RTD is then measured. Ohms law is then used to find the resistance of the probe, and from that the temperature is calculated. Lead wire resistance can be a source of error in the RTD probe measurement. To account for this, RTD probes can be found in 3 wire and 4 wire packages. These additional wires feed the excitation current through one pair and use the other wire(s) to read the voltage, this way the resistance of the wires is ignored. An important thing to note with RTDs is that you are feeding a known current through a resistor. There will be some self-heating, which can throw off very cold or sensitive measurements. Their main benefits lie in their accuracy and linearity. The only downsides would be their cost and additional circuitry needed to give the excitation current and read the voltage.

The NTC (Negative Temperature Coefficient) thermistor is a semiconductor device whose resistance decreases as temperature increases. These sensors are also given an excitation. Their voltage is measured in an external voltage division circuit. The NTCs are highly nonlinear. There is no fixed change in resistance based on a fixed change in temperature. Instead, the voltage across the NTC is taken into software and compared against a curve or lookup table to find the appropriate temperature. They are simpler to implement hardware wise, but require special programming to be able to decode the temperatures. They also offer smaller temperature sensing ranges than the other options.

The thermocouple is a joint of two different metals. This junction will have a voltage across it based on the current temperature. There are various types and classes of thermocouple. The thermocouple is very robust, usually used in hard applications with rough environments and high temperatures. Thermocouples are also nonlinear. These devices rely on polynomial functions or lookup tables to determine their temperatures based on the measured voltages.

The analog ICs are built in units that take in a voltage level and usually have a BJT with variable gain based on temperature. These units will have 3 wires, one for input, one for sense, and one for ground. These usually have good linearity, but not a very high temperature measurement range.

The digital ICs use the same sensing technology as analog ICs, but they also have integrated ADCs and linearization/calibration tables internally that help the output be more accurate. These can have 3 wires for power, ground, and data or 2 wires if they have parasitic power based on the data signal. These are simpler to use than the analog sensors but can cost more. They also have a more limited temperature measurement range.

The last temperature measurement technique is the infrared non-contact type. This is the technology behind IR sensors and guns that record temperatures of objects without direct contact. They rely on reading the emissive radiation of a source and then calculating the temperature of the object. These usually have a higher temperature measurement range, but can have various effects based on the material they are measuring. Shiny objects such as metals reflect infrared and cannot be measured reliably unless you paint it or cover portions of the surface.

3.9.1 - Temperature Sensing Technology Comparison and Selection

We can now summarize the technologies listed and explained above in a table. The table compares the key figures of merit of a temperature sensor: sensing range, accuracy, linearity, cost, and integration effort on our end. As we said before, the sensor needs to be able to support the range of temperatures we expect on the discharge heatsink. It also needs to be accurate. The linearity is the change in how much a sensor's output changes based on how much its input changes. A linear temperature sensor may always output an additional 10mV for every 5 degrees C it reads. A nonlinear sensor might only output 5mV for a 5 degrees C change when it reaches 150 C. Linearity makes processing a temperature sensor's information easier. Cost is also a prohibiting factor. While we are not absolutely maximizing cost, picking technologies/components for quality instead, we still try to pick the most reasonable option. The integration effort summarizes how complex it would be to use the specific sensor.

Technology	Sensing Range	Accuracy	Linearity	Cost	Integration Effort
RTD	-50 to 250 C	+/- 0.3 to 0.8 C	High	High	Medium
NTC	-40 to 125 C	+/- 0.5 to 2 C	Nonlinear	Low	Low
Thermocouple	0 to 800 C	+/- 1.1 to 2.2 C	Nonlinear	Medium	High
Analog IC	-40 to 125C	+/- 0.5 to 2 C	Medium	Low	Very Low
Digital IC	-40 to 125C	+/- 0.5 C	Medium	Low	Low
IR non-contact	-70 to 350 C	+/- 0.5 C	Nonlinear	High	High

Based on the above table, the RTD wins out in terms of range, accuracy, and linearity, with its drawbacks coming from the cost and integration effort. The RTD also is unique compared to the analog/digital ICs in that it provides pre-made thermal probes, some of which come with holes for easier mounting. One of these was suggested by our sponsor as an item that would work with our systems temperature range, was well priced, and would easily mount to our discharge plate. The RTD costs could be much higher, but because our probe and digital converter were not extremely expensive, we decided to use the RTD sensor for our device.

3.10 - Temperature Sensing Component Selection

3.11 - Isolation Technology

Isolation is an important part of our project. Our system discharges a high voltage capacitor (max expected value of 1200V with an absolute maximum 1500V). This voltage level is very dangerous and can kill or severely injure instantly. It is important that we keep areas that users/operators are expected to touch and can come into contact with at a safe voltage level. To be able to ensure this, we use isolation technology. This technology allows us to transfer power or communicate data between high voltage and low voltage/safe portions of our PCB and system. In this section, we will be going over the various kinds of isolation technology and strategy that will allow our system to remain safe and operational.

When selecting isolation technology, there's a few things we need to understand about our system. The first is that it should not be an unlimited power supply. The systems are disconnected from the mains lines and the capacitors have a finite amount of energy stored in them. There's also whether we need to withstand or isolate a constant high voltage level or if we will be seeing short term (less than 1 minute) voltage spikes up to the max level. The main guidelines that relate to our PCB design and selection will be the creepage and clearance. These relate to the distance along a material that high voltage can travel and the air gap that high voltage can travel respectively. Our system is designed to discharge 1650uF capacitors that are rated for usage at 1200V. Based on conversations with the sponsor, the capacitors should rarely be at/around the 1200V level, most discharges should start at a lower level. We also have a max voltage of 1500V, as that is what the capacitor's max voltage rating is. When comparing isolation technology there are a variety of ways you can group it, whether that be by the underlying technology, the specific device's operation technique, or by the device's purpose.

The first kind of isolation transfers analog signals between the high voltage and low voltage sides. These can “copy” voltages and currents also carrying the data from analog sensors such as temperature sensors. There are a few different types of analog isolation devices including but not limited to the isolation amplifier, isolated sigma-delta modulator, and linear optocoupler. The isolation amplifier modulates the HV side voltage level across the isolation barrier to the low voltage side where it is demodulated and re-created. The delta-sigma modulator has an internal ADC and DAC that transfers the digital signal across the isolation barrier. The linear optocoupler uses an LED and photodetector to sink currents. This is the most inaccurate version of the analog isolation devices. It also often requires additional power on the HV side.

The next technology is for digital communications. To do this we have logical optocouplers, magnetic isolators, and capacitive isolators. It is important to note that certain digital communications protocols, beyond requiring certain numbers of pins may also require certain pins to be pulled high/low by both sides of the line. For this reason, special digital isolators are needed that can perform this function. The optocouplers again are the weakest in this category, requiring the most power to activate and not having the highest communication rate capability. It should be noted that many digital isolators require an external source on the HV side in order for them to transfer data properly. This adds additional components and failure points.

Another technology used in isolation is how you transfer power between the low voltage and high voltage sides. These are often in the form of DC/DC isolated converters. Some isolated DC/DC converters copy over the same voltage, but some also act as regulators taking a low voltage input level and converting that into an isolated separate voltage level on the high voltage side. These components are necessary if there are any electronics that need power on the high voltage side. These converters modulate DC voltage into high frequency AC that they then transfer over to the HV side through transformer windings.

3.11.1 - Isolation Technology Comparison and Selection

Summarizing the above, we looked at a few different kinds of technology used in isolation. Our analog isolators form the simplest base requiring the fewest components and having the simplest operation. The digital isolators are usually paired with isolated power converters and are more complicated needing to support high frequency signals that can be pulled high or low. The isolated power converters are used in conjunction with our signal isolators as well as to power the rest of our components.

Technology	Use	Accuracy	Simplicity	Integration Effort
Analog Isolator	Copying analog signals	High	High	Low
Digital Isolator	Digital communications protocols	Very High	Low	High
Isolated Power Converter	Transferring power between high and low voltage sides	High	Medium	Medium

3.12 - Isolation Component Selection

3.13 - Microcontroller Technology

When deciding what will be the brains of any embedded system, there are an abundance of considerations that must be accounted for prior to the first prototype. Some factors that influence the decision would be the clock speed required to run the software, what other components need to connect with the microcontroller, how much and what types of input and output pins will be needed, along with multiple other variables specific to each project.

3.13.1 - Clock Speed

To keep track of the latest voltage levels, the microcontroller needs to have a sufficient clock frequency to perform all required computation, including user interactions, numerical conversions, state updates and outputs to the relays and discharge indicators. Additionally, there needs to be enough overhead to comfortably run the display program that allows the user to configure the stages in the first place.
Part of the calculation for how fast the processor needs to run will also be determined by the efficiency of the software implementation. For example, a poorly designed system might split the program into time slices where sub-routines are run for a long period of time. In extreme situations, that might lead to a button press being missed from a user. On the other hand, a well-planned interrupt-based approach could respond to time-critical events as needed, while handling data sampling, state changes and communication protocols in the background.

3.13.2 - I/O & Connectivity

When selecting a processor to be used in a project, another important consideration is the type and rate of data transfer required to support the system's operation. This can include the number of buttons required, such as over a hundred on a full-size keyboard or just a handful on an alarm clock. Additionally, driving a large display directly from the main microcontroller could significantly reduce the amount of compute time available to perform the rest of the program required by a given system. Another consideration is that the package must either have enough current output to power connected devices or rely on other components to supply the power requirements of the devices it controls.

3.13.3 - Project-Specific Considerations

In this project, the microcontroller will also need to read a scaled analog voltage to determine which stage to set the relays, which requires either receiving data from an external analog to digital converter or finding a microcontroller that has one built in. At the same time, the internal clock must be fast enough to drive communication protocols with other components in the system, such as a display or sensors. Due to its isolation from the high-voltage components of the system, the microcontroller will not be directly driving the relays but rather controlling amplifiers that drive the relays, significantly reducing the current output requirements of the controller itself.

The physical package must be reasonably large enough to place by hand using equipment available in the Senior Design lab, while also having enough general purpose I/O pins to support four digital outputs (one per relay and one for the safe indication), at least three buttons for directional navigation and control, along with at least one analog input of sufficient resolution to determine if the scaled voltage is under the ten volt safe threshold and at least two groups of pins able to run communication protocols such as SPI, I^2C and UART.

3.13.4 - Microcontroller Technology Comparison

Below is a table of comparisons between three major manufacturers of processors that we have considered for the project, considering factors listed above along with other factors that will affect the development of software on each platform.

Table 11: Microcontroller Comparisons

	Arduino	**ESP32**	**STM32**
Familiarity	Medium	Low	Medium
Library Availability	High	Medium	Low
Documentation	Medium	High	Low
Feature Sets	Low	Medium	High
Power Consumption	Medium	High	Low
Processor Speeds	Medium	High	Medium
I/O Options	Low	Medium	High

Given the hardware accelerated features such as ADC oversampling, direct memory access, and a full hardware abstraction layer, we decided to select a microcontroller from the options provided by ST Microelectronics.

3.14 - Microcontroller Selection

Of the variety of microprocessor options available from ST, our use case was able to fit into their Mainstream MCU category, which includes the STM32 C, F and G families. The family of microcontrollers that matched our requirements was the STM32G4, which had a high feature density and clock rate while keeping power consumption low. We found a microcontroller and development board pair, the STM32G431RB, which had the required I/O and hardware to support our use case, and selected the STM32G431RBT6 because it had the largest pin spacing, and would therefore be the easiest package to solder of the product line.

3.15 - Display Technology

When designing a computing device that needs to be observed and controlled by a human user, one of the important design considerations is how the device's data should be presented and how the user can manipulate the device's state. An example would be how most computers use a video display to show information, while taking a combination of keyboard and mouse inputs. However, a digital clock does not have the same level of complexity and usually has somewhere between 3 and 5 buttons to control its current time and alarms. For embedded devices and other systems driven by microcontrollers, there are a few common ways a user can interact with the system that each have unique constraints, strengths and weaknesses. Below is a comparison of different display and control technologies considered for this project.

3.15.1 - Segmented LED Displays

One of the first digital display technologies was the segmented LED display. Common variants include the 7 and 14-segment displays, which are used commonly in clocks, kitchen appliances and simple calculators. Segmented displays excel in devices that prominently display a small amount of simple data or in applications with extremely low power requirements, in addition to being very inexpensive compared to other display technologies. However, the practicality of this display technology is limited by the number of general-purpose output pins on the microcontroller, as each segment requires its own output pin and can quickly outnumber the I/O capabilities of a smaller chip.

3.15.2 - Dot Matrix Displays

The modern alternative to segmented displays, the Dot Matrix display, operates by displaying data as a grid of pixels rather than a fixed set of segments. This type of display encompasses a wide range of technologies, which range from the OLED displays seen on modern phones to the 16-character 2-line LCDs that are used in the EEL3946 Junior Design project here at UCF. Dot Matrix displays almost always come with a separate processor to drive the display, which is controlled using a protocol such as SPI or UART by the main microprocessor of the system, thereby overcoming the I/O limitations posed by segmented display technologies, at the cost of a slightly reduced response time. These displays can display text or graphics, with options for both black-and-white and color in a wide range of sizes, visibility angles and lighting conditions, and some even include touchscreen input capabilities. Additionally, there are many open-source libraries available designed to support modern user interface paradigms on low power processors and microcontrollers.

3.15.3 - Display Technology Comparison

Below is a table to compare the previously discussed display technology using a few metrics that inform our decision for how our project will communicate information to the user.

Table 12: Display Technology Comparisons

	Dot Matrix	**Segmented LED**
Visibility	Variable, Low to Medium	High
Detail	High	Low
Information Density	High	Low
Versatility	High	Low
Simplicity	Low	High
GPIO Required	Low to Medium	High

Given that this project needs to present the user with a variety of changing information during the various discharge stages, it would not be feasible to implement the user interface on a segmented LEDs, so we chose to use a dot matrix display, and specifically an LCD display because of their widespread availability and integration with embedded systems. However, there will be dedicated indicator LEDs that activate when the system is powered on, when each stage is active, and when the system has finished discharging the capacitors.

3.16 - Display Component Selection

While researching display options available, we were advised to investigate displays that used communication protocols to communicate with a dedicated coprocessor, as that would allow the main microcontroller to not store or compute the graphics itself, which in turn would allow for more responsive operations and faster sampling rates for our connected sensors. When searching for a display matching these characteristics, we found the NHD-5.0-800480FT-CTXL-T by Newhaven Display, which is a 5” LCD panel with a FT812 graphics coprocessor. It has a 20-pin header on the back, which would allow us to mount it directly to our main PCB and control the display using SPI.

3.17 - User Input Technology

3.17.1 - Touchscreen Displays

With the improvements in display technology, many embedded devices have shifted from the push-button and dial interface in favor of a touchscreen. This allows the user to interact with the device using the same interface the device uses to communicate with the user. Touchscreens grant much more intuitive experiences for navigation and control, with the drawbacks of a higher cost for an equivalent non-touchscreen display and requiring more system resources during runtime for handling interactions. Another consideration specific to this project is that the device is intended to be used in laboratory conditions with high voltage operations. As such, the user should have PPE equipped, which may include handwear that would prevent the user’s touch from being detected.

3.17.2 - Push Buttons

The simplest way of controlling the system would be a set of three or five buttons, with two or four respectively for directional navigation and one for selection. The benefits of this control technology include simplicity for both the design implementation and user experience. These types of buttons would also be operatable even if the user wears personal protective equipment and provide both mechanical and sometime audible feedback that the push button has been actuated.

3.17.3 - Safety Buttons

When working with high voltage, heavy machinery or any other equipment that could potentially cause harm to someone, there are often emergency shutoff buttons, or E-stop buttons. These differ from typical push buttons in two major ways, both of which are critical for ensuring safety when working. First, the housing and actuation of E-stop buttons are intentionally designed to be easily pressed, mechanically lock into its depressed state, and difficult to reset by accident.

Common examples include large, mushroom-shaped keycaps so the E-stop button can be pressed from any direction, red coloring with warning icons or labels, or a mechanism requiring the button head to be twisted to reset after a locking linear depression. Second, the button is normally closed allowing current to flow through to the rest of the system. This allows the E-stop button to physically disconnect the rest of the system from power in the event of an emergency shutoff. As such, these buttons are typically mounted in an easily accessible panel and are expected to handle much higher voltage and current loads compared to the rest of the user interface.

3.17.4 - Input Technology Comparison

Below is a comparison of several factors that could affect the development and usability of each of the discussed user input methods.

Table 13: Input Comparisons

	Touchscreen	**Push Buttons**	**Safety Buttons**
Ease of Use	Variable, Med. to High	High	Low
Ease of Implementation	Low	High	High
Intuitiveness	High	Medium	Variable, Low to Med.
Accessibility	Medium	High	Low
Haptic Feedback	Low	Medium	High

While the selected display is capable of touch input, we decided to use a set of push buttons arranged in a directional navigation style to allow the user to move through software menus and control the system without needing to use a touchscreen or stylus.

3.18 - User Input Component Selection

For user input, we decided to use the Cherry MX Blue switches. This decision was formed by the accessibility of the user, who may use personal protective equipment while connecting the capacitor bank to the discharge tool, so they can use the system without having to remove gloves or delay the process to interact with the tool. The Cherry MX Blue push buttons were identified for their clicky mechanism, which is used on both mechanical keyboards and some industrial equipment to give the user both tactile and audible feedback of the button actuation, which could be useful in the situation where the user’s sense of touch is impeded by a glove or other PPE.

3.19 - External Power Technology

3.19.1 - Power table

A power table like the one below provides a look at the overall power distribution system and enables the team to account for the amount of power required for certain specific components. It is important to keep in mind that the set amount of specific regulators can vary depending on design so the team decided to use more of a general estimate. Dividing up the voltages also allows for estimations on how many 3.3- and 5-volt regulators would be roughly required. The values in general used are not totally accurate, but detailed estimations based on the specifications sheets of the respective components and their usage within the system. In addition, the estimations are more on the high end, naturally for in case more wage is required, than on the low end of the overall range.

Table 14: Power Table

Component	Maximum Current Required	Voltage Required	Quantity	Maximum Power Consumption
Isolation Amplifier	48 mA	5V	1	240 mW
Dual Operational Amplifier	15 mA	5V	2	150 mW
General Voltage Reference	50 mA	5V	1	250 mW
Relays	85 mA	24V	3	6.12 W
Transistor	20 mA	3.3 V	3	99 mW
RTD to Digital	3.5 mA	3.3V	1	11.5 mW
MCU	50 mA	3.3V	1	165 mW
Display	100 mA	3.3V	1	330 mW
LED's	20 mA	3.3V	4	26.4 mW
Current limiting resistors for buttons	40 mA	3.3 V	3	396 mW
3.3- and 5-volt regulators	3 A(for both)	3.3 V/5V	2(1 of each)	5V- 0.191 mW 3.3V- 0.342 mW
Display driver	590 mA	3.3V	1	1.947 mW
Total Power Consumption	-	-	-	7.79 W

External Power supplies are an extremely important aspect of the design. A power supply unit (PSU) provides the initial electrical energy that will be later be further regulated into energy suitable for use. [28] The main function of a power supply is to convert electrical energy, which tends to be in the form of high voltage alternating current (AC), into lower voltage direct current that is safer for further testing. [29] [28]

In the case of this circuit, the power supply is essential in order to provide the DC current that will then be further adjusted by the regulators to propel the microcontroller and other components of the design. If the PSU wasn't in the design, then there would be no safe launchpad from which the relays, alarms and even LEDs could receive a suitable level of voltage for their respective compatibilities. In a sense, the power supply functions as the first point of energy into the system, from which the regulator acts as the controller and adjustor of said energy. The blow listed research studies a small variety of power supplies in the market to gain an adequate perspective of their advantages and disadvantages, of which a suitable selection can be made based on the scope of the project. [30]

3.19.2 - Battery Powered Options

Battery power is a fundamentally crucial consideration for the design of the project. Batteries provide a stable and powerful source of energy, allowing for the operation of the system even if no AC power is available. Furthermore, the choice of exact battery type is critical as well, as the correlation between type of battery and energy density, safety and longevity is high. [31] Battery systems also relate to power management, as they function as the initial boost of energy that will be further rectified and adjusted by other components in the circuit.

For this specific discharge circuit, battery power would not be the only component required, as other supporting elements would be needed. Firstly, a charging circuit would be useful, with the first stage being an AC to DC adapter converting initial voltage into a usable DC level. Next, a charging system would be used in order to provide a consistent level of current during charging up to when the battery reaches its maximum nominal voltage, in which the system would then provide a constant level of that voltage. [31] In addition, throughout the process, protections against excessive voltage and potential thermal monitoring would be necessary to ensure added safety within the design. Once a stabilized output from the battery is reached, the voltage from that stage would be sent to the regulator stage, allowing for the microcontroller and other low voltage components to receive adequate and consistent levels of voltage. [31]

Lithium-Ion batteries

Lithium-Ion batteries are among the most widely used batteries for energy storage. For the cathode side, either lithium iron phosphate or lithium cobalt oxide is used. While the two share similar levels of rechargeability and cycle life, they differ slightly in terms of overall nominal voltage. Lithium cobalt oxide typically have a nominal voltage range of 3.6-3.8 volts per cell, while lithium iron phosphate has a slightly smaller range of 3.2-3.4 volts per cell. [32] [33] These voltage levels make both these sub types of batteries suitable options for our circuit, as steady energy delivery and no self-discharging are crucial features required in order to ensure efficiency. [32]

Within the two options, lithium cobalt has a slightly higher energy density, around 150-250 Wh/kg compared to 90-160 Wm/kg. [32] [33] Lithium cobalt also tends to perform better in more chilly conditions compared to lithium iron phosphate, which may be relevant depending on the heat dissipation in other parts of the circuit. However, lithium cobalt also comes with serious ramifications. Cobalt is comfortably less abundant than phosphate, which raises the cost of using lithium cobalt oxide as a battery type. [33] Working better in colder conditions means that the thermal resistance of the material is comparatively weaker. In contrast, lithium iron phosphate, while not as powerful, is cheaper, safer, more abundant and has a significantly longer shelf and cycle life than cobalt. [32] [33] Based on this information, it follows that lithium iron phosphate would be the overall better option. The lower cost, extended battery life and the stability compared to cobalt outweigh the slightly better energy density and efficiency that cobalt provides. [32] [33]

Nickel Metal Hydroxide

Nickel Metal Hydroxide batteries were first considered as a suitable substitute for comparatively older nickel cadmium due to their higher nominal voltage and lessened impact on the environment. The nominal voltage range for this battery material tends to range from 1.1-1.4 volts, and like lithium, these batteries are rechargeable, making them beneficial for longer use, and are relatively cheaper, as compared to lithium. [34]

However, nickel metal hydroxide batteries have the lowest nominal voltage of all the options considered, rendering it suitable for medium voltage applications at best. While nickel metal batteries are rechargeable, the potential for self-discharge is higher, in other words, the ability to lose charge if left unused for a significant time period. [34] In addition, heat can also build up significantly during the charging process, and nickel batteries tend to weigh a lot more than lithium or even alkaline batteries. Both limitations could lead to additional measures being required if nickel batteries were to be a suitable option within the circuit. Overall, nickel metal hydroxide batteries would offer a safer and cheaper alternative to other options for more moderate voltage levels and longevity. [34]

Alkaline

Alkaline batteries remain one of the popular options for consumers looking for a cheap and moderately effective battery type for power. A zinc anode along with a potassium hydroxide electrolyte is used. [35] The nominal voltage for an alkaline cell ranges from 1.4-1.7 volts, higher than nickel metal hydroxide. [36] Moreover, the abundance of alkaline ensures that the cost will always be significantly lower than it would be for the other types of batteries on the market. The shelf life of alkaline is excellent and able to last around 5 to 10 years without need of a replacement. [36] Alkaline batteries are ideal for low power applications that provide a simple and stable tool of energy at a very minuscule cost.

Regardless of these benefits, alkaline batteries do carry a variety of disadvantages. It is very difficult to recharge an alkaline battery, meaning that it is single use and very inefficient. [35] Furthermore, when faced with heavier loads, the performance of the battery faces a sharp decline, not ideal for a high voltage scale like our design will be expected to bear. Hence, while alkaline batteries are inexpensive and suitable for low voltage power applications, implementing this type of battery within the scope of a high voltage and consistent supply would be a challenge

Lead Acid

Lead Acid Batteries are one of the oldest rechargeable battery options available. Lead dioxide is used at the positive electrode side, while sulfuric acid lies at the electrolyte side. [37] The nominal voltage for lead acid ranges from 1.9-2.2 volts, so it is higher than alkaline and nickel metal hydroxide. [38] The abundance of lead is common, rendering the production cost for the battery

type fairly minimal. In addition, the self-discharge rate is a lot slower compared to other compositions, allowing charge to be held for longer periods without usage.
The main drawback to using lead acid as a battery type comes with the environmental impact, due to the toxic lead content and sulfuric acid use that has long terms ramifications for the environment. Furthermore, the energy density for lead acid is the lowest out of all other battery types considered, along with a relatively short cycle and shelf life. These drawbacks would make it complicated to implement the use of this battery type within the scope of the circuit, as aspects need to be running at maximum efficiency.

3.19.3 - AC DC Power options

It should be noted that both battery power and AC DC power would require an AC-DC adapter in the design of the circuit. The difference in this case would be that the adapter would take wall power in and power the circuit directly. This is slightly in contrast to battery power which would take the power from the adapter and power the circuit. Both of these methods come with distinct advantages and disadvantages that will be further illustrated.

Direct wall mount
Wall mounted AC DC power adapters, or external power supplies, are a very common and cost effective to provide power to low and medium voltage devices or circuits. These adapters take in AC power from the outlet, rectify and smooth the resulting wave signal into a recognizable but still higher voltage DC input. A switching transistor then takes that resulting input and cuts the DC input, which is further decreased by a transformer into a safer range of voltage. The waveform is then rectified and filtered further in order to obtain a final low voltage and safe DC output for regulated circuits. [39] In addition, protection measures against initial inrush current are abundant, along with shutdown measures in the case of a short or overcurrent. [39]

The plus side of AC to DC external adapter connected directly lie in the high availability, as well as the built in safety measures, which in turn makes the cost of the product extremely affordable in the scope of the project. [40] Also, a wide range of power levels, from 1-100 watts, are available, scaled to a decent variety of output voltages. Because the adapters are globally standardized in terms of production, it is also very simple to replace if required. However, the limitations of the product include, mainly, slightly lower efficiency when compared with battery power. Batteries provide scalable energy storage to provide further input and can keep running even if wall power goes out, while direct connection using an adapter will be dependent on a stable, nonfluctuating wall power source.

Internal PSU
An internal PSU can convert AC power directly into regulated DC voltage within the PSU. Like a wall mounted adapter, AC input is filtered and rectified, then cut and stepped down by a transistor and transformer respectively. [41] The waveform is then further measured and stabilized by using feedback loops to compare to a set reference voltage. [41] This design, due to being within the PSU, comes with increased measures and isolation barriers, which is a major advantage. It should be noted that the main difference between these two devices lies in the fact that the mount to adapter to regulator design converts AC to DC outside the main circuit, while an internal open frame PSU converts AC to DC within the main capacitor discharge circuit.

The main advantage of using an Internal PSU comes with its compactness and versatility, which allows for multiple input and output rails. [41] In addition, the power production for the internal PSU has more potential than the wall mount adapter , and the internal PSU is better in terms of cooling due to the fact that heat can spread across a larger space and dissipate. However, this all comes with added complexity of integration within the circuit, which can lead to increased costs. The PSU would need to be built from the ground up, and safety certifications would have to be obtained for industry use. [42] There would also need to be even more protection and shielding required for the function of the Internal PSU due to its integration within the design.

Internal PSU and wall mount adapter

As explained earlier, the primary difference between the two options lies in the location, as the wall mount adapter's conversion and function lies outside the device, while the internal PSU would need to be integrated within the device. Conversely, this would result in some fundamental shifts in design being required for the prototype. All in all, the plug to adapter to regulator connection would be considered a safer and simple option while the internal PSU would be the more varied, but more integrable option. A comparison between the two devices is shown below

Table 15: Wall Mount vs Internal PSU

AC to DC Power Type:	Wall mount (external adapter)	Internal PSU (open frame)
Safety	Fully enclosed and insulated with no exposure to AC power.	Parts are exposed and further protection measures must be taken.
Regulatory burden	Adapter already certified	Entire device must obtain various certifications.
Heat management	Heat stays internal and outside the device	Heat is inside the enclosure but in open air so will dissipate easier.
Replaceability	Very easily replaceable	Would require servicing through others not the user to function properly again, extremely time consuming
Flexibility	Only one set fixed DC voltage	Can provide multiple options/rails(5, 12, 24 V)
Cost	Lower cost, and no money for enclosure or protection measures	Higher cost due to extra money for additional protection design

Based on the research and comparison between the two products, the wall mount to adapter design would be a better option compared to the open frame internal PSU based on the benefits in cost, safety and overall management and maintenance of the two devices. However, this does not mean the wall mount would be the best option entirely, for that, the effectiveness of using an AC to DC adapter needs to be compared to the effectiveness of using Battery power.

Wall mount to adapter and direct battery power

Ultimately, in terms of providing the initial power to the capacitor discharge circuit, both battery power(with an AC to DC adapter) and AC to DC power(on its own) are viable and very similar, at the core, options that could feasibly be used. The best options from both sides, the lithium ion phosphate battery type and the AC to Dc wall mount direct connection need to be compared through a variety of metrics, but it is also important to consider the implications of using batteries through the necessity of a BMS(Battery Management System), the nucleus behind ensuring the use of batteries is safe, efficient and for a high of a time period as possible. In case of excess voltage, current or temperature, a BMS ensures that battery cells can return to equilibrium at a safe output and are balanced in terms of performance. [43] However, this would also allow for additional expenses that would need to be specified for in the Bill of Materials.

Table 16: Battery power vs AC to DC adapter

Feature	**Lithium Iron phosphate batteries**	**AC to DC wall mount charger**
Power Source	Stored energy from rechargeable cells which would require	All power directly from AC mains (wide voltage range)
Safety	Requires BMS to prevent overcharging and overheating	Protection is integrated within the brick and externally outside device.
Charging	A charging circuit and a BMS would be otherwise required to maintain the circuit.	No real maintenance or charging circuit required.
Lifetime	Well beyond 5 years [44]	Can run for a very long time (almost unlimited)
Cost	Cost would be higher as BMS and batteries would be needed	A one-time cost would be relatively cheap due to the abundance of DC adapters on the market.
Output Stability	Voltage decreases as the battery discharges which renders the use of a BMS.	Consistent DC output with regulation and a small voltage drop
Environmental Impact	Lithium would need to be mined, which could cause damage to non-degradable areas.	No replacement issues for the most part.
Integration	Direct AC input into charging requires more shielding and more internal design work within circuits.	No internal integration required beyond basic connections.
Power Capacity	Wide range of wattage with no breakage for lack of runtime required.	Time required for recharge with efficiency limited by nominal voltage of battery.

Based on the research and comparison completed, the wall mount to adapter directly seems like the ideal option, due to the flexibility and simplicity of the design with a relative low cost to efficiency ratio that will allow for more flexibility in other parts of the product if needed. Using battery power would have been a viable option, but the combination of increased protection measures, along with the increasingly complex way of implementing the battery itself with the battery management system included, dissuaded the team from pursuing the option.

It should be noted that both battery power and AC DC power would require an AC-DC adapter in the design of the circuit. The difference in this case would be that the adapter would take wall power in and power the circuit directly. This is slightly in contrast to battery power which would take the power from the adapter and power the circuit. Both of these methods come with distinct advantages and disadvantages that will be further illustrated.

3.20 - External Power Component Selection

After researching various different external power technologies and concluding that the most well suited design for our project would be a wall mount plug connected to an AC-DC adapter, which would then connect to a regulators, the following options were listed as the most suitable for the current scope. These options were more general and would depend on certain specifications since it should be compatible with other parts of the circuit, including the DC voltage rating, current limitations and other protection measures.

3.20.1 - GST160A24-R7B

The GST160A is an AC-DC adapter that is designed to take in AC input and convert to a suitable low DC output voltage range to be used for further applications. Within the GST160 series, a variety of different AC-DC adapters exist, depending on the wattage and voltage required, but the interest for our project would concern the 24 volts version, as that is the voltage of external power required to further be converted into the regulator. With an input voltage range that can be as low as 85 VAC and range as high to 264 VAC, a wide interval of AC input can be supported and converted. [45] In addition, the high amount of power consumption potential, at 160 watts, is ideal in case our device ends up consuming a lot of power, which is not the intention, but it is good to have spare wattage available if so. [45] The load current the device can take ranges from 0 to 6.67 amps, which is also ideal considering the regulator load current in all regulator research was at most 5 amps. [45] The efficiency is also high, at 93%, which makes the device ideal for high power applications like the prototype. [45] Along with built in protection measures against short current and overheating and the production of the adapter by Mean Well, a trusted producer of power supplies with a secure reputation in the electronics industry, the GST160A24-R7B is a very tempting option to consider the provide the external power required of our project.

However, there are still some disadvantages of the device. Primarily, a possibly issue can come from the use of a 4 pin DIN, not a standard barrel connector, which would make the further design more of a hassle in terms of connections to the regulator. [45] However, the packaging appears to emphasize that a male barrel connector is available and would just require a further adapter. The high support wattage of 160 watts can also prove to be a disadvantage as our design is currently only consuming around 30 watts of power, and with such a light load, efficiency might drop as well, as efficiency percentages are based around using the full wattage and that would not be the case if the device were to be used for this project. Similarly, building on the same concept, the cost and current capabilities also come into question, as a higher current load would require thicker wiring accordingly. The cost is within range, but might be expensive comparing to the required wattage, around 30-40 watts. In addition, an AC input cord would have to be purchased separately to the adapter. [45] Overall, this adapter is a good option, but a smaller adapter could be more adept and suited to this specific scope of our design requirements.

3.20.2 - QFWB-65 series

The Qualtek 65 watt wide mount AC to DC adapter is a similarly designed device to take in AC input and convert to DC output that can be used for further application within our design. Similarly, as with the GST160 series, there are a wide variety of adapters available for use, the primary interest for our project would be the 24 volt version, that can support up to 2.70 amps of load current, along with 100-240 VAC, which is suitable for our project scope. [46] The load current being less may prove to be a disadvantage depending on how much current the rest of the circuit may require. Conversely, the power consumption of the series of adapters, as told by the 65 in the description, is 65 watts, which is more suitable to the scope of the project compared to 160 watts. [46] Consuming a higher percentage of the power available, even if still not close to the maximum power available, would lead to overall higher efficiency. The efficiency in the datasheet for the adapter is not listed, but under efficiency, "Energy Efficiency Level VI " is listed. [46] This seems to be an industry certified standard that confirms a certain level of proficient effectiveness for the device, but not having an exact value means selection the option comes with an element of risk. The no load power consumption is less than 0.1 watts, [46] meaning that when the device is not in use, very little energy is being wasted, maximizing efficiency. However, there are some disadvantages to the product as well, the decreased efficiency under higher temperature conditions, which will happen given the integration and natural design of our system. Given that the design will likely require the use of multiple regulators rather than one, the system might require closer to 70-90 watts as each regulator, with its own level of efficiency, requires slightly more power to function. Conversely, a major advantage for this design comes with the male barrel connector, which will make connections to the regulator and PCB significantly easier with application, upon the purchase of a female connector. The AC input cord also comes with the design, which is not the case for the GST series, sparing a further purchase that may not be compatible. Overall, this makes the Qualtek a solid option that should be seriously considered for the final scope of the design.

3.20.3 - GST60A24-P1J

Another adapter from the Mean Well family, the fundamental difference between the two adapters lies in the difference in wattage. While GST160 contains 160 watts, GST60 merely has 60 watts. [47] However, this could prove to be an advantage provided the system only consumes 30-50 watts of power, which it is set to do. Higher potential efficiency could result. Like with all the other power adapters mentioned, the 24 volt version is what would be in the best interests for our project. The efficiency is very high, at 90.5%, and with a AC voltage input range from 90-264 VAC, taking in energy from the wall mount should not be an issue. [47] Another major advantage of this specific device lies in its use of a male barrel connector and a female equivalent being available for easy access. This would make connection to the big PCB board very simple given the soldering it would require and would result in a moderately simple design that would be ideal for further lab application. The cost, unlike the 160 watt Mean Well, is relatively affordable and decently cheap. A possible disadvantage to using this component specifically could be the relatively small current range, at 2.5 amps maximum. [47] Since the current range of the adapter needs to be somewhat similar in terms of range to the current range of the regulator, the relatively low current, which makes sense since the power range is also relatively moderate, could make further alignment with the switching regulator a challenge.

3.20.4 - DiodeDrive Series

The DiodeDrive series of external power adapters offers both 12 VDC and 24 VDC options, which is in the scope of our design. In addition, added flexibility comes with two power options, for 60 watts and 120 watts. [48] It should be noted that one would still have to choose from one of the two options, for the purchase of a single adapter, but the flexibility and comfortability in getting to choose relatively. Accordingly, the output current is also suitable, with 2.5 amps for the 60 watt version and 5 amps for the 120-watt version. [48] A male barrel connector, along with an AC input cord is also part of the package. [48] At around 20 dollars, the price is comparable and reasonable when looking at typical market values both on Amazon and DigiKey. A potential notable advantage could come from the extended AC input cord that offers up to 48 inches of wire length. [48] The design may require the adapter to be reasonable far from the main circuit and in this case, the added distance could prove essential. Overall, the DiodeDrive series of external power adapters offer a reasonable option and price to be considered when looking at out final external power option.

3.20.5 - Altiove power adapter

The Altiove power adapter is a common external power source often seen on Amazon for use. Offering 144 watts of power, this provides a major advantage as ultimately although the estimated power consumption of the device is set for around 40-60 watts, one can never be sure of the exact wattage that will actually be needed given the potential difficulties that come with actually constructing the circuit. [49] With 6 amps of output current, current to the regulator should not be an issue, and with a male barrel connector and AC input cord stretching to 48 inches, the efficiency of the adapter renders it an adequate option. [49] The cost is slightly higher at around 24 dollars compared to others so far, [49] and another potential concerning factor regards the description listed on Amazon that declares its use more ideal for as a converter for LED strip lights. However, the listing of the product on Altiove contains no such description, and for the purpose of the project, the function is as a normal power adapter that can be used for the scope of the project.

3.20.6 - External Power Adapter Comparison and Selection

Table 17: External Power Adapter Table

Adapter	GST160A	QFWB65	GST60A	DiodeDrive(60)	DiodeDrive(120)	Altiove
Wattage	160 W	65 W	60 W	60 W	120 W	144 W
Current capability	0-6.67A	0-2.7A	0-2.5A	0-2.5A	0-5A	0-6A
Voltage capability	85-264 VAC	100-240 VAC	90-264 VAC	100-240 VAC	100-240 VAC	100-240 VAC
Efficiency	93%	Level XI	90.5%	89.5%	89.5%	Not clearely specfied
Price	$50.40	$19.59	$18.60	$19.99	$49.99	$29.99

After constructing the adapter comparison table, as the actual function of the adapter within the scope of the project was simple, it was left to the team to decide what adapter would be best suited for the design. The power table, even if not accounting for the regulators, is still less than 30 watts, meaning that 60 watts or more should be more than enough for the discharge system. The efficiencies and current limits are well above what is required for the system, so the decision was made based on whether they came with a barrel connector or not and not wanting to waste wattage. After careful consideration we decided that the DiodeDrive 120 watts would be the external power adapter for our prototype.

3.21 - Voltage Regulator Technology

Voltage regulators are a fundamentally critical element of the project. Regulators are the nucleus of external power to the rest of the circuit, providing az stable and consistent output voltage during both ideal and non-ideal conditions and input loads. [50] Regulators are able to accomplish this through the use of a feedback loop that compares the current output to a set reference output. [51] When a discrepancy between the two values is noted, the system adjusts by either increasing or decreasing the duty cycle to ensure a steady output supply. Regulators can be used to either step down, decreasing a direct current (DC) voltage from its initial input, or to step up, increasing DC voltage from its initial output, in accordance to the specifications of the device. [50]

For this discharge current in particular, a regulator would be necessary in order to ensure the microcontroller runs as effectively as possible. [52] The external power supply cannot be used directly, since any deviations in power would lead to errors in when alarms would go off or even lead to a failure in the system. In addition, regulators enable relays to receive power without being exposed to an extreme amount of direct voltage, as the voltage would be scaled down to a usable and safe level before coming in contact with relays and other low voltage parts of the circuit. [52] Conversely, given our design is meant to be effective for high level of voltage, regulators act as a shield between the potentially hazardous high voltage side and the safer control side with small voltage levels. [53] To enable efficient performance, a variety of regulator types were researched to identify what would best be suited to the discharge circuit.

3.21.1 - Linear Regulators

Linear regulators are one of the most established and experienced methods for providing steady DC voltage to electrical systems. [50] The essence of linear regulators is based on constant monitoring of the output voltage and a feedback loop to compare set voltage to a reference. [54] An error amplifier, often in tandem located with an operational amplifier, connects to a transistor in series with the load. This transistor acts as a extra resistor in terms of passing voltage through the circuit. If the output voltage is lower than the reference voltage, the transistor will enable more current to pass through and increase the output voltage as a corresponding result. If the output voltage is too high to allow for effective efficiency, the transistor will allow for less current to pass through, which will in turn decrease the output voltage. [50] [55] However, this extra energy that results due to the voltage difference between input and output dissipates as heat, which noticeably decreases the effectiveness of this product, despite its simplicity. [55]

As a result, the efficiency of this device is highly dependent on the numerical difference between the output and input voltage at any given time. [55] The smaller the difference between the output and input voltages, the more effective the regulator is at that given point. In contrast, a larger difference between the two voltages results in a big drop and a big loss in power, and therefore heat. Hence, linear regulators tend to be preferred when there is a small to moderate difference in adjustments between voltages. [50] An immense advantage of a small voltage difference within the use of a linear regulator would be the lack of noise compared to switching regulators, both at the input and output side. [56] This would even result in a decreased power loss, since the Power lost is calculated by $P_{loss} = (V_{in} - V_{out}) \times I_{load}$ [55]. Therefore, regulators with high voltage drops will and need to be designed with adequate protection for heat dissipation in mind, which could affect other elements of the discharge circuit. [56]

Within linear regulators, another subtype to consider would be the shunt regulator. The shunt regulator operates in a different manner compared to other regulators, with a Zener diode often placed in parallel with the load. [54] A resistor is then placed in series with the initial input voltage, and depending on the load current, the Zener diode either draws in current for the output voltage or shunts the current through the regulator to be released as heat. [54] For low current uses, the shunt regulator can be extremely useful, but as current increases, as the flow is always going to be there regardless of necessity, the Zener diode will just dissipate more heat accordingly, which severely damages the effectiveness of the circuit, and series regulators are used in more complex and varied designs. [50] [54] Overall, due to the effectiveness to cost ratio, and the simplicity of design, linear regulators should provide a suitable option for further consideration within the tool.

3.21.2 - Buck Converters

Buck converters are an extremely popular DC-DC converter, in which an initial DC voltage is otherwise converted into a lower DC output voltage. [57] In layman terms, the buck converter is called a step-down converter as voltage is slowly decreased downwards. The major components of a buck converter include a switch, an inductor, a diode, and a capacitor to ensure effective energy storage and transfer. [57] [58] When the switch turns on in the circuit, current comes into the inductor, which proceeds to store energy within its magnetic field, and the inductive current continues to supply the load current. This results in a ripple effect due to the peak and trough current reaction of the inductor. This extra current is taken in by the capacitor, which uses the current to generate inner charge, which provides an increase in the output voltage. The capacitor can then even and steady out the final output into a steady increased voltage. Similarly, once the switch turns off, the reverse process occurs in which less current is seen by the capacitor, allowing for the capacitor to discharge and release energy, which results in a lower output voltage that is further evened out into a smaller stable voltage. The inner workings that enable the switch to be aware of turning on and off, and the resulting adjustments that the components make, is due to the controller and the duty cycle. The output voltage is equal to D, or the duty cycle, which is equivalent to the time period the switch is on for, times the input voltage. The duty cycle is always a fraction of the time period the switch is on, hence why the output voltage will always be lower than the input voltage: $V_{out} = D \times V_{in}$ [59]

A feedback line to the controller compares the current output voltage to a set reference voltage. Accordingly, if the output voltage is too high, the duty cycle will decrease in order to turn the switch on for less time to decrease the output voltage, and if too low, the duty cycle will otherwise increase in order to turn the switch on for a certain period of time to increase the output voltage. [58] This period switching process enables buck converters to regulate a consistent output voltage throughout various lows and highs and different types of input conditions. [57] [58]

Buck converters offer a variety of significant advantages to linear regulators. The effectiveness is significantly higher as the power loss is not released outwards as heat, but instead thrown back into the circuit in accordance to the drop or raise in duty cycle. Efficiencies range from around 85%-90%, [60] and in a system that is designed to minimize heat abundance within the circuit, this is a very good level. The response level to potential load differences is very fast compared to linear regulators, along with potential built-in measures and protections within components on the current market. As opposed to linear regulators that only work for a certain rigid level of input voltage due to the required difference in input and output voltage being minimal, buck converters work for a wide variety of input voltages. However, potential drawbacks of buck converters include the increased cost compared to linear regulators due to a broader scope in design. The output ripple that results require careful filtering that would be an additional hazard in the design. The complexity as a whole, as opposed to other options, pose a problem to the consideration of this technology considering the limited time available for completion of the device, yet overall buck converters have to be considered as a serious option due to the increased efficiency and flexibility that is provided for powering both low level voltages, along with high level voltages for the long term scope of the project.

3.21.3 - Boost Converters

Boost converters are another type of switching regulator, in which an initial DC voltage is converted into a higher DC output voltage, which would otherwise be known as a step up converter, as the voltage is increasing. [61] The parts included in the device are the same as the buck converter, yet the inductor is placed before the switch and diode as compared to after in the buck converter. When the switch is on, the inductor takes in current and stores energy within its own magnetic field. However, the diode being reverse biased proceeds to block the current flow, resulting in the capacitor discharging in order to maintain the output voltage stability, resulting in a lower output voltage compared to the initial voltage. [62] Similarly, when the switch is off, the inductor releases energy and the input voltage is added to the inductor's voltage. The diode is then forward biased, which allows for a higher level of current to be received by the capacitor and load. The capacitor then charges up and this results in an increased output voltage compared to the input. It should be noted that in both cases, the capacitor also smooths out the rough current taken in by the inductor. [61]

About the duty cycle, the basic logic is similar between both types of converters. A feedback loop is used to compare the current voltage to a reference voltage. If the output voltage is too high or too low, the duty cycle, or fraction of time for the switch being on, which will never exceed 1, will increase or decrease accordingly. The difference lies in the equation for the output voltage for the converters. For the boost converter, the voltage output can be calculated through this equation.
$V_{out} = \frac{V_{in}}{1-D}$ where V_{out} is the output voltage, V_{in} is the input voltage, and D is the fraction input for the duty cycle. [61] [63]

As the value of D increases, the difference between the input and output voltage gets smaller. As a result, the output voltage increases and increases beyond the value of the input voltage, but with the cost of increased ripple noise and component capabilities, so to an extent. [61] Looking at both converters, the correlation between output voltage behavior and duty cycle changes is the same, with the key difference being that the input voltage for a buck converter will always be greater than the output, and the input voltage for a boost converter will always be less than the output.
The advantages of boost converters over other types of regulators are various, mainly regarding increased efficiency. Like buck converters, boost converters have an ability to operate over a wide variety of input voltages. This makes boost converters an ideal option for industries where a tool

with adaptability is essential, such as renewable technology. [62] However, boost converters are rigid to a degree, being only step down, and the increased ripple effect is still present in the output, which would require further filtering in order to maintain performance levels. [63]

Building on the idea of step up or step converters, there is a device that can operate on either basis if needs be, called a buck-boost converter. The functional process would be the same as for a buck or boost converter, but the added adaptability provides a fail-safe in case things go wrong. At a low duty cycle value, the device works as a buck regulator would, and at a high duty cycle value, the device works as a boost converter. Flexibility can be very valuable when the input voltage frequently falls above and below the preferred output voltage. However, this type of converter would be very costly and very complex to design. [63]

3.21.4 - Flyback Converter

Flyback converters are an older more isolated class of DC-DC regulators that can either step up or step down depending on what is required within the circuit. [64]At the essence, flyback converters work like buck and boost converters, yet a transformer is used in order to generate the momentum for current and energy. [64] When the switch is on, current flows through the primary side of the transformer, which then stores that energy. However, the diode is reverse biased which prevents current from reaching the load. Similarly, the capacitor discharges as a result, and the output voltage drops and maintains stability. When the switch is off, the capacitor then charges up, which results in a rise in output voltage and the smoothing out of the rough output current from the inductor. [65]

For designs that require electrical isolation, flyback converters are ideal as the protection measures are increased and the transformer based design allows for isolation without a specific isolation stage of production. [66] In addition, flyback converters are also designed to be adjustable for a wide variety of input voltages and the input noise ripple is extremely minimal compared to boost or buck converters. [66] [65] These advantages combine to make flyback converters an ideal option for smaller scale voltage designs, as the cost is also affordable and on the level of linear regulators. [65]

Despite these benefits, flyback converters also come up with some serious drawbacks as well. While the input noise ripple is manageable, the output noise ripple is still significant, requiring further filtering. [65] The efficiency of the device is also overall lower than linear and other switching regulators, and this is further emphasized as the power scope goes up. This is due to increased strain on the transformer and transistor as usage increases. [64] [65] [66] While the separation and isolation the flyback converter provides between the high voltage and low voltage sides of the application is a major benefit, the lack of efficiency must be noted when comparing to similar options.

3.21.5 - Regulator Comparison and Selection

Table 18: Regulator type selection table

Feature	**Linear regulator**	**Buck Converter**	**Boost Converter**	**Flyback Converter**

Voltage type	Steps down voltage and dissipates any extra energy as heat	Step down voltage by using an inductor to obtain control.	Step up voltage by using an inductor and switches control.	Step ups and steps down by switching transformers and isolating other components.
Effciency	Low (30-60) and drops lower under significant voltage strain. [67] [68]	High (80-90) for majority of loads [69]	High (80-90) for majority of loads. [69]	Moderate (70-80) but can drop depending on load and transformer stability. [70]
Cost	Low cost initially but decreased efficiency	Moderate but widely available and accessible designs reduce overall cost. [69]	Moderate but similar to buck converters, widely available and accessible designs reduce the overall cost. [69]	High due to requirement of transformers and other additional components.
Complexity	Very simple with few components	Moderate, requirement of inductor, switch and diode.	Moderate requirement of inductor, switch and diode.	High due to transformers and extra isolation being required
Power	Very limited with high power applications with extra heat dissipated.	Able to deal with high power loads with relative ease.	Able to deal with high power loads with relative simplicity	Average ability to deal with high power due to transformer limitations.

Based on the research and the comparison shown above, it is clear that buck or boost converters are the most ideal option to pursue. Unlike linear regulators, which dissipate a large percentage of power to heat, buck and boost regulators have a high level of efficiency while staying relatively compact and maintaining low thermal waste. However, the design requires voltage to be decreased to be suitable to work with other components, which renders the use of a boost converter ineffective, and the ability to step up and step down, which flyback converters have, is not very useful for this specific product. In addition, flyback converters can create further design issues to account for the use of a transformer, and overall, buck converters are clearly the best option to pursue further.

3.22 - Regulator Component Selection

After establishing that a buck converter would be most suitable for the scope of the project design, it was decided to research and ultimately select established regulators in the market, suitable for step down voltages for various standardized input and output volt values. After intense further research, it was decided that these below options would be most suitable for discussion and to choose a final option.

It should be noted that while purchasing the regulator is one aspect, other aspects of the circuit will need to be bought as well. In the case of LM 2576 and 2596 and 2575 an input and output capacitor, as well as a diode and an inductor, are necessary, and this cost will also further the overall budget for the project, along with the regulator purchase. The values of these components are in the micro henry or micro farad range and should not be too much of an issue in terms of integration. However, in the case of LM 2678, due to its unique design with the DMOS output switch, more capacitors in parallel, both on the input and the output side, are required, which makes the adaptability of that design something to be considered before choosing that option. In contrast, for the TPS regulators, more parts are required, and this should be a factor when building the PCB for the added difficult soldering those parts and additional circuit requirements may also factor in.

3.22.1 - LM 2576

The LM 2576 is a step-down buck converter that provides, at a maximum, 3 amps of load current with a variety of suitable output voltages that are compatible with the hardware and software within our system. [71] These output voltages range from 3.3 volts to 15 volts, along with an option for adjustable unspecified output voltage if needs be. [71] The input voltage ranges from 4 to around 40 volts as well, allowing for adjustable input that leads to further ease in adaptation. [71] In addition, the device also contains current limits, ranging from 4.2 to 6.9 amps in current, along with thermal shutdown protection, as well as external shutdown protection with 50 micro amps of standby current in case. [71] Efficiency for the device rises as the output voltage rises, ranging from 75% efficiency for 3.3 volts to 88% efficiency for 15 volts. [71] However, in comparison to other regulators on the market, the switching frequency is relatively small, 52 kilohertz, which requires larger sized components and renders the size of the PCB board to be larger. [71] A great advantage to the LM 2576 is in its cost, as major electronic sellers currently have the price at 3- 4 dollars. The cheap cost and wide availability, along with a simple design and implementation, means the LM 2576 is a great option to consider for use within this project.

3.22.2 - LM 2596

The LM 2596, like the 2576, is a step down buck converter that can provide 3 amps of load current with the same provided output voltages that can potentially be adaptable and suited to our power design. [72] The output voltages and input voltages are relatively similar, if not the same as LM 2576, but the switching frequency is notably higher, at around 152 kilohertz, which leads to ultimately a higher comparative efficiency at each voltage point, ranging from 73% at 3 volts, to 90% at 15 volts. [72] The same thermal protection and isolation measures located in LM 2576 are also in place, with standby current also in place, and slightly higher than LM 2576, at 80 micro amps. [72] A higher switching frequency leads to smaller components and easier placement on the PCB board, which would make further design a lot simpler. In addition, the LM 2596 is relatively costly, costing around 3-4 dollars, and the more complex design integration, in spite of the smaller circuitry parts, would make using this regulator a slight challenge, but the improved efficiency, along with the increased versatility to support other subsystems of the PCB board, still make the LM 2596 a viable option to be considered. [72]

3.22.3 - LM 2678

The LM 2678 is comparatively unique, but ultimately still a step down buck regulator that contains a DMOS output switch, a difference to the other buck regulators mentioned. The current load can provide up to 5 amps and efficiency is overall higher for each output voltage value, ranging from 82% for 3.3 volts to 92% for 12 volts. [73] The switching frequency is a lot higher than both LM 2576 or LM 2596, at 260 kilohertz, which contributes to the overall increased efficiency. [73] However, it also leads to extreme output ripple noise, which could lead to complications later on. The thermal shutdown and current limit protections are in order, but the input voltage is slightly more limited, with 8 to 40 volts being the overall range. [73] The LM 2678 is also older compared to the other regulators, which may lead to less efficiency in terms of integration with other parts of the circuit, and also would be a little more costly in comparison to the other options available. [73]

3.22.4 - LM 2575

LM 2575 is a switching regulator designed to provide a simple and efficient solution for low to moderate power applications. With a maximum load current of 1 amp, and a default switching frequency of 52 kilohertz, the efficiency would be slightly less than the 85%-90% max efficiency seen in other regulators, yet in terms of simple power handling and extremely cheap availability, LM 2575 would seem to be a very good option. [74] However, despite the standard thermal protections and isolation measures, along with the standby current, the load current max is far too small to be used in most modern applications, and the switching frequency, being the same as LM 2575, is also relatively miniscule, and would represent a real challenge in terms of board size and placement if used. Most newer models can offer increased frequency, load current and provide similar levels of stability, if not more, when connected to other parts of a circuit design, or more specifically, to the microcontroller. [74]

3.22.5 - TPS 5430

The TPS brand of regulators are also funded by Texas Instruments, with the TPS standing for "TI Power Supply "and contain a couple of key differences in comparison to the LM family. The current specs are very similar, with a maximum of 3 amps being offered for the current input. The TPS 5430 offers a wide voltage range from 5.5 volts to 36 volts, which is roughly similar to the LM family, yet due to circuit design, one can choose the output voltage they want to emit. [75] This is in contrast to the LM regulators which offers 3.3-, 5- and 12-volt output step down voltages, with a small option for an adjustable voltage. The circuit design of this specific TPS step down regulator contains two resistors through a voltage divider, and a way to manipulate an output voltage through the following equation.

$V_{out} = V_{ref} * (1+R1/R2)$ in which R1 is the upper resistor and R2 is the lower resistor. The voltage reference, Vref, is merely the reference voltage that is used for control of feedback. [75]

Based on this equation, the resistor values can be selected in a manner to easily obtain most desired voltages. In addition, the TPS 5430 has a significantly higher switching frequency, around 500 kilohertz, which in effect contributes to its superior efficiency. [75] While there is no set efficiency, as it tends to lower depending on the variance between the difference between input voltage and final set voltage after step down. For example, going from 24 volts to 3.3 volts may result in a lower efficiency than going from 24 volts to 16 volts. Overall, the efficiency was still higher than the LMs on average, given the step down voltage ratios. The TPS also contains all the standard thermal and current protections located in the LM regulators as well to offer safety in case of potential shutdown. However, the main disadvantage of using the TPS regulator comes with actually building the regulator. Ultimately, building the PCB of the regulator is the main focus, and the more parts and phases of the circuit required, the harder it is to ensure a safe and functional PCB. The TPS design contains an extra couple of capacitors and resistors that may be no issue to breadboard, but will provide significant strain when actually soldering and building the PCB, and it would be an essential question to consider the tradeoff ratio between the slightly higher efficiency that the TPS 5430 offers versus the long term issues that may come with designing and building the regulator. [75]

3.22.6 - Regulator Component Comparison and Selection

Table 19: Buck Regulators Comparison Table

Category	LM 2576	LM 2575	LM 2596	LM 2678	TPS 5430
Maximum Output Current	3 A	1 A	3 A	5 A	3-4 A
Input voltage range	4-40 V	4.75-40 V	4.5-40V	8-40V	5.5-36V
Output voltage range	1.25-37V [71]	1.25-37V [74]	1.25-37V [72]	1.25-37V [73]	1.22-32V [75]
Switching Frequency	52 kHz	52 kHz	150 kHz	260 kHz	500 kHz
General Efficiency	75-88%	75-88%	73-90%	82-92%	95%(maximum)
Safety Features	UVLO, thermal shutdown	UVLO thermal shutdown, 3 A switch	UVLO, thermal	UVLO, thermal	UVLO, thermal, stop-start
Additional components	1 inductor + 2 capacitors+ 1 diode	Same as LM 2575	Same as LM 2576	Same as LM 2678	Same as LM 2678 plus additional capacitors and additional resistors
Approximate per unit cost(from DigiKey)	$3.86	$3.98	$5.37	$6.99	$5.10
Thermal performance	Relatively cooler as long as the current does not exceed 1 amp.	Runs relatively warm till max current	Similar thermal behavior to the LM 2596	Requires large copper sink	Requires some sort of power pad for extra heat.
Main disadvantages	Only can deliver/take in	Larger inductor and a lower	A higher EMI is noticed	Lower range of input voltage, meaning the	Layout of extra components and overall PCB design

	1 amp at maximum.	frequency means more clunky parts in general.		overall buffer/margin of error is less.	will be much more difficult than the other regulators

Based on the table and prior research, the team needed to come up with an option that was able to balance suitable performance with reasonable economic and long term reliability. For the LM 2575, the maximum 1 amp limit was seen as a major drawback that the team felt would result in potential risks for certain components that might draw close to that total current, and we did not want to use close to the maximum current in any case. The TPS5430, while technically the most efficient, would have required a much larger soldering and overall PCB effort with a high chance of failure, so the team decided not to consider that regulator as an option. Efficiency wise, there is, when looking at the big picture, a very miniscule difference between 88 percent and 92 percent so the thought then came to the increasingly large switching frequencies for the cases of the LM 2596 and LM 2678 respectively. This could be a potential hindrance as the duty cycle switches are off for longer periods and a higher input voltage is required, making the startup process increasingly difficult. For this reason, it was ultimately decided to go with the LM 2576 regulator as it is most suitable at combining overall efficiency with higher reliability.

3.23 - Communication Technology

3.23.1 - Universal Asynchronous Receiver/Transmitter

The Universal Asynchronous Receiver/Transmitter protocol, abbreviated to UART, is one of the three main communication protocols used in embedded systems. It is the oldest, and the only asynchronous communication protocol of the three considered for this project. It is commonly used for communication between embedded and general-purpose computers to facilitate debugging or transferring small amounts of data.

3.23.2 - Inter Integrated Circuit

Another commonly used embedded communication protocol is Inter Integrated Circuit, or I^2C. It is a bus-based communication protocol that implements the master-slave paradigm. However, I^2C stands out because it allows for multiple devices to act as both the master and slave, at the cost of drastically slower communication times as more devices are added to the I^2C bus.

3.23.3 - Serial Peripheral Interface

Like I^2C, the Serial Peripheral Interface (SPI) is a synchronous communication protocol using the idea of one device issuing commands to another device. However, a major difference is that SPI is designed such that there is a main chip that is responsible for selecting which target it wants to send and/or receive data from. This difference allows SPI to reach speeds far higher than I^2C, but all connected devices must be controlled by the main microcontroller.

3.23.4 - Communication Protocol Comparison

Below is a table to provide comparison of the three main communication protocols used in embedded systems, which consider ease of implementation, each protocol's availability given our part selections, and ability to transfer data.

Table 20: Communication Protocol Comparisons

	UART	**I^2C**	**SPI**
Ease of Implementation	High	Low	Medium
Used in Selected Parts	Some	Some	All
Data Rate	Low	Medium	High

3.24 - Communication Protocol Selection

Due to SPI's availability in our selected hardware, along with its high data rate, well-documented implementation, and its ability to connect multiple devices on the same bus if needed, we decided to implement SPI as our primary communication protocol between chips in our system.

3.25 - Programming Language Technology

3.25.1 - C (or C++)

The C family of languages has been synonymous with manual memory manipulation and management since the early 1970s, which lends itself to the field of embedded programming. It has been the go-to language for microcontrollers due to the language's high speed and easy conversion to machine code. Later, the C++ language built upon the foundation of C to provide additional features including the object-oriented paradigm while retaining the benefits of C.

3.25.2 - Python

A more recent development has been the programming language, Python. Unlike C, Python code is not compiled, rather it is interpreted line by line. Combined with its modern and looser syntax, this allows Python to be an easier language for some people to pick up compared to other languages including C. However, Python's interpreted nature comes at a significant cost of both processing speed and the hardware requirements to run it. For example, MicroPython is a variant specifically designed for use on microcontrollers and embedded devices but requires "256k of code space and 16k of RAM" [76].

3.25.3 - Programming Language Comparison

Below is a table to compare the familiarity, execution speed, level of abstraction and manufacturer support for each discussed programming language.

Table 21: Programming Language Comparisons

	C / C++	**MicroPython**
Familiarity	High	Medium

Speed	High	Low
Abstraction	Medium	High
Support on Selected MCU	High	Variable, Low to Medium

3.26 - Programming Language Selection

Given the higher familiarity, more common use in industry projects, and support from the manufacturer, the code for this project will be written in a combination of C and C++.

3.27 - Integrated Development Environment

3.27.1 - STM32CubeIDE

The STM32CubeIDE is ST Microelectronics' integrated development environment for programming their microcontrollers. It has a free license but is often regarded as confusing and hard to use compared to other IDEs.

3.27.2 - JetBrains CLion

CLion is the integrated development environment for the C family of languages developed by JetBrains. Like most other JetBrains' products, it requires a license to use, but JetBrains offers educational licenses for students and university projects. It includes many built-in features not offered by many other IDEs, and has plugins from both JetBrains, microcontroller manufacturers and third parties to support development of software and debugging tools for embedded projects.

3.27.3 - Visual Studio

Visual Studio is the family of multi-purpose IDEs owned by Microsoft. There are multiple variants, including versions with free licenses for individuals, students and open-source projects. It offers a variety of plugins to work in different languages and build targets, including some for embedded development.

3.27.4 - IDE Comparison

Table 22: Integrated Development Environment Comparisons

	STM32CubeIDE	**CLion**	**Visual Studio**
Familiarity	Low	High	Medium
License	Free	Student	Student
MCU Flashing	Native	First Party Plugin	Third Party Plugin
Feature Set	Low	High	Medium

3.28 - Integrated Development Environment Selection

Due to familiarity with CLion and the JetBrains development environment, along with its features, this project's software will be developed in CLion. However, to ensure maximum compatibility, the codebase will be designed to compile with open source or free tools, such as the Gnu Compiler Collection (GCC).

Chapter 4: Standards and Design Constraints

4.1 - Applicable Standards

4.1.1 - IPC-2221/2222: Standard on PCB Design

IPC originally stood for the “Institute of Printed Circuits”. It was founded in 157 as a trade association. It now is recognized as the Global Electronics Association. They created standards that cover data transfer, base materials, board qualifications, soldering of components, and more. One standard they are in charge of is IPC-2221, the “Generic Standard on Printed Board Design”. This covers the general requirements of PCBs and component mounting. It is broken up into a few subcategories of PCB and device type: IPC-2222 through IPC-2227. These cover the following items/types of boards: rigid, flex, PC card, MCM-L, HDI, and Embedded Passive Devices respectively. I will be discussing the section on rigid PCBs (IPC-2222), as that is what is relevant to us and our project.

One of the first aspects of the IPC-2222 standard is defining “performance” classes for the products. These define the complexity, functionality, and quality/testing frequency of the end-product boards. These classes (1, 2, 3) are as follows: General Electronic Products, Dedicated Service Electronics Products, and High Reliability Electronic Products. Boards are divided between these categories based on what kind of service and reliability is needed. Boards that are used in critical safety roles in say the medical, automotive, or aeronautic industries would be class 3. Their failure would mean risk of injury to people. The next class, class 2, would be for automotive, but non-safety electronics and industrial or business equipment where long-term reliability and performance are required, but it’s not safety critical if the component fails. The last, class 1, is products where function is the only requirement. These would be items like electronic toys, hand calculators, and the like. These still need to function and follow a standard, but it is not critical how long they last or for safety.

As part of being a standard on PCBs, the IPC talks about minimum spacings for electrical traces and openings. Table 6-1 in the IPC-2222 standard discusses various minimum spacings between electrical conductors based on whether they are coated, uncoated, what kind of coating, what kind of conductor, and what the voltage difference between the two conductors is. This section is relevant to us because it helps to tell us what the minimum spacings will be for our high voltage side of our PCB. While the table tops out at over 500 volts, it does list a specific formula to use. This formula involves taking the voltage over 500 and multiplying it by 0.0025mm and adding that to the current distance to come up with the new clearance distance value. Another important note they mention is that you should not rely on the solder mask to maintain isolation/resistance. You should make your traces in accordance with the open conductor spacing and having them coated will act as a supplement.

The standards do mention materials and minimum widths and thicknesses in section 6.2 and table 6.4 of the standard. A trace’s conductivity relates to its current temperature and its cross section. The larger a trace’s cross section, the more conductive it becomes. The lower temperature a trace is, the more conductive it is. Traces that are carrying high current on PCBs need to have thick traces. The thickness of the copper traces are called the weights. A “heavier” copper relates to a larger thickness trace. When designing your PCB and ordering it, you can select different weights of copper to adjust how thick the copper layers are on your board. If you need a certain width of trace and more current carrying capacity, you can select a heavier copper pour to increase the conductivity. You can also route traces in parallel to increase the effective total cross section. Another thing this section calls out is to account for the variance in thickness due to the process. Often times you base your values on the minimum final thickness (the minimum thickness that your trace can be after all processing is completed).

Getting more into the layout/placement of traces, there are plenty of rules or guidelines to follow. The standard introduces the idea of "necking down" or "beefing-up" traces, where traces need to temporarily have their widths decreased or increased. These should be avoided, and the traces should be made a standard width wherever possible. If possible, all traces should run in a vertical, horizontal, or 45 degree orientation. This makes the documentation/layout for the PCBs easier and makes the computer programs to drill/create the traces simpler. It stated that 90 degree bends should be avoided also for electrical characteristic reasons. It is also mentioned that there may be special rules for higher speed communications like SPI. You need to account for the line impedance and length/locations of branches relative to each other. When routing traces through pads or holes in the PCB, the traces should be equally spaced in the center between the holes and lands. Locations that will be subject to solder by hand need relief. If the hole is connected to a large ground plane, then the ground plane will suck heat away from the hole and the solder iron will need to stay to pump heat to make the joint. Instead, of a direct connection, an empty ring is made around the holes and thin traces connect the hole outwards. This increases thermal resistance so the join can be heated up quick enough to solder then leave. This helps reduce cooking certain portions of the board with soldering irons.

Concerning the vias and lands and holes, the items that make up internal and external connections on the PCB, there are various standards. Holes have a minimum thickness for the area between the hole and the edge of the copper fill around it. This minimum thickness is referred to as the minimum annular ring. The thickness of the land that makes up the portion the hole is centered in comes from an equation involving the maximum diameter of the finished hole, minimum annual ring requirement, and standard fabrication allowance (the variation in process). For vias, the connections between layers on a PCB, there are requirements for minimum spacing depending on PCB layer thickness and the class of board. Small holes will require electrical or laser drilling, while larger holes may use traditional drill bits. Holes should be sized in accordance with standard drill bit sizes if possible and larger. Otherwise, custom milling will be necessary.

The solder mask is the top layer of the PCB coating, usually made of polymer that covers the copper traces. Included in the solder mask is how the vias in the PCB are covered. Some vias are left exposed, but if an application requires insulation for electrical or corrosion-resistance reasons, a covering can be applied to the via openings. If the solder mask is used for electrical resistance and characteristics, your design should specify the minimum thickness. This way you can ensure that your design will be correct after manufacturing. Some boards that require extra insulation can have conformal coatings. The thickness and materials of these coatings vary.

The standard also mentions power delivery schemes to help reduce noise in AC systems. To do this, it recommends using a multilayer board and having ground planes underneath of high frequency traces. The ground planes here act as mirrors and copy the AC signal creating an image signal. Also recommended is adequate decoupling capacitors connected at the power/grounds of the device to help reduce AC effects. It is common in ICs to see decoupling capacitors recommended to be placed directly at the ICs to stabilize the voltage. The various digital signals are also broken up into four classes: noncritical signals, semi-critical signals, critical signals, and super-critical signals

4.1.2 - IEC-60664: Standard on Insulation Coordination

IEC-60664 is one of the main industry standards that engineers utilize to prevent hazardous conditions such as electrical shock, arcing, and insulation failure within a device. This prevention is achieved by adhering to the recommended creepage distances, clearance distances, and insulation performance presented within the standard. IEC-60664 applies to general electrical equipment, including PCBs, with nominal voltages up to 1000V AC or 1500V DC. With the system in this senior design project needing to be designed for a peak voltage of 1200V DC, the standard clearly applies. As a result, an adequate understanding of creepage, clearance, and insulation is required.

Creepage and clearance distances are relatively simple concepts that can play a large role in the safety of an electrical device at higher voltages. Creepage is defined as the shortest distance along the surface of an insulating material between two conductors. Clearance is defined as the shortest distance in air between two conductors. Although they are similar concepts, the actual values for creepage and clearance have no physical relationship to each other. This will be further evident when the process of finding adequate distances for a particular application is covered. It is also worth noting that for most applications, the creepage distance will be a higher value than the clearance distance, but awareness of both is still critical in design.

In order to find the adequate creepage distance for an application, three factors need to be known: The working voltage of the system, the pollution degree of the environment, and the material group of the insulator. The working voltage of the system is defined by the standard as the Root Mean Squared (RMS) value of the AC or DC voltage across the insulation. The pollution degree of the environment and material group of the insulator are more complex factors that warrant further discussion. Starting with pollution degrees, the main idea that this factor tries to communicate is that certain environmental conditions can make conductive paths along a surface easier to develop. Dust particles, condensation, and different types of debris can all build up over time on the surface of an electronic device and make potential arcing easier. IEC-60664 categorizes different types of environments under four distinct pollution degrees labeled degree 1 through 4. Pollution degree 1 is the most ideal of the four and assumes that only dry, nonconductive pollution occurs. By contrast, pollution degree 4 is the worst case and assumes that conductive dust and wet conditions such as rain are present. Finally, the material of an insulator is based on the Comparative Tracking Index (CTI), which is a voltage value derived from standardized testing done on an insulator to measure its resistance to dielectric breakdown along its surface. Based on the CTI, materials are categorized into four groups: group 1, 2, 3a, and 3b. Group 1 is the strongest of the four and is reserved for materials with a CTI of greater than 600V. The CTI thresholds then progressively decrease down the list of groups, with group 3b being the worst. CTI values are typically known for a given material, however if unknown then the worst-case material group can be assumed under the standard.

Finding adequate clearance distances also depends on three factors: the transient overvoltage seen in the system, the pollution degree of the environment, and altitude at which the system operates. Since pollution degrees were already discussed with creepage distances, they will not be reiterated here. Concerning transient overvoltages, IEC-60664 defines these as an increased voltage level that can be oscillatory or no oscillatory, but typically lasting only a few milliseconds. Transient events of this nature are considered more in clearance measurements because arcing or flash events in the air can happen in an instant. Electrical tracking, which is what creepage distances seek to prevent, by contrast is a process that takes longer to develop. In addition to transient overvoltage, altitude is also taken into consideration in regard to clearance distances. This is because of the dielectric strength of air decreases at higher altitudes due to the breakdown voltage being a function of air pressure. IEC-60664 takes this phenomenon into account for clearance calculations by providing correction values to be used for altitudes above 2000 meters.

With a better understanding of IEC-60664, it becomes much simpler to analyze and estimate creepage and clearance distances required for this senior design project. Beginning with clearance, the main factors to account for will be transient overvoltages and the pollution degree of the environment. Since NextEra Energy has specified that this product will be used in a laboratory environment within the state of Florida, the altitude that this product will operate at will not exceed 2000m. Therefore, utilizing the altitude correction factors for clearance calculations is not required. The specified laboratory environment also implies that a very ideal pollution degree of 1 can be assumed. Lastly, while transient overvoltage for the system may be difficult to know precisely, a conservative estimate of 2kV can be made, which is significantly higher than the nominal voltage of 1.2kV for the system. With all the major factors defined, clearance tables defined by IEC-60664 can be used to find a recommended clearance for this system of about 1.2 millimeters. The two other factors needed to define the creepage distance will be the working voltage of the system and the material group of whatever insulator will be considered. Despite the voltage in the discharge interfacing portions of the system decreasing over time from a peak of 1200V, it is safer to assume 1200V as the fixed working voltage for those components in this analysis. Additionally, it is also safe to assume a material group of 3b as a worse case for the creepage distance. Together these factors determine a creepage distance of 4.2 millimeters which, as expected, is larger than the required clearance distance. Overall, the calculated distances for this application are fairly reasonable and will need to be incorporated into our designs for proper operation and safety.

4.1.3 - IEC-60063: Preferred Number Series for Resistors and Capacitors

IEC-60063 standardizes values for resistors, capacitors, and other electronic components. In general, the standardization of these components helps to ease manufacturing burdens and simplifies how component values should be stocked. Rather than having to constantly create custom component values, manufacturers can depend on designers utilizing preset standardized values. Over time this lowers manufacturing costs and makes components cheaper.

In terms of how the values are determined, IEC-60063 incorporates what is known as various E-series sets of component values based on various tolerances. These include E3, E6, E12, E24, E48, E96, and E192. The numbers associated with each series designate the number of equal logarithmic steps or values are available for each decade. For example, a decade of resistances could include values between 1Ω and 10Ω. Within this defined range, the E12 series will only specify 12 unique resistance values between 1Ω and 10Ω while the E96 series would specify 96 unique values. Additionally, because the E96 series fits more values within the same decade, the tolerance between each value must be much tighter than the E12 series. In fact, the typical tolerance for E12 series resistors is 10%, while the tolerance for E96 series resistors is 1%. Lastly, the fixed spacing between the values in a series can be found via the following formula: $10^{\frac{1}{m}}$, where m is the number associated with a particular series (3, 6, 12, etc.)

In terms of this project, this standard is important to be aware of when underdoing design. When designing it can be possible to specify component values that may not be standard and readily available on the market. Additionally, tolerancing can have effects that must be accounted for within a circuit. This is especially important for the discharge stages and other circuitry that can be very sensitive to or dependent on component values.

4.1.4 - Serial Peripheral Interface

While the Serial Peripheral Interface (SPI) is not defined by one of the major standards organizations, its ubiquity with synchronous inter-device communication has made SPI the go-to communication protocol for systems that require full-duplex interaction between two or more devices. Originally introduced by Motorola as a feature on a line of microprocessors, SPI follows the Master-Slave paradigm which has one main "master" device selecting and sending data either directly to a single "slave" device or a bus of receiving devices distinguished by the main device's chip selection, and uses four wires: one for a shared clock, two for simultaneous bidirectional communication, and a dedicated per-device active-low chip select signal [77].

Each time a SPI slave device receives a clock and is selected, it uses bit shifting to write a single bit to the master device, and writes the input provided by the master to the newly vacated bit. One downside of this protocol is that both the master and slave devices need to send their respective LSB or MSB, otherwise the data must be converted by each device after reading. Alternatively, projects that implement multiple devices using SPI but do not want to use the master device to waste time reading from one device and immediately writing to another can implement a "daisy-chain" network, where the output of each device is connected to the input of the next device until the data is sent to the device where it originated. Then, when the master sends the chip select signal, all devices in the chain will shift the data by a bit, allowing multiple devices to read data from multiple other devices while the full system still being controlled by a master device.

4.2 - Design Constraints

To ensure that we develop a realistic prototype in accordance to the set standards, it is essential that some constraints are also developed in order to allow for a narrower scope, which will allow the team to have increased clarity on certain elements of the design. This includes the overall space of the design, with a separate area for the chassis board for discharge. as well as the method for providing wattage to the overall circuit.

4.2.1 - Power Constraints

The power of the overall circuit must be manageable for both the team, and NextEra in the future if they want to expand on this prototype, to work with suitably without compromising safety and efficiency. A majority of the power would go towards powering the relays and ensuring the relays are always working properly. Regarding the power system, some form of adapter would likely be used, be it an external power adapter or a AC/DC converter, to provide a steady supply of voltage to be supplied into a switching regulator, such as the LM2576, and its numerous versions that allow for different voltage outputs. Certain components may require 5 volts, and certain components may require 3.3 volts, and many different components require varying degrees of power, such as the sensors and op amps, as well as the software-based components such as the microcontroller unit and the light emitting diodes. If power is not suitably managed, the system may potentially experience voltage inconsistencies, excess heat, and overall instability and inefficiency, which may severely damage the long-term functionality of the prototype.

The system contains a couple of parts that will likely require much of the overall power provided, mainly the three relays being implemented in the sensing system. A relay, at its simplest essence, is a long and thing wire coiled up to work like an electromagnet, which with current creates an electromagnetic field which thus latches and unlatches accordingly. Because the wire is so long, there is considerably increased resistance compared to a wire of normal length, and thus more voltage is required in order to ensure a high current and ensure the device latches and unlatches at the correct times. Therefore, a constant and frequent source of power is required in order to guarantee that this process flows and will not be interrupted.

Ensuring that the regulation of power is stable and efficient is essential in allowing for the steady operation of the overall capacitor discharge system. Being efficient with the use of steady power supply into the initial circuit and requiring proper voltage regulation and resource management is general will enable a system that provides stability, efficiency and long term reliability without worrying about system breakdown.

4.2.2 - Space Constraints

In a capacitor discharge system integrated onto a chassis board with supporting components such as regulators and relays, design space becomes a factor of major importance. Each subsystem requires cautious placement in order to minimize tangling and interference, and designing short current paths for high current pathways, as well as making sure heat protection is adequate. The majority of the footprint is compromised of the large storage capacitors, and thus their layout will, in turn, dictate the amount of space required for the other components. Then, within the level of space that the other components such as the regulators and sensors will have, they need to be positioned in a manner to allow for efficient protection and isolation between the low voltage and high voltage sides of the circuit.

Given the outline of the circuit design, space constraints are made more important by the need to find a balance between electrical performance with workability and accessibility. Furthermore, the inclusion of so many components requires that PCB construction might be more difficult, and more layered PCB design would likely be required. Overall, effective use of the horizontal space and efficient positing of both the high and low voltage zones would provide assurance of reliability and longevity.

4.3 - General Constraints

While the design of the prototype contains practical limits in terms of the power consumption and the size of the PCB board and chaise, more general, non-engineering constraints need to be considered as well. Money and time have always been objects of consideration for every senior design project, but the complexity of needing to produce high voltage calculations and a low voltage design that should, with a couple of minor changes and step ups in terms of component values, be able to be applicable at higher voltages as well. The location of the use of the product also needs to be considered, as the safety measures vary depending on whether the location is lab based or in a more public setting where higher prioritization needs to be placed on exposure to others.

4.3.1 - Time

Our capacitor discharge project is subject to the constraints imposed by the Senior Design schedule, which is divided into Senior Design 1, which focuses more on research and initial development, and Senior Design 2, focuses on PCB construction and finalization. Both courses come with their own sets of deadlines and deliverables which combine to ensure that timing is tight and the margin of error in every department of the design process is extremely slim.

Senior Design 1 emphasizes completing scheduled based tasks, such as planning of the project, designation of team roles, and documentation of project based progress and deadlines. The bulk of the focus for this course focuses on research of component parts and design framework. In order to maintain this, certain deadlines have been set, including the submission of the Midterm Milestones document by October 31st 2025, and completing the demonstration of the capability of the project, including showing certain components have been ordered and work to a functional capability. These deadlines are absolutely fundamental to ensuring the groundwork for our project is established and that all required research and planning and processing is completed before moving on to other focal points of actual implementation and PCB design.

The team also has some additional challenges, both internal and external, to deal with that may serve as additional roadblocks in order to complete the required deliverables. With only one computer engineer on hand, it means that at least one other member of the team will be required to step up, and all three electrical members have limited outside experience dealing with C++ and microcontroller applications and coding beyond undergraduate class labs and lessons. The knowledge gap these members have may put increased pressure on the sole computer engineering student, who may not be able to have much reliance or fallback options if things go incorrect during the software process. At best, extra time would be needed in order for an electrical member to be caught up to speed on what he needs to do in order to best help the computer engineering student, and at worst, this could lead to potential failure based on one scope part of the system and execution of said part. Moreover, the team would be dealing with a new potential hardware system for the schematic, known as Atriun. It is a application, while decently popular and familiar to the sponsor of the project, NextEra, the team lacks overall experience in this department which could cause problems when designing our PCB board and time would be required in order to master certain uses of the design.

Moreover, the team is also enrolled in other classes, with the projects and exams that class entails and maintains a level of priority to other commitments. One of our team members, Kealan, maintains a four-class schedule, along with work in the semiconductor lab as well as a position as the workshop chair for the Institute of Electrical Engineers(IEEE), while another one of the members of the team, Will, in addition to a four class schedule, also works at another job on the weekends. Balancing the workloads and commitments of the other members can and may lead to difficulties when scheduling consistent meetings with both other team members and the sponsor of our project. This may lead to certain team members not being on the same page as other, and other forms of general communication may need to take over, such as calls on online platforms such as Discord or Zoom.

Another aspect of the project where time would be a serious constraint regards the ordering of parts and the testing phase of the PCB. It is very important that parts are ordered relatively early because certain elements, such as the chips for the regulators, need to be breadboarded properly into a circuit to ensure the adequate voltage is being delivered, and if discrepancies are noted, new parts need to be then ordered even more urgently to replace them. During actual PCB construction, it is almost a given that the initial design will not work and modifications will have to be made, so time needs to be allotted, as has been done in Chapter 10, for errors to be made and corrections to be implemented accordingly. The team also needs to be in constant communication when ordering parts, since certain models of components may not meet the required standards that other components require, and for that reason, it is essential that every team member is staying on top of their specific sub system and coming together to discuss errors and correct errors both in part ordering and actual manufacturing.

Overall, to meet these deadlines and submit the required deliverables, the team will need to maintain and follow a tight schedule, be in constant communication in terms of what is required and be quick to address and solve any issues that may and will arise, given the lack of overall experience in this project experience and setting. Furthermore, consistent and efficient time management will be important among team members in order to ensure a successful completion of the Senior Design course and project.

4.3.2 - Economic

The economic constraints of the prototype primarily revolve around the costs and budget of the overall design, both in terms of our economic contribution and what NextEra will provide. Being that this project is sponsored, the overall current budget listed in Chapter 10 may be accurate, but the difference may lie in terms of costs that we pay from out of our pocket and what certain aspects NextEra may cover. Parts that may be required more urgently and with less time available, as well as certain cheaper components, will likely be covered from the team, while more costly components, most of the discharge system, for example, that can afford to be purchased later than other components, may be more likely to be covered by Next Era. While the support of a sponsor provides us with a buffer of sort, they have stated a general budget that they would like us to exceed, so some degree of limitation is in place regardless.

The team recognizes that with the limitations of budget, certain aspects of the design may not have been as enhanced as we would have liked. There was a tradeoff that needed to be made in terms of designing a product that was cost effective or a higher efficient performance. A balance between the efficiency and productivity of the product while maintaining a certain level of economic efficiency in terms of spending would be essential. This especially applied when considering the protection and distinction between the high voltage elements and the low voltage elements where separation of the two was crucial to not only ensuring safety but also allowing for an effective transition.

Other aspects to consider economically including the designation of potential backup funding. With an initial budget already looking around 1500 dollars, something that needed to be factored in was potential backup expenses in case parts didn't work the first time, or in case the initial designs failed. While this does provide buffer of sorts in case certain things go wrong, it also further narrows our time and economic scope considering this backup budget is likely money that would be coming out of pocket and not from the sponsor. A factor that also had to be considered was unexpected delays in terms of shipping and increased demand for certain components, which may lead to us spending extra money in order to ship the part relatively quickly. It is important that these small, yet potentially significant factors be factored into the overall budget and then we maintain a level of smartness and caution when planning and managing our financial pool to prevent needless spending.

Overall, the economic constraints provide significant barriers that could prove fairly detrimental if market research is not done adequately efficiently. The use of a budget limits us in terms of looking for products that are cost effective rather than simply the best available products on the market to accomplish the design goals. By allocating some extra money for backup in the case of component or design failures, we can afford a degree of flexibility and significant decrease the financial stress both we, and our sponsor, would be under. Furthermore, by discussing and carefully planning our budget, focusing on the purchase of the most crucial components first, and making educated and researched decisions about things to prioritize when making financial decisions in the project, we will be able to complete and design our prototype without compromising both effectiveness and the project scope.

4.3.3 - Manufacturability

A key constraint to consider lies in the manufacturability with the design and potential further implementation of the prototype. The sponsor, NextEra, has told us that the prototype we are designing is meant to be used in a research lab setting, with adequate potential protection available for anyone who will use the product in the future. Our prototype is aimed at being used as a testing, more experimental base for both low and high voltage applications. If the prototype works to a suitable level of efficiency, the sponsor will aim to use the calculations and design to replicate future versions for lab use. Thus, it is essential that the design can be manufactured effectively since it is a process that needs to be repeated by other parties.

One of the main manufacturability issues will be PCB design and implementation. The design includes a separation between high voltage and low voltage elements. Developing a printed circuit board, or a PCB, for this system requires high levels of accuracy, obtaining specific components that fit the size and are relatively simple to solder. It should be noted that a high level company like NextEra obviously has more resources to solder and to design and make PCB's so we can be a bit more flexible in terms of the actual building, yet it is still essential that the layout is proper and there are no issues with component selection and fitting. Any error, even an extremely small one, on the PCB board can lead to disastrous consequences in large scale and long term manufacturing.

Durability and long term use is also one of the main manufacturability concerns of the system. The capacitor discharge needs to function reliability over very long stretches of time, and needs to be able to be resistant to changes in temperature and ripple effects from electrical current noise. This is especially important due to the lack of temperature sensors, so the users will not be immediately sure of a drastic change in temperature until a visual or sense based indication, such as touching and feeling the heat within the components. In a lab setting, the enclosure and protection, as well as the isolation measures, would need to meet certain industry requirements in order to maintain effective performance in the future. Our prototype is primarily focused on efficiency and functionality for both high and low levels of voltage, yet in a professional lab setting, a manufacturable version of the capacitor discharge would need to pass further tests and obtain electrical safety certifications, especially on the protection parts.

In order to address and fully solve these potential issues, the selection of proper fitting components, optimization of the PCB layout, and maintaining a balance between cost and efficiency will be essential. Our current design is merely designed for functionality, but in order to make it ideal for larger scale manufacturing, these constraints need to be addressed properly within the design choices and selection we ultimately make, and furthermore, need to be adaptable and flexible in case they are changed, within the project process or within the long term manufacturing process that NextEra may take.

4.3.4 - Scalability

Scalability is perhaps a crucial aspect of this project more than any other specific idea due to the distinction of the project scope between low and high voltage requirements. While the general understanding was that a low voltage prototype that should theoretically also work at high voltages, with calculations provided, was thought to be suitable, the team decided to make a high voltage version as well, given that the calculations were already being made. While this has made the system a more usable and realistic application for industry use, it also results in increased difficulty in terms of getting the system to function and increased costs in now having to cover more components than originally planned.

Thus, having increased the workload of the original system significantly, it was essential to develop a way to incorporate the elements of a higher voltage application, which would likely be just larger values of components for the low-scale application, while not compromising the protection and effectiveness of the original system and still achieving the baseline goals and objectives. This means that further costs and space in the budget would need to be outlined for HV(high voltage) parts along with a separation measure between low and high voltage, as the team wanted to make sure the LV(low voltage) didn’t affect the HV and vice versa. This requires further space on the board and increases the overall footprint of the PCB design. With these potential roadblocks in mind, the team needs to make sure that the HV and LV sides do not interfere and that the space and capacity of other components, such as the discharge overall and the microcontroller, have the capacity to handle HV application.

4.3.5 - Health and Safety

The safety of both the team and the users of the product is something that needs to be taken into account both before and after construction of the prototype. Dealing with such high levels of voltage, and specifically discharging said levels, can be extremely hazardous, both for the team and for any long term scaling of the product that NextEra may want to contribute. For this specific reason, it was outlined that the team would not be allowed to test the prototype at high levels of voltage, with the inference being that if the system works at low levels of voltage, then with the right component values the system should also work at high levels as well, which is a fair assumption. Thus, it is essential that the product is tested only in lab settings, even with low levels of voltage, an aspect also outlined by NextEra for its future long term use of the product.

Electrical safety is the primary aspect of the design that needs to be properly considered. Since we will be using AC power from a wall outlet, all wiring and power components need to be adequately protected, with potential copper covering on the regulator chips in order to prevent overheating. In addition, further precautionary measures may need to be taken in order to prevent typical electrical safety concerns such as short circuits or other electrical failures.

Chapter 5: Comparison of ChatGPT with other Similar Platforms

Over time, large language models have rapidly developed and gained increased popularity among the public, industry, and academia. By utilizing unique training algorithms along with a massive amount of training data, AI chatbots can now rapidly retrieve and summarize information, brainstorm creative ideas, debug code, and edit writing. Due to their increased popularity and capability, there is a new focus among many industries to investigate ways in which large language models can help streamline work and increase productivity. Similarly, throughout this senior design project AI tools were utilized to assist in general research and design considerations to increase understanding and productivity. Whether this was achieved, however, depended heavily on the case of use. Some of these cases are analyzed below along with general limitations of AI chatbots. The cases are divided among the specific subsystem of the project that they were used for.

5.1 - AI Chatbots and Their Limitations

Before discussing specific case studies, it is necessary to provide context on existing AI chatbots and general limitations across their models. These limitations impact how the team utilized AI and provides a background for analyzing the AI's response.

5.1.1 - ChatGPT

Many AI chatbots exist, but undoubtedly the most popular of them all is ChatGPT which is developed by OpenAI, a private company focused on AI research and development. The current free model of ChatGPT available to users is GPT5 which was released in August 2025. [78] GPT5 is marketed as having reduced instances of hallucinations (instances where the AI provides false or misleading information as fact), while also increasing performance in writing, coding, and health queries. [78] Despite these performance improvements, OpenAI still lists some limitations of the tool. For starters, despite reducing instances of hallucinations, they can still exist, and it is important to be able fact check the responses that the model provides. [78] The prompts provided also have a huge impact on the quality of the model's answer. Even small changes in the prompt phrasing can change the potential response. While ChatGPT is able to ask for clarifying questions to provide a better response, it is crucial to write an initial prompt that is clear, specific, and concise to guarantee the best potential outcome.

5.1.2 - Google Gemini

Google Gemini is the main AI tool which was developed by Google DeepMind and provides a variety of functions including the ability to converse and understand text, as well as being able to adequately respond to audio and visual images, and be able to provide coding advice and application. [79] The current version of Google Gemini is Gemini 2.5, which was released around June 2025. [79] The latest version of Google Gemini is marketed as having improved efficiency in all departments, which include image generation and audio instruction. [79] In addition, the latest version of Google Gemini also includes some experimental and innovative measures such as enhanced reasoning, which aims to use parallel thinking and learning through repetition in order to allow the AI to think of numerous possibilities before generating a well-rounded response. Furthermore, Gemini seamlessly integrates with other Google apps such as Google Maps, Docs, and Drive. Despite these innovations and noticeable overall improvements in the design, Google Gemini still has some notable limitations. Like ChatGPT, hallucinations are still present, and for that reason it is essential to check responses and weblinks sent to make sure they exist and the information seen from weblinks are valid. The model also heavily depends on the user's knowledge of said subject when asking for information, as a less detailed question will lead to an increasingly vague reply. It is essential to always be clear and very detailed when writing prompts within Gemini as even with the tool's built in feature to ask for clarity, it is very easy to be steered in the wrong direction and lose crucial understanding. Google Gemini also struggles with more higher scale operations, such as massive data loads, which leads to a slower and less accurate response in comparison to other platforms.

5.1.3 - Copilot

Microsoft Copilot is the primary AI tool developed by Microsoft for Microsoft technologies, particularly Microsoft Word, PowerPoint, Excel and Teams. It provides significant major assistance when it comes to coding applications, integrating well with Visual Studio Code and providing coding suggestions and blocks of code. [80] It should be noted that while ChatGPT is capable of the same function, Copilot focuses more in depth on coding as a whole and can provide more detailed responses in comparison. [80] Furthermore, the application is integrated into all the products mentioned. [80] In addition, the software can offer many of the same benefits as ChatGPT and Gemini such as image generation and audio understanding. In addition, Copilot also offers very integrated methods to collaborate with others, such as document collaboration and offering scheduling conveniences for timings within Microsoft Teams. Potential limitations within the scope of Copilot include the quality of said AI-generated code that needs to be fact checked and rechecked repeatedly before implementation. [80] This also leads towards copyright limitations as code is taken from other aspects of the Internet and can lead to potential plagiarism implications. [80] Another limitation within the tool includes cybersecurity and suggesting elements of code that contain security issues. Extra precautions would need to be put in place to use the tool further, given all the concerns. [80]

5.1.4 - General Pros and Cons/Comparison

Large Language Models(LLM) come with a variety of benefits and downsides when put into use. Idea generation and new insights are a highly valued benefit of using LLM's as the tool offers different perspectives on a topic, along with inquiring in depth about what specific knowledge a user is requiring, which allows for increasingly detailed inquiries and responses to further knowledge down to specific ideals. [81] Scalability is also a great benefit to using LLM's as the tools are adapted to manage and view a variety of applications and databases before providing analysis. [81] That way, an inquiry can be effectively researched by the LLM before delivering a response, as opposed to searching countless sources on open source engines such as Google or Bing. Improved communication is another significant upside to using LLM's both in the context of translating languages, as in verbal languages, allowing for people with different linguistic abilities to benefit massively with communication with other cultures [81]. Another aspect of improved communication that LLM's assist with regard writing, specifically generating outlines and paragraph structure. Furthermore, writing assistance also comes with suggestions of focal points and fixing grammatical errors.

At the same time, these AI tools also come with a variety of downsides when put in application. Often when writing, the user will ask for a source for the information being generated, and while a source will come in, the source is often a weblink to an expired page that can no longer be accessed, which puts the user at risk of plagiarism. [82] Inaccuracy is also a major issue within these tools as they operate based on pattern recognition from large datasets, but true critical thinking and self-contextual applicability is lacking within the models, which results in lack of accuracy when posed with increasingly more specific inquiries. [82] Bias and misinformation is another negative implication as LLM's are typically trained on massive datasets that may contain biases and inaccuracies. [82] Thus, it is essential to fact check, both personally, and from others, information given from LLM's, in addition for developers of AI in the future to finetune and adjust future versions of the tool to be less susceptible to biases. Finally, with the advent of AI as a whole, it is a common danger for students to become overly reliant on AI which could have severe ramifications on the critical thinking and problem-solving skills, as well as decreasing levels of creativity and uniqueness within the report and writing style.

5.2 - Case Studies Within the Discharge System

For the discharge system, AI was used as part of the research process to provide a starting point for understanding what technologies existed for various component types. Within Appendix E, case study 1 highlights an example prompt [1a] of AI being specifically for general resistor research along with the responses from each of the three LLMs discussed. Of the three, the response from ChatGPT [1b] is the most detailed, offering the most amount of content while also summarizing that content effectively in the form of various tables. Copilot [1c] also followed a similar structure, highlighting the same resistor technologies and summarizing effectively through tables. The detail of the content, however, was much less. Of the three, Gemini [1d] was the most unique. In its output it offered a feature to create a specific research plan for the topic and approve of the AI's strategy for conducting said research. It then took multiple minutes for the AI to follow that research plan before providing an output. The ability to have more customizability over how AI conducts research is an exciting feature. In reality, however, the output only provided 40+ sources of information, rather than summarizing the information. This defeated the goal of using the AI in the first place. There are some options to have the AI build certain features off the sources of information (flashcards, webpages, etc.), but having to take the extra steps to better organize and understand the information is a weakness.

Another important thing worth noting when utilizing AI for research in this manner is the availability/nicheness of the topic itself. Resistors are a very old and common component with over a century of maturity. As a result, there are a plethora of quality resources, articles, and webpages that AI can pull from to produce a informative and helpful output. If technology research was done on a topic that is more cutting edge, then its possible AI has less to pull from in terms of sources. Fortunately, the technology utilized in the discharge is very standard (resistors, relays, wire), so AI can be a great source for expediting research.

In order to provide a more open ended prompt to the different AI applications, a prompt was fed for the AI to explain what their process would be for calculating the temperature rise in an TE HSC100 power resistor over the course of a 30 second discharge cycle. The datasheet for the resistors was also attached. The exact prompt can be found within Appendix E under case study 2. Without getting into specifics about the exact theory pertaining to the prompt itself, it seemed as though ChatGPT (2b) gave the most thoughtful answer. Rather than trying to provide one very specific answer, it outlined multiple assumptions it was making and provided a range of answers based on different cases. Copilot (2c) also was able to do this, but to a lesser extent than ChatGPT. It outlined key assumptions and uncertainties and clearly explained its thought behind the theory, but an attempt to provide a single answer was still made. This shows that ChatGPT can more effectively understand nuance, estimation, potential grey areas. The Gemini response (2d) also unique under this prompt. Of all the LLMs, it was the only one that made an attempt to read from the graphs included in the datasheet. ChatGPT and Copilot did pull written information from the datasheet, and acknowledged the existence of the provided graphical data, but they did not source as having used them to develop their answer. This made the response from Gemini more practical in the sense that it did not get overly cluttered by assumptions and calculations. It simply read straight from the document. The answer it provided was also fairly within the range of the other AI models.

This second case study provides insight into how AI should be used to approach engineering design and calculations. Firstly, the assumptions that AI applications have to be clearly understood in order to provide context to the answer. None of the AIs in case study 2 provided the same answers, but their approaches and assumptions differed. Engineers need to be able to understand the differences and even be able to specify their own assumptions to the AI for better results. Additionally, the outputs for these cases are estimates, and no AI response at the moment will ever be able to provide concrete answers for more complex design considerations. But even then, having a resource that can provide estimates and act as another backcheck of an engineers work is a valuable tool as long as its limitations are understood.

5.3 - Case Studies Within the Sensing System

There was AI usage regarding the sensing system and components. It was used to help find different technologies to compare, understand data sheets, and figuring out what components to select. AI and generative LLMs are very powerful tools, especially those trained well and with access to the internet/searches. In this section I compare a few of the main tools (Grok 4 Expert, Claude Sonnet 4.5, Gemini 2.5 Pro) against each other. The first prompt I gave was a question asking the LLM to list all of the possible voltage sensing systems/components/categories that could possibly read the voltage level of the capacitor and translate that into the MCU. Reading through the prompts each model had their pros and cons. Each model talked about the different kinds of technologies as well as listed some example components. I liked the response that Gemini gave the best. It listed off the various kinds of architectures and ways to solve the problem, then under each category, it gave a few more specific examples of how to apply specific ICs to solve that problem in that category. Claude gave a shorter outline filled with many more specific examples of ICs that could be used. The list was very complete, covering more technologies than the other LLMs, and while I understand the different technologies, it would have been nice for it to re-explain how each technology works along with their strengths and weaknesses. Grok did a good job at this, it listed off many of the kinds of technology as well as a specific example for each and a summary of how it works with strengths and weaknesses. However, Grok did not summarize this or provide a separate comparison between or recommendation of a specific technology/component to use like the other LLMs did. There were also follow-up prompts/questions provided by both Gemini and Claude, asking about creating a block diagram or schematic. This would have worked fine, unless the schematic/diagram was a image generation, these LLMs are not great at schematic generation. Grok's app had follow up prompts, but nothing in the message it sent.

In the same chats of each LLM app, I made another prompt asking about the temperature sensing technologies and components that would be able to work with my systems parameters and translate the temperature of the discharge heatsink/plate into our MCU. The responses to the prompts were similar to the responses seen in the previous cases. Claude listed out multiple different kinds of technologies, but with either very brief or non-existent explanations of each. It did cover many different kinds of sensors as well as specific model numbers for all the sensors. The table provided at the end was filled with each technology and one to three examples or subsets of each technology. The comparing values section included the accuracy, cost, range, mounting ease, and more. It then gave detailed recommendations. The recommendations it gave were a best overall, best for highest accuracy, best digital only solution, and more. It provided me with the options to choose the best based on what I valued or needed most from the temperature sensor. Grok's response to this prompt was pretty good. It gave multiple different kinds of technologies as categories then gave subcategories within those of more specific kinds of technology. It listed pros, cons, examples, and explanations throughout the response text. In the comparison table it listed off all the values we would care about (accuracy, temperature range, pros, cons, etc.) Gemini's response was good, but not as detailed or with as many options presented as the other two. It did do a good job of explaining how each type of temperature sensor works, where its pros and drawbacks come from, and why or why not it would be a good fit for my application. That may have been partially why it did not include as many examples or types of technologies. Some are just unpractical for our specific needs regarding temperature range, accuracy, packaging, and power. It did not list as much information, but it was good information. Questions were again asked by Gemini and Claude directly, but only indirectly with Grok.

The third prompt asked about specifics of isolation technologies, strategies, and components. It also asked if there were any gaps in understanding or principle in my idea of the design so far. Gemini did a good job at summarizing what I asked. It explained what items would need to be grounded and which items would need to be isolated. It then went on to explain how to isolate those items, what kind of features the isolators for these systems would need, specifications and such. After that, Gemini went into depth about the different kinds of isolators, what each are good at, and how they work. It summarized all of this information into a table comparing the technologies of isolators, what their best use cases would be, their pros, their cons, etc. Grok provided a similar response. It covered IEC and UL standards for PCB and electric isolation. It mentioned all the items that should be isolated/grounded. It mentioned how to handle isolated power on the HV side and control/signal paths between items that cross the LV-HV boundary. It also summarized this in a table, comparing the different types of isolators. Claude was an interesting case on this. The response from the prompt by Claude was much longer than any of the others. I had to tell it to continue multiple times to get the rest of the information. It started by listing many areas that would need protection/isolation. It then went into explaining the different kinds of isolation technology and components. For each kind of isolation technology, it listed the subcategories and multiple examples within each subcategory. It then had a short summary listing the advantages and disadvantages at the end of each subcategory. It also did a similar thing for grounding and other safety strategies such as interlocks or case open warning systems, double isolation, overcurrent protection, etc. It then started to make many tables comparing isolation technology for various situations. It then went into recommending specifics (technologies and components) for my situation and use case.

As said before, generative AI and LLMs are very powerful tools that have many applications. We see companies using AI to analyze weather data and forecast the weather better than any reporter has been able to. We see it being used to predict finance markets and when to best perform maintenance on equipment. Many companies are also integrating their own LLMs trained on private company data to better help the people who work there communicate and get tasks done in accordance with company standards, practices, quality, etc. LLMs are valuable tools. They are trained on massive amounts of data and have that data retained perfectly in their memory. Before, if you had a question, you would have to try to think about how you could get your question to be solved. Now, you can just ask your question directly. It speeds up the question-answer process, leading to information being learned in those who use it. However, it is not without its drawbacks. Some argue that it decreases brain functionality or capability. Some argue that half of learning comes from having to struggle to find the material or the background/side material you learn on your way to answering a deeper question. One issue we may have in senior design in particular is thinking that an answer given by an LLM is correct because it uses technical jargon or is long, but it may still be missing key information or be factually incorrect. These errors are called hallucinations. They are especially dangerous in LLMs, because the LLMs will say them with full confidence, but still be incorrect. Often, confidence is associated with correctness, but it can be a detriment in this case.

5.4 - Case Studies Within the Power System

For the power system, AI was used as a component of the research process to provide a starting point for what regulators were available for a capacitor discharge project. Case study 3 and 4 within Appendix E show the responses given by ChatGPT, Gemini and Copilot in exactness, as well as the elaborated prompt in detail. On an overall basis, the level of detail ChatGPT gave in terms of design considerations was vastly superior to the other two tools. All three tools recommended roughly the same types of regulators, such as linear regulators, switching (including buck and boost) regulators, yet GPT further provided recommendations for type of regulator based on the function of the project. For example, if the capacitor voltage is numerically higher than the load voltage, then ChatGPT recommended a buck converter, which will be the case during our project. Google Gemini merely listed a brief description of each type of regulator, while Copilot listed out a brief list of advantages and disadvantages for each type of regulator, including more uncommon cases such as shunt regulators. ChatGPT had all the above listed already, in addition to use cases, marking it clearly more detailed in comparison to its competition. Furthermore, both ChatGPT and Copilot also asked follow up questions to the inquiry, such as whether I would need assistance choosing components or a comparison table to be made of the trade offs of each type of regulator. The latter inquiry asked by ChatGPT was clearly the more detailed response, demonstrating that in this specific inquiry, it was clearly the most well equipped to handle further questions.

Elaborating on the inquiry, it was asked whether ChatGPT could come up with the mentioned table, along with different types of buck converters equipped for both 3.3 volts and 5 volts at a minimum. In response to this, a variety of types were suggested, such as non-synchronous and synchronous buck, along with more specific types from Texas Instruments. However, since my inquiry was more general, the lack of detail was clear. On a more general note, all 3 applications provided a decent start on a more knowledge-based inquiry, where AI applications can provide in depth information based on massive searches and data sets.

The next inquiry that was in mind was more creativity based, which can be verified in Appendix E, Case Study 4, mainly on what additional features could be added to the power subsystem besides the requirements such as the regulators and AC-DC adapter? From all three AI applications, I received roughly similar answers, mainly the use of bleeding resistors, temperature and current sensing, isolation and protection materials along with power switching with a MOSFET. However, all of these features would already be located within other aspects of the design, and it is there where the lack of creativity and context that AI is limited by acts as a determent. While ChatGPT was able to provide the most information and different types of components for further use, it felt like it was just giving me a list of every possible component to use in general, rather than something specifically needed for a power subsystem. ChatGPT lists out UART as a example of a communication/telemetry feature, which clearly deals more with software than power. Similarly, Copilot provides status indicators such as LED's or displays as a component for a power subsystem, again an aspect of a system that has more to do with the software side in terms of programming lights to turn on or off. With further context, AI could obviously be more specific, such as if I provided the design for the other subsystems with the microcontroller and user interface. Ultimately, the responses received show that given context and clarity regarding a question or inquiry, all 3 platforms are able to provide competent responses yet ChatGPT provides more options and general information as opposed to Copilot or Gemini. Yet when questions get more general, as users often asking questions will not have true clarity on a topic hence why the question is being asked, AI responses get extremely general and rely on user clarity and detail for further instruction, a major note to take into consideration when using AI software in the future.

5.5 - Case Studies Within the Computing System

One of the areas of interest surrounding the emerging technology of large language models is their ability to assist with software development by augmenting the writing code phase of a project. Over the past few years, there have been several notable plugins developed to insert these tools into integrated development environments, such as Google's Gemini into Android Studio or Microsoft's Copilot into GitHub. In past projects where the use of these generative transformers and subsequent documentation of the experience of using the tools was required, I have struggled with the phenomenon of LLMs forgetting the context of a conversation or "hallucinating" a non-existent function. More case studies for the computing system will be added for the process of implementing our project's software design in an embedded environment.

On the other hand, a strong point of LLMs is the summarization of well-documented topics, where they are less prone, but not entirely immune, to generating mistakes due to the high volume of data surrounding the subject during the model's training. For example, when searching Google and prompting Microsoft's Copilot for common application of the Serial Peripheral Interface, both models highlighted the use of SPI in memory, industrial devices and audio interfaces. Gemini highlighted the connectivity applications of SPI, while Copilot included a section to explain why SPI has risen to be an unofficial standard of the embedded world.

Chapter 6: Hardware Design

6.1 - Discharge System and High Voltage Calculations

Since the scope of this project involves designing a discharge tool for high voltage applications but only testing the device at low voltage, theoretical calculations and simulations become especially important. As a result, the following section will focus on the theory behind a controlled capacitor discharge and the calculations and simulations used to determine the discharge time, power draw, working voltage, and thermal performance.

6.1.1 - Capacitor Discharge Energy and Voltage Setpoints

The energy stored in the electric field of a capacitor can be expressed as a function of its capacitance and the voltage across it. This is shown in the following equation:

$$E = \frac{1}{2}CV^2$$

Based on the requested specifications from NextEra, the discharge system is designed to operate on capacitor banks with a capacitance of 1650μF and a rated voltage of 1200 V. This yields a stored energy of 1188 J. In order to design an effective discharge system, the distribution of dissipated energy across the three discharge stages needs to be considered. The energy absorbed by a stage is determined by the change in capacitor voltage it experiences before the subsequent stage activates. As a result, the voltage setpoints for each stage become the main way of controlling their energy dissipation.

The first stage of the discharge process should be designed to handle the bulk of the capacitor energy. This then provides flexibility for the other stages to handle less energy, but at a much faster rate to meet the less than 30 seconds discharge requirement. Within the current design, stage 2 of the discharge can begin anywhere between 800 to 600 V. This means that stage 1 will absorb anywhere between 55% and 75% of the capacitor's initial energy. Stage 3 of the discharge can begin anywhere between 400 to 200 V. So, stage 2 will absorb anywhere between 14% and 42% of the capacitor's initial energy, and stage 3 will absorb anywhere between 3% and 11% of the capacitor's initial energy.

Table 23: Bounds for Voltage Setpoints

Stage	Start Voltage (V)
1	1200
2	800 to 600
3	400 to 200

As stated before, stage 1 will see the majority of the energy in the system in addition to the highest voltage level. This means that the equivalent resistance of that stage will need to be higher in order to handle the start of the discharge. As will be discussed soon, this higher resistance will create a slower rate of discharge initially. However, since the second and third stage see less energy and voltage, their equivalent resistance can be much lower and create a faster discharge rate that makes up for the slow speed of the first stage.

6.1.2 - Discharge Time and Stage Resistance

The voltage decay of a discharging capacitor can be expressed as an exponential decay function as seen below:

$$V = V_o e^{-\frac{t}{RC}}$$

In this equation, the discharge is related to the initial and final voltage being analyzed along with the RC time constant, which is a product of the capacitor's capacitance and the equivalent resistance that it sees in the system. With the voltage setpoints established for each stage, it is possible to impose a max discharge time on the stages as a starting point for finding adequate resistance values. Initially, it was assumed that the max time for each stage would be 10 seconds. Below are the initial calculations under that assumption:

$$R1_{Eq} = \frac{-10}{0.001650\ln(600/1200)} \approx 8743.6\Omega$$
$$R2_{Eq} = \frac{-10}{0.001650\ln(200/800)} \approx 4371.8\Omega$$
$$R3_{Eq} = \frac{-10}{0.001650\ln(10/400)} \approx 1642.9\Omega$$

To be closer to standard E-series resistance values, and to accommodate the availability of certain resistances in chassis mount resistors on the market, the following choices were made for each stage's individual resistance values: $R1 = 10k\Omega$, $R2 = 4.7k\Omega$, $R3 = 1.8k\Omega$. It is worth noting, however, that these selected values are not the equivalent resistance of each stage. In fact, the equivalent resistance will be lower since stages are added in parallel to each other over the discharge cycle. After taking this parallel effect into account, the following are the true equivalent resistances: $R1_{Eq} = 10k\Omega$, $R2_{Eq} = 3.2k\Omega$, $R3_{Eq} = 1.2k\Omega$. As seen, with the exception of the first stage, the equivalent resistances are under the initial values obtained from the max time assumption. The first stage taking longer than 10 seconds is acceptable since it needs to dissipate the most energy and the other stages will be faster to make up for it. Below is the initial LTSPICE circuit with simulation results for the maximum and minimum discharge time, followed by a table summarizing various discharge time for each stage at different edge cases of voltage setpoints:

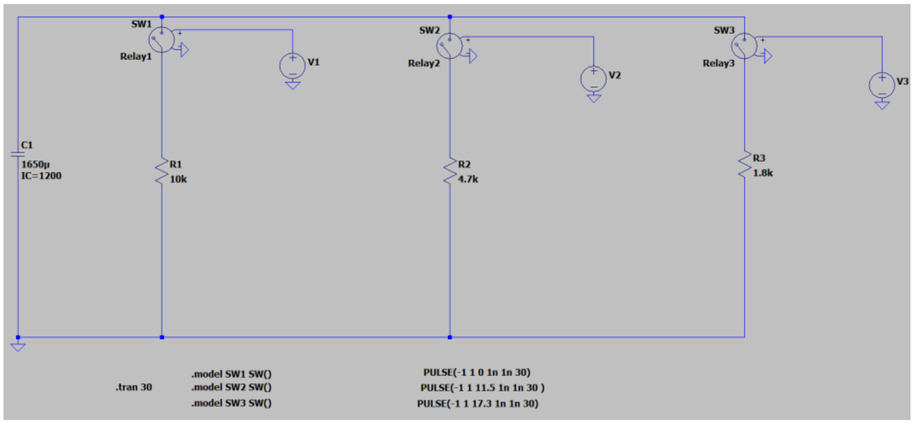


Figure 4: LTSPICE Model with Equivalent Stage Resistances

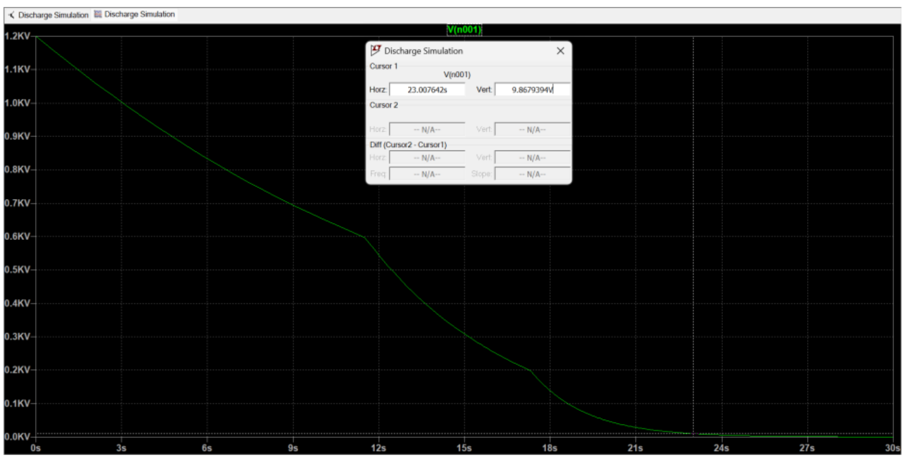


Figure 5: Max Discharge Time Simulation

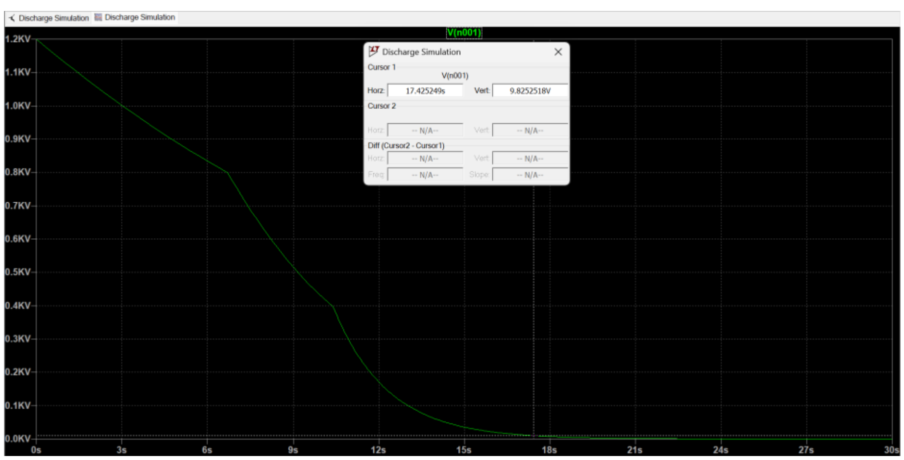


Figure 6: Minimum Discharge Time Simulation

Table 24: Discharge Time for Voltage Setpoint Possibilities

	Voltage Range (V)	Time (secs)
Stage 1	1200 to 800	6.7
	1200 to 600	11.5
Stage 2	800 to 400	3.7
	800 to 200	7.4
	600 to 400	2.2
	600 to 200	5.8
Stage 3	400 to 10	7.1
	200 to 10	5.7

So, based on the simulations, the maximum time that this discharge design should take to reach a safe voltage level (<10 V) would be around 23 seconds. This provides an adequate amount of margin for the small effects of increased external resistance from items such as wires and the relays and overall switching/processing time for each stage to activate. The minimum time would be around 17.5 seconds. Based on the voltage setpoint ranges, this provides around 5.5 seconds of possible adjustment to the discharge time based on user input, which is suitable to the sponsor.

6.1.3 - Voltage, Power, and Current Ratings

Arguably more important than the discharge time is the ability of the resistors to handle the applied voltage and pulse of power from the capacitor. When comparing the power and voltage handling, it became clear that the working voltage of the resistors will be much more limiting to the design than their power capabilities. As a result, the working voltage calculations will be discussed first, followed by the power calculations, and concluded by the calculations of the maximum expected current in the system.

To calculate the maximum working voltage of a resistor, some important information from the datasheet is required. The datasheet for TE Connectivity's HSC100 series of chassis mount, wire wound power resistors can be found in appendix C. Within it, the maximum working voltage, assuming the power rating is not exceeded, is listed at 1900V. This is much higher than the max voltage seen by the system which is 1200V. Taking the power rating into account, however, allows for the calculation of a maximum working voltage that is derived from ohms law. This is shown in the formula below:

$$V_{max} = \sqrt{P_{max} R}$$

The actual working voltage of a resistor will be the lower value between the 1900 V provided in the datasheet, and the value provided by the formula. To make use of this formula, the max power of the resistor must be known. According to the datasheet, the HSC100 resistors are rated for 100 W. This, however, assumes very ideal thermal management of the resistors on a standard heatsink. Although it is planned within the design for these power resistors to be mounted onto an aluminum plate which will provide some heatsinking, it is more conservative to utilize the resistor power rating in the absence of a heatsink, which is 50 W. This way, the discharge design will not fully depend upon a perfect heatsink design. Under this assumption, the following working voltages were calculated for resistance values utilized in the final design and series combinations of resistors were used to ensure that the voltage for each resistor did not exceed the calculated working voltage:

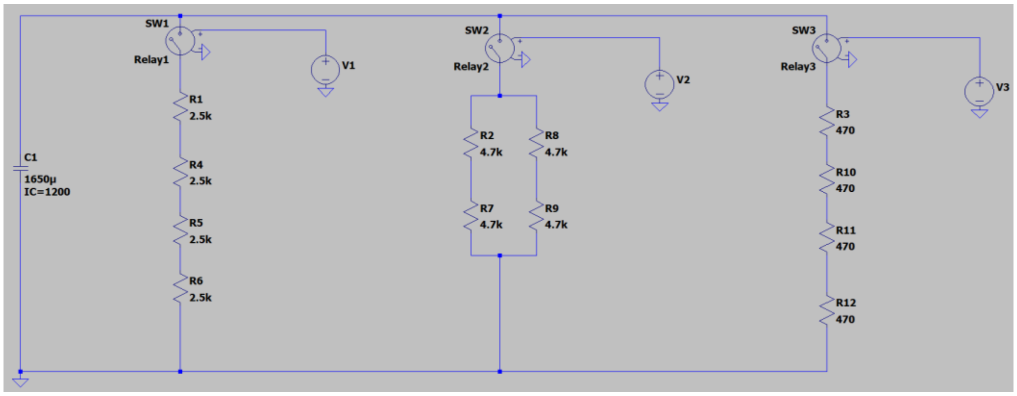


Figure 7: Final LTSPICE Model for Discharge Stages

Table 25: Voltage Margins per Discharge Resistor

Resistance (Ω)	Calculated Max Working Voltage (V)	Max Voltage Seen in Design (V)	Margin (%)
470	153.29	100	34.64
2500	353.55	300	15.01
4700	484.76	400	17.36

Both the peak power and average power that each of the resistors see in the system was also analyzed. This was done by isolating each stage of the design and applying the maximum initial voltage that a stage would see. The stage was then left connected for the maximum amount of time it is expected to operate in the discharge system. For example, when analyzing the first stage, the initial condition of the capacitor in the simulation was set to 1200V and only the first stage was connected to the capacitor for 30 seconds. For the second stage, the initial voltage would change to 800V, and the stage would be left connected for about 23 seconds. For the final stage, the initial voltage was set to 400V, and the stage would be left connected for about 19 seconds. Below is a table summarizing the results for all three stages:

Table 26: Peak and Average Power per Resistor

Resistance (Ω)	Initial Voltage During Test (V)	Test Runtime (secs)	Peak Power (W)	Average Power (W)
2500	1200	30	36	9.64
4700	800	23	34	5.73
470	400	19	21.2	1.73

Lastly, the maximum current in the entire system was analyzed by setting the stages to activate at their highest voltage setpoint and simulating the current through the capacitor throughout the discharge process. Since all the stages are in parallel, and the stage resistance progressively decreases, and the current waveform will have three distinct spikes over the discharge time. The largest of these spikes helped inform decisions on suitable wire gauge and relay selections for the project. The largest spike seen coming from the capacitor peaks at around 335mA. For good margin in the design, a wire gauge that can support at least double this current would be ideal. As shown in previous research, most wire options with high voltage insulation will offer minimum wire gauges of around 22 AWG. The current carrying capacity at this wire guage should be more than sufficient to handle the expected current in the system. The simulation results can be seen below:

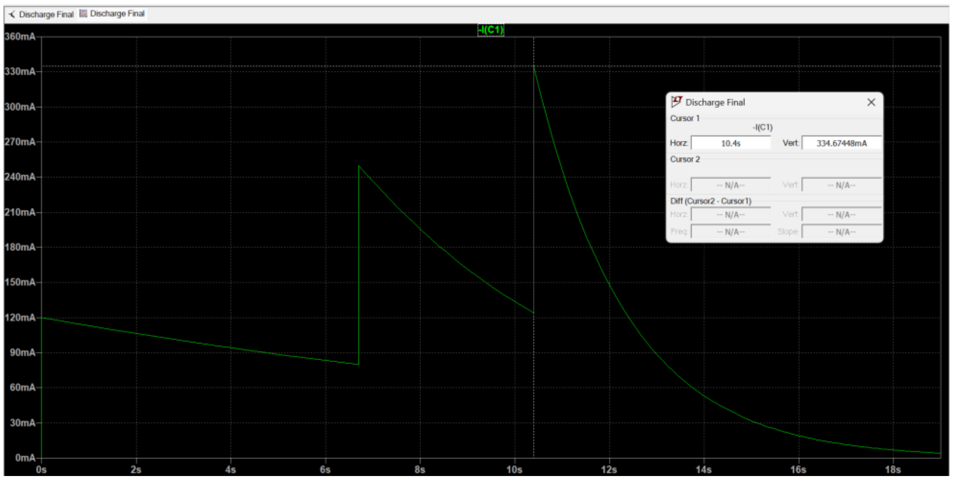


Figure 8: Capacitor Current Profile during Discharge

6.1.4 - Effect of Component Tolerances and Switching Speeds

Since the designed discharge time is extremely dependent on the resistor and capacitor values because of the RC time constant, it is worth analyzing the effect that component tolerances will have on the discharge time. All the discharge resistors have a ±5% tolerance on their values. Additionally, NextEra has specified that the tolerance on the capacitor banks that they utilize is ±10%. To simulate a worst-case discharge time, the capacitor value will be increased by 10% and all resistor values will be increased by 5%. This creates the highest, and subsequently slowest, possible RC time constant. The simulation on LTSPICE was run in the same manner in which the original discharge time simulations were run, and the results can be seen below.

Table 27: Discharge Times Accounting for Component Tolerances

	Voltage Range (V)	Time (secs)
Stage 1	1200 to 800	7.87
	1200 to 600	13.55
Stage 2	800 to 400	4.37
	800 to 200	8.67

	600 to 400	2.53
	600 to 200	6.88
Stage 3	400 to 10	8.56
	200 to 10	7.02

Under the specified conditions, the maximum discharge time rises to 27.45 seconds. As a worst-case figure, its also worth accounting for the max operating time of each relay, which is 25 milliseconds. With three relays in the system, this adds 75 milliseconds to the overall discharge time. The digital components that control and drive the relays also have switching speeds associated with them, but when compared to operating time of the relays, they are fairly negligible. Thie brings the final max discharge time to be 27.525 seconds.

6.1.5 - Thermals and Mechanical Design

When it comes to predicting the thermal performance of the discharge resistors and the aluminum heatsink, the following calculations will act more as estimates as opposed to an in-depth analysis and simulation. Starting off with the potential temperature rise in the heatsink, the highest of the previously calculated average power for the discharge resistors can be used as a starting point for knowing how much energy the aluminum heatsink will absorb. With this it can be assumed that each of the 12 resistors in the discharge design will dissipate an average power of 10W over the course of 30 seconds. So the total energy across all of the resistors can be found via the formula below:

$$Q = P \cdot t = 120 \cdot 30 = 3600 \text{ J}$$

Its worth noting at this point that 3600 J of energy is much higher than the 1180 J of energy that was calculated to be stored in the capacitor at 1200V. This means that the initial assumption for this calculation will yield a very worst case scenario result. Assuming that all of this energy gets absorbed by the aluminum plate, then the temperature rise in the plate will be dependent on the plate's mass and its specific heat capacity. For the discharge design, the aluminum chassis shall be a 1 foot by 2 foot plate of 6061 aluminum with a thickness of 0.25 inches. For comparison, the standard heatsink size recommended by the resistor's data sheet is about 1 foot by 1 foot and 0.12 inches thick. After converting this sizing to metric units, the total volume of the selected plate will end up being 0.001179 cubic meters. With the density of 6061 aluminum being 2700 kilograms per cubic meter, the total mass of the plate is roughly 3.18 kilograms. Lastly, with the specific heat of 6061 aluminum being known to be about 900 Joules per kilogram degree Celsius, the following formula can be used to calculate the temperature rise:

$$\Delta T = \frac{Q}{mC} = \frac{3600}{(3.18)(900)} = 1.26\ ℃$$

So, at worst, the aluminum plate over the course of a 30 second discharge would only experience a little more than a 1 degree increase above ambient temperature. This is perfectly tolerable, however its worth noting once again that this assumes all the dissipated energy is going straight into the aluminum plate. In practicality, some of the energy will dissipate through the air, but a good portion will also dissipate through the body of the resistors. As a result, it is worth also looking at a worse case estimate of the temperature rise in the resistor bodies as well based on information presented in their datasheet. The first graph of importance shows how resistor surface temperature rise relates to power dissipation. For the HSC100 series of resistors, assuming the highest average power of 10W, there should only be an increase of around 10 °C per resistor. Considering that the power dissipation will end up being over the course 30 second pulse, the temperature rise calculated would also seem to be a worst-case scenario. Lastly, looking at the derating curve for these resistors shows that even at temperatures much higher than what was calculated, the power handling capabilities of the resistor should not be compromised.

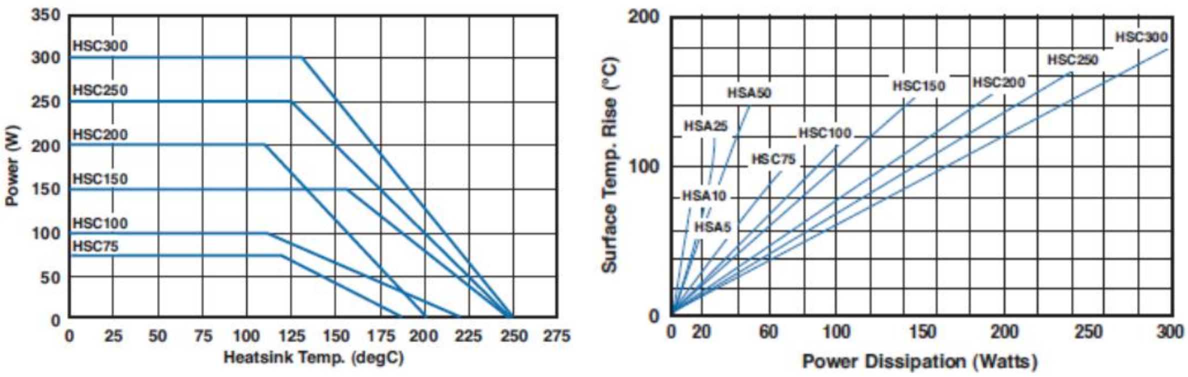


Figure 9: Power Derating and Surface Temperature Rise Curves of HSC100 Resistors

With the thermal considerations analyzed, the discharge design consisting of 12 HSC100 power resistors, three P115 contactors, and a 1ft by 2ft, 0.25in thick aluminum can be finalized. At 1200V in free air, the clearance distance for components is about 1 millimeter. The terminals of both the resistors and the contactors include the necessary insulation / insulating walls to cover the creepage distances at this voltage. The following 3D model shows a potential layout for the components when mounted on the chassis. Wire connections between the resistors and contactors are not shown.

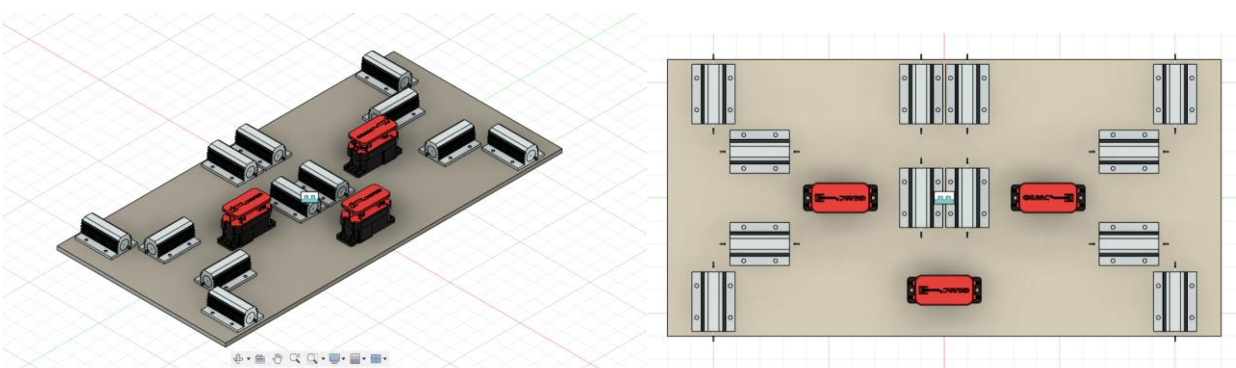


Figure 10: Isometric View and Top View of Discharge Chassis

6.1.6 - Test Bank Circuit

While not entirely within the scope of the project, a method of simulating the 1650uF capacitor at a low voltage for testing and validation purposes is required. As a result, a simple capacitor bank circuit was developed. The circuit includes three capacitors in parallel to create an equivalent capacitance of 1660uF, which is slightly higher than the expected 1650uF of the real capacitor bank, but acceptable for testing purposes. Screw terminals are included on both sides of the circuit. The left side allows for a power supply connection to charge the bank at 12 V, and the left side allows for connection to the discharge system. The included switch allows for disconnection of the charging side in order to isolate the charged capacitors for discharging. Its worth noting that with a 1000 ohm limiting resistor, the expected peak charging current at 12 V is only 12mA. The resistor itself is rated for 1W, and the capacitors are rated for 50V, which is more than enough for this application. The extra margin included allows for potentially higher voltage testing, say at 24V, if time allows for it.

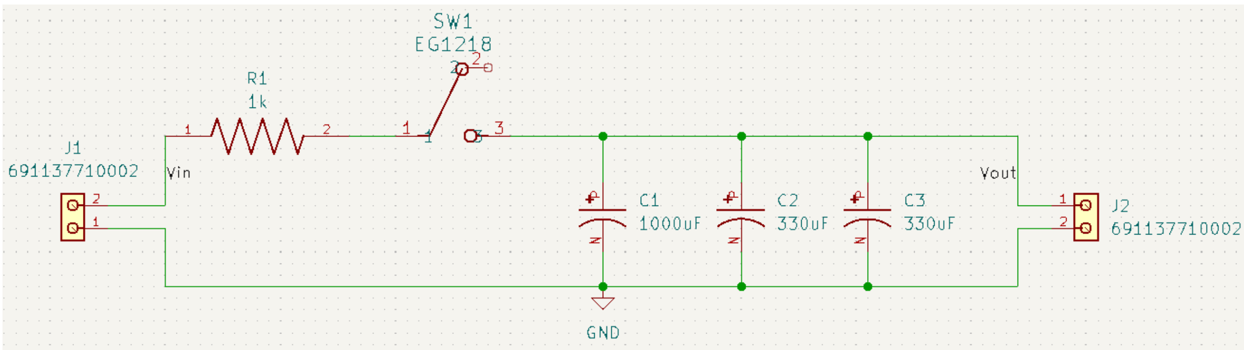


Figure 11: Test Bank Circuit

6.2 - Voltage Sensing and Isolation

One of the main goals of this project is that it is safe in its functionality. Part of the systems functionality depends on reading the voltage. This meant we had to incorporate some kind of analog-to-digital converter to read the voltage level of the capacitor into the MCU. While we are doing that we need to maintain safety in the system by isolating the high voltage side of the board from the low voltage side of the board. To do this, we selected an analog isolation amplifier that copies an analog signal and recreates it as a differential signal all the while keeping the two sides isolated.

That specific IC, the AMC3330QDWERQ1, only needs power from the low voltage side. It has an internal switching supply that transforms the DC on the low voltage side into DC on the high voltage side. Because this IC has a high internal switching frequency it is susceptible to noise and other radiative effects. The datasheet calls for a specific set and size of capacitors and ferrite beads to help minimize it. Sometimes capacitors are used in parallel on the same pin in order to properly counter different frequencies of signal. The data sheet also recommends a specific layout or organization of the capacitors. You want to get them as close to the IC as possible, so it specs out 0603 components and shows you where to connect them on the PCB.

Our analog isolation amplifier requires a bias current over the resistor it is measuring of 100 micro amps. Based on our estimated max volage of 1500V and that bias current, we got our total resistance needing to be around 15M ohm. This 15M ohm value was split between the top and the bottom to form the divider. It was then split again between resistors so that the voltage across each resistor is a manageable amount. Shown below is the high voltage portion of the schematic that shows the voltage divider, and some of the capacitors and ferrite beads used to help control noise on the IC.

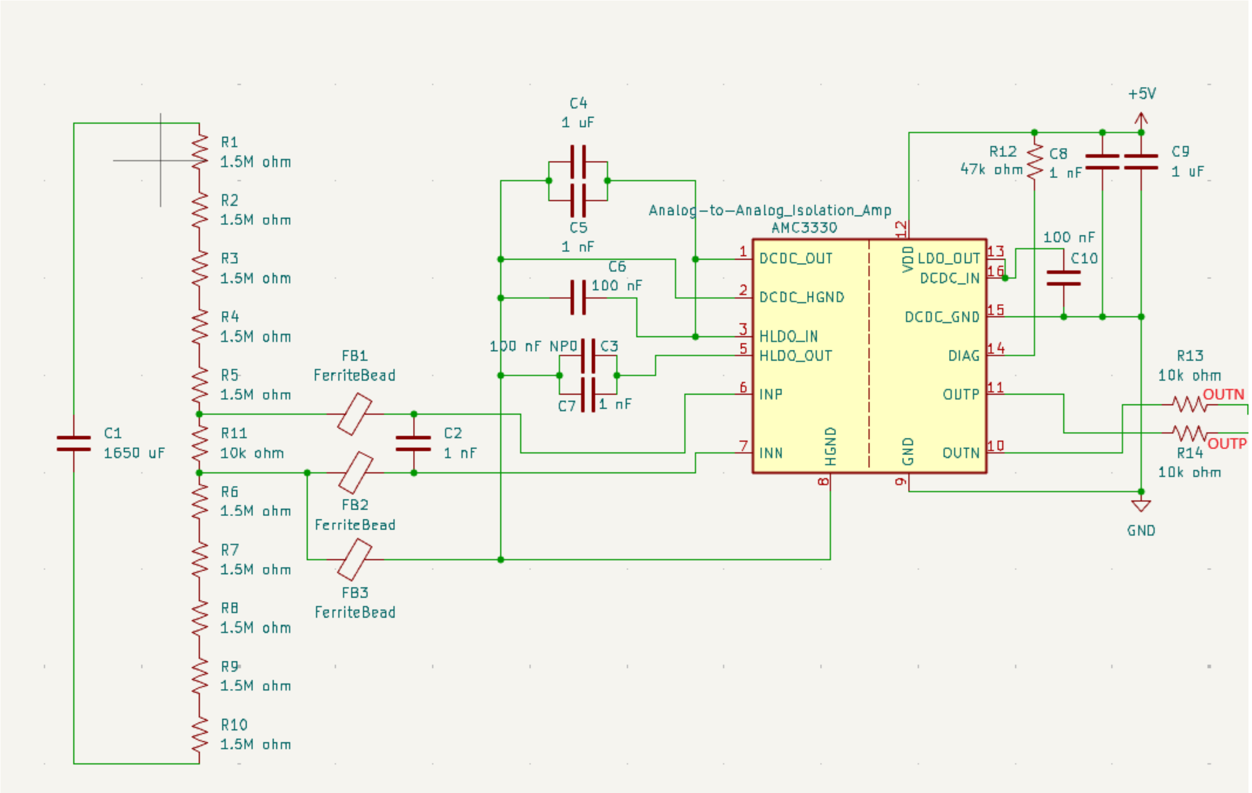


Figure 12: High Side of Isolation Amplifier

Moving to the low voltage side of the isolation amplifier, we are given a differential output centered around a common mode of 1.44V. While the STM32 does have an internal differential measurement mode, relying on this would make us lose resolution because the pins would only go up to 2.44V instead of the measurement range of 3.3V. This would equate to a roughly 40% loss in resolution or accuracy. So, according to the datasheet, we add a summing op amp that converts the differential signal into a single ended signal with a range between 0-3.3V matching the input voltage between -1 and 1V. The summing op amps gain is set based on the fact that we want it to match our 3.3V range. We also have to set a reference pin that is half of our range. This we set by a reference IC with a buffer amp to supply more current if needed. Below is a picture of the low voltage side of the isolation amplifier IC with the summing amplifier circuitry.

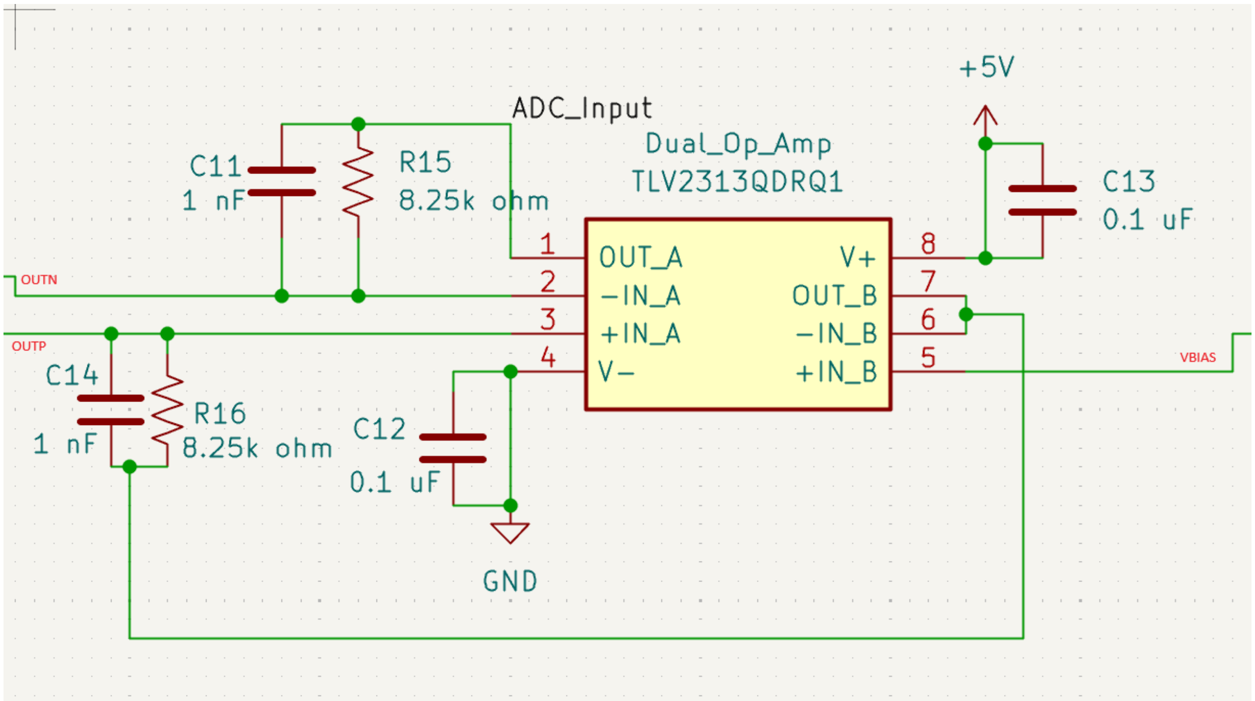


Figure 13: Low Side of Isolation Amplifier

To verify that this setup would work, the summing amplifier, I ran a series of tests simulating the op amp and the expected isolation amplifier differential outputs to see if the final ADC input mapped correctly to the 0-3.3V range. Below is one screenshot from the simulation and a table of the given inputs and expected outputs based on my design and testing.

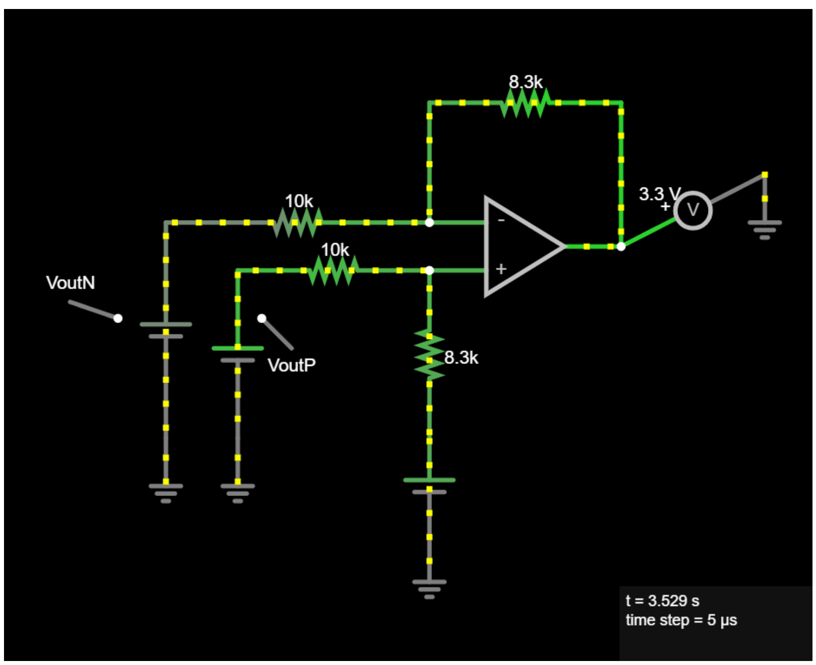


Figure 14: Summing Amp Simulation

Table 28: Summing Amp Simulation Results

VIN	VOUTP	VOUTN	Diff (P–N)	VADC
−1.00	0.44	2.44	−2.00	0.00
−0.50	0.94	1.94	−1.00	0.825
0.00	1.44	1.44	0.00	1.65
+0.50	1.94	0.94	+1.00	2.475
+1.00	2.44	0.44	+2.00	3.30

Going back to the differential to single ended up op conversion, because we need to source a bit of current for the 3.3/2 supply voltage, we need a buffer amp. Because the voltage of this pin determines how the summing amp works, we need an accurate source. To do this, as said before, a reference IC was picked that outputs both 3.3V and 1.65V reference levels. The 3.3V reference level we can plug back into our MCU for it's internal ADC. The 1.65V pin goes into the positive input of the B buffer amp. Below is a picture showing the reference IC.

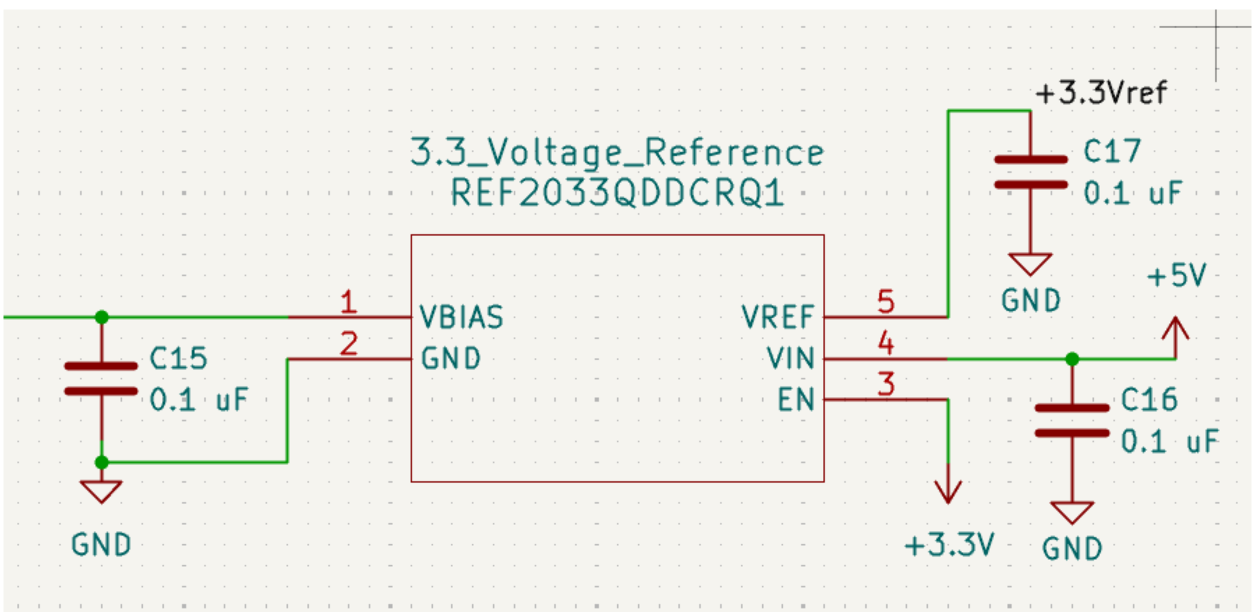


Figure 15: Voltage Reference Schematic

6.3 - Relay Driving and Isolation

Our relays/contactors are made to withstand 1500V. Contactors are internally and intrinsically isolated. There is a magnetic field that is used to pull a piece of metal shut to complete a connection. This separation and "connection" by the magnetic field makes the contactor isolated. The control pins of the contactors we selected run on 24V. The nominal hold current is 0.085A. This means to control the contactor and activate the resistor bank, we need to supply 0.085A of current to the contactor. The MCU pins do not operate at 24V or are able to sink enough current to activate the relays. In order to, we use nmos mosfets, controlled by the MCU GPIO pins to sink enough current for the relays. These mosfets have a resistor to limit current to the gate. They also have a pull down resistor to make sure they remain off unless the MCU is pulling the pin high. Below is a schematic showing the three different stage control relays and their connections.

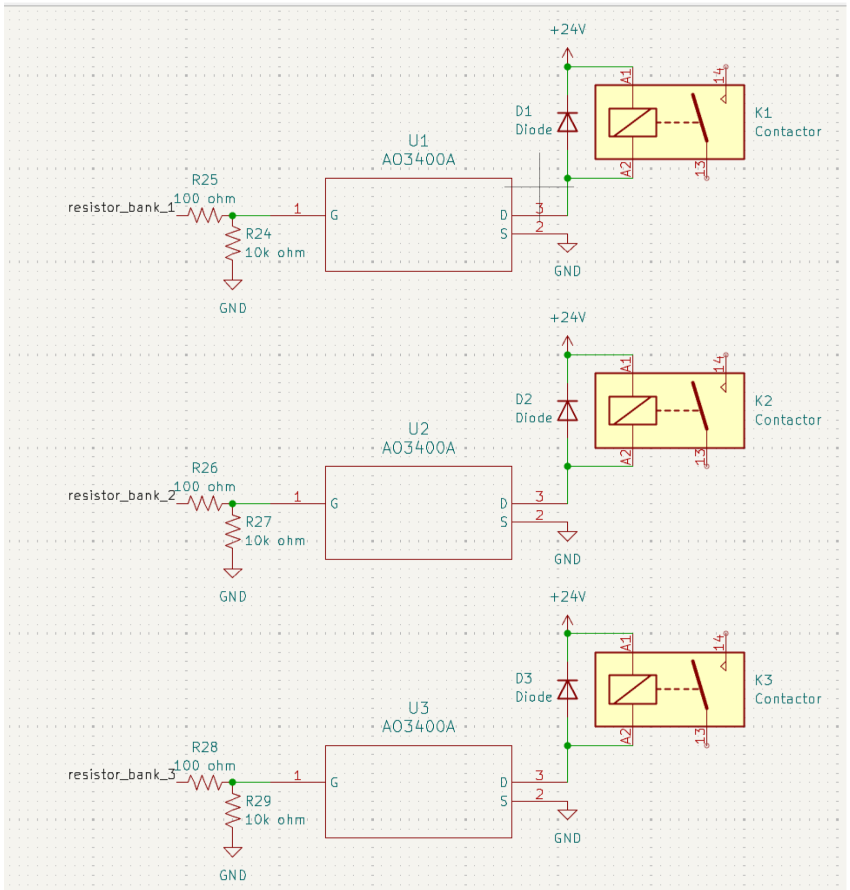


Figure 16: Relay Driving Schematic

6.4 - Temperature Sensing

Our temperature sensing comes from a combination of an RTD thermal probe and an RTD-to-Digital decoder IC made by analog devices. The RTD converter IC has a few different settings or variations you can choose from. Depending on the resistance of probe you select, you change the bias resistor value. For instance, the datasheet recommends using a 4.7k ohm resistor value for RTDs of 1000 ohms, and a 470 ohm resistor for RTDs of 100 ohms. Along with this, you wire the connects differently depending on what kind of connection you are using, and ho many wires it has. In a 2 wire RTD, you have to connect the FORCE+ and FORCE- pins directly to the RTDIN+ and RTDIN- ports. There are also plenty of places for decoupling and smoothing capacitors for stability. One important note about this IC is that it uses SPI for communications. SPI is a very fast protocol. Because of this, on select lines I choose pull up resistors to help the lines maintain signal integrity. I also added in line resistors of just 100 ohms to help prevent reflections when you get fast incoming signals. The pins to connect to the MCU are also labeled in the net list, but specific GPIO numbers on the MCU have not been chosen yet.

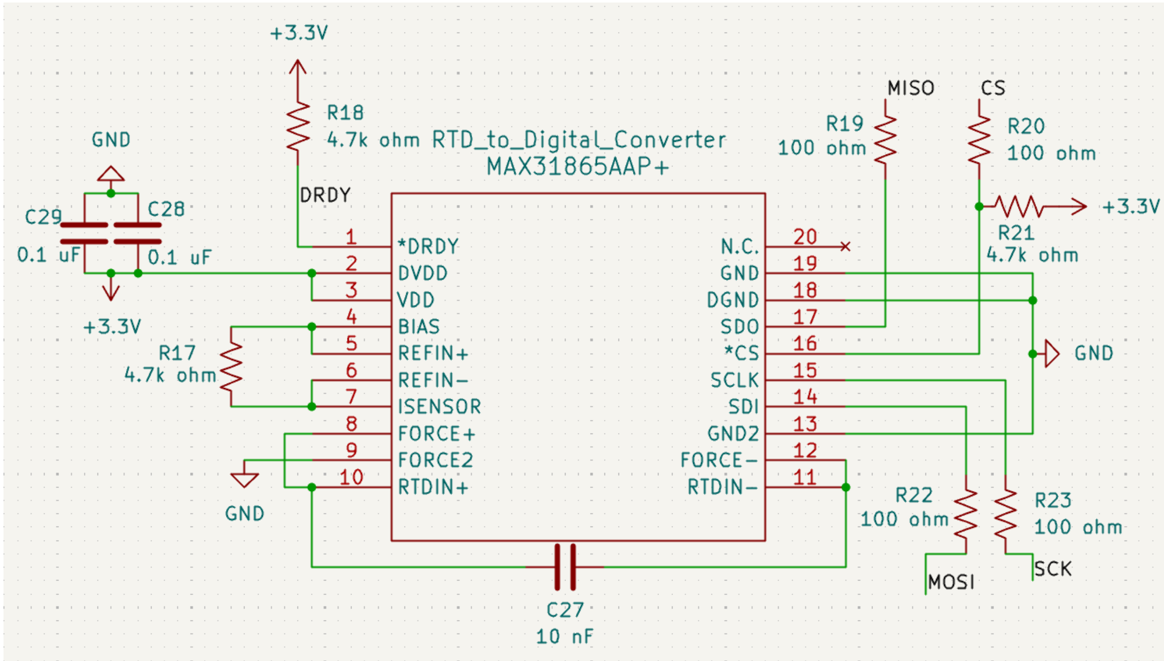


Figure 17: RTD to Digital Converter Schematic

6.5 - MCU

The MCU design and pin selection comes from the MCUs specific datasheet. Every ground and supply pin need to be connected. It was recommended to have decoupling/supply caps located near the individual supply pins on the MCU. The MCU also takes in the external reference voltage from earlier as well as the voltage to be read, the serial data from the RTD-to-Digital converter, the data from the buttons, and it outputs the data to the screen/relays/LEDs. Most of the GPIO pins on the MCU are configurable, but that needs to be looked at further. SPI may not be compatible on all GPIO pins, and only work with certain pins.

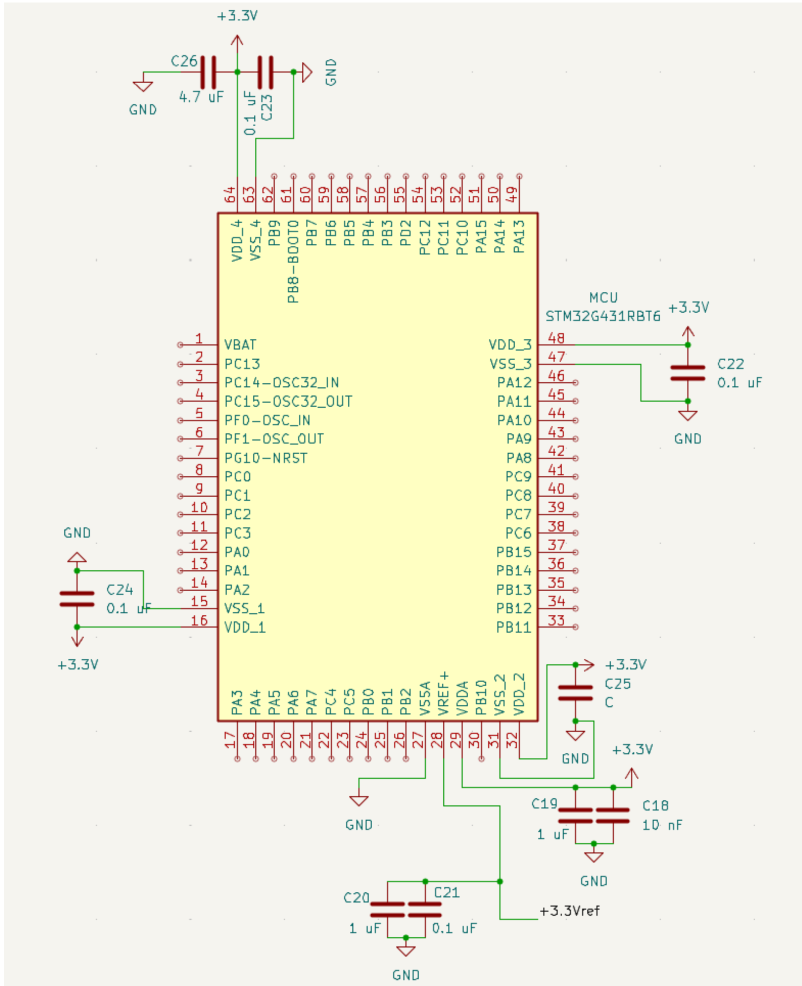


Figure 18: Current MCU Schematic

6.6 - Display and User Inputs

6.7 - External Power and Regulators

The power delivery system is best optimized to deliver power to all the major components in their respective subsystems. The system starts with a 24-volt external power adapter receiving current from the wall plug. This voltage is then fed into different 3.3 volt and 5-volt regulator for various design components. The 3.3-volt regulator feeds voltage into many of the software-based parts, such as the microcontroller, LED's and driver, along with the transistor. In contrast, the 5-volt regulator will mainly provide drive for the sensing-based components, such as the isolation and operational amplifiers. Both the regulators are supported by suitable input and output capacitors, along with a functional diode and inductor placed according to the data sheet standards. Overall, this power structure with two efficient regulators provides an effective level of power to all the major components of the capacitor discharge system.

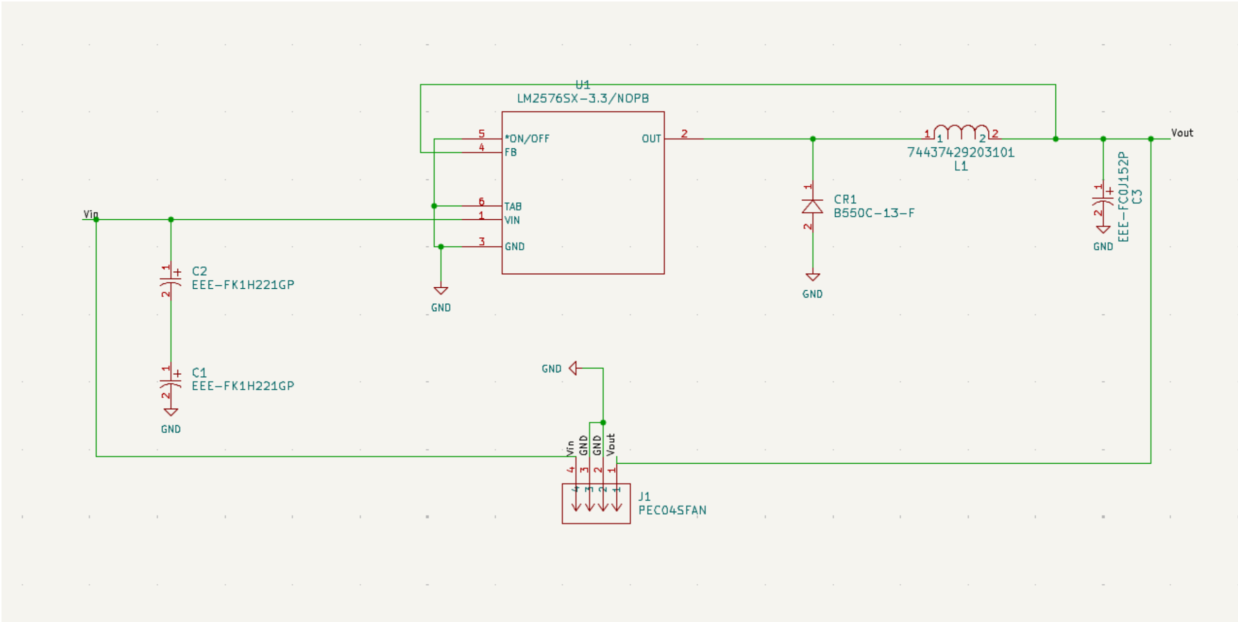


Figure 19: Schematic of the LM 2576 3.3-volt regulator

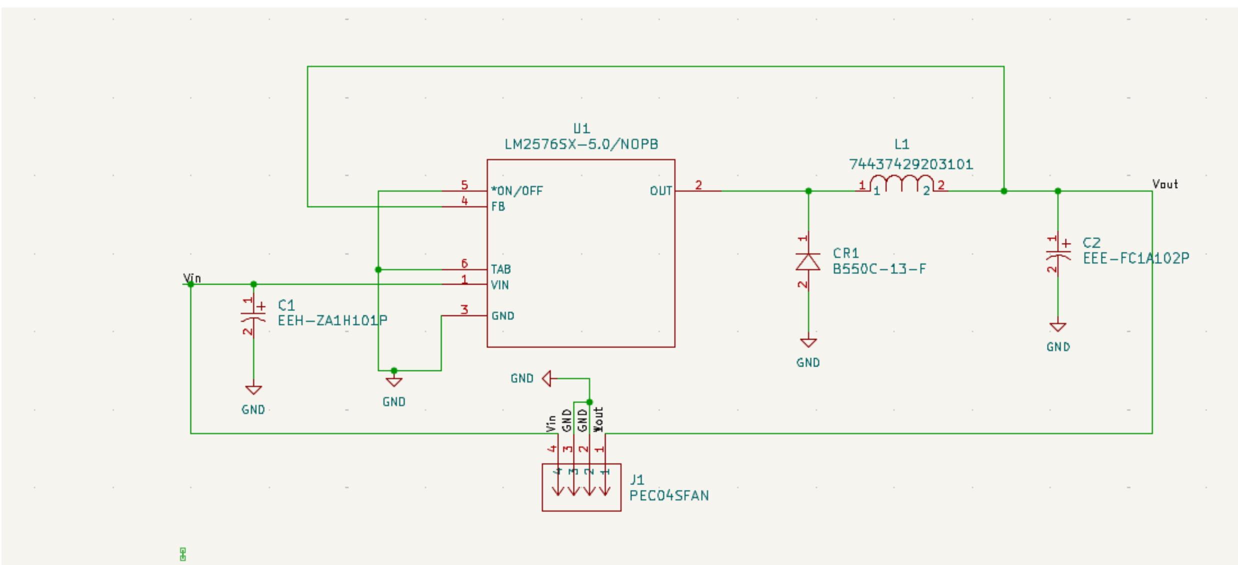


Figure 20: Schematic of the LM 2576 5 volt regulator

Chapter 7: Software Design

For this project, the software will be running on a primary microcontroller which will receive inputs from the scaled-down voltage difference across the discharge network, the temperature of the heatsink attached to the resistors, and the user of the device. In turn, it will accordingly set the outputs of the relays to control the rate of discharge, along with controlling LEDs and a display to communicate information about its state to the user.

Like many other embedded systems, this project's software needs both perform background tasks such as sending data over synchronous communication protocols (i.e. SPI) or polling data from input sources. However, it also needs to be responsive to inputs from the user and changes detected by its built-in ADC. On general-purpose computing systems this balance is maintained by the operating system, but most embedded hardware lacks the resource overhead to store such a program. A common solution is to implement a real-time operating system (RTOS) which are specifically designed to adhere to strict timing of background tasks while also supporting customizable interrupt handling for inconsistent but important events such as user input. The STM32 microcontroller we selected for this project is built around an ARM Cortex-M4 microprocessor and is built around the Thread and Handler paradigm, which splits the program into threads that are "used to execute application software" with a single handler which is responsible for managing the priority of up to two-hundred and forty interrupts and any exceptions that occur during runtime [83]. As such, the software can be implemented as a state machine while also remaining responsive to input from the user.

7.1 - User Interface

This project's user interface consists of a display, three buttons, and a variety of colored indicator LEDs to facilitate communication with the user. The primary method the system will use to communicate with the user shall be on the LCD using a graphical user interface, with the indicator LEDs intended to provide information about whether the device is powered, which stages are currently active, and whether the discharge sequence has brought the capacitors below the safe voltage threshold. To allow simple, intuitive and responsive controls, the system will use a primary selector button with two secondary inputs representing the up and down directions.

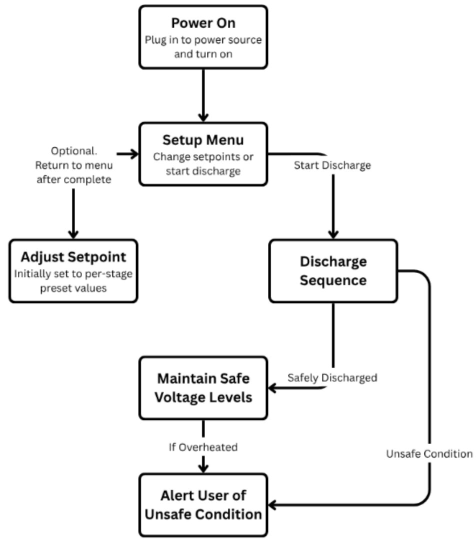


Figure 21: User Use Case Diagram

7.1.1 - Configuration Menu

When the user is in the configuration menu, the program should display four options on the menu: reset the voltage setpoints to their predefined default values; adjust the voltage threshold setpoint where the second discharge stage will activate; adjust the voltage threshold setpoint where the third discharge stage will activate; and start the discharge sequence with the current values as the setpoints. Because the first stage will activate at the start of the discharge sequence, and the project requirements specified $10V$ as the safety threshold, there are no setpoints to define at the start of the first stage nor the end of the third stage. Below is a figure to approximate the configuration menu's appearance on the LCD when implemented, with the Reset to Defaults option selected and the threshold stages one and two modified to start at a custom voltage.

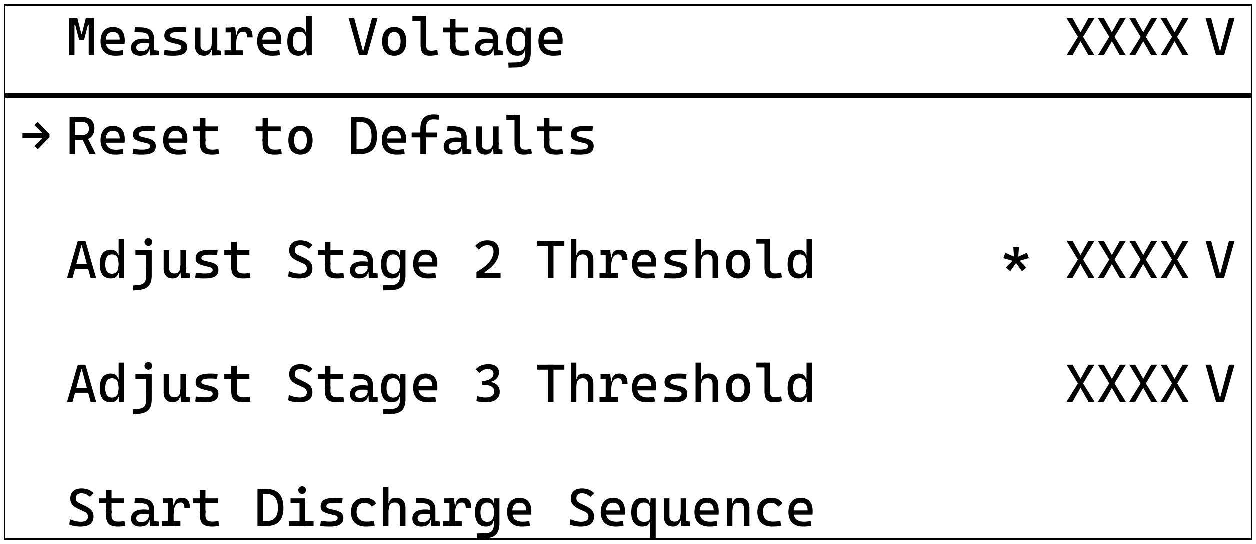


Figure 22: Wireframe Diagram of Configuration Menu

7.1.2 - Setpoint Adjustment

When the selected menu option is one of the voltage threshold setpoints, the cursor will be moved from the left margin and split into two arrows, or a hyphen to indicate if the value cannot be adjusted further in the given direction.

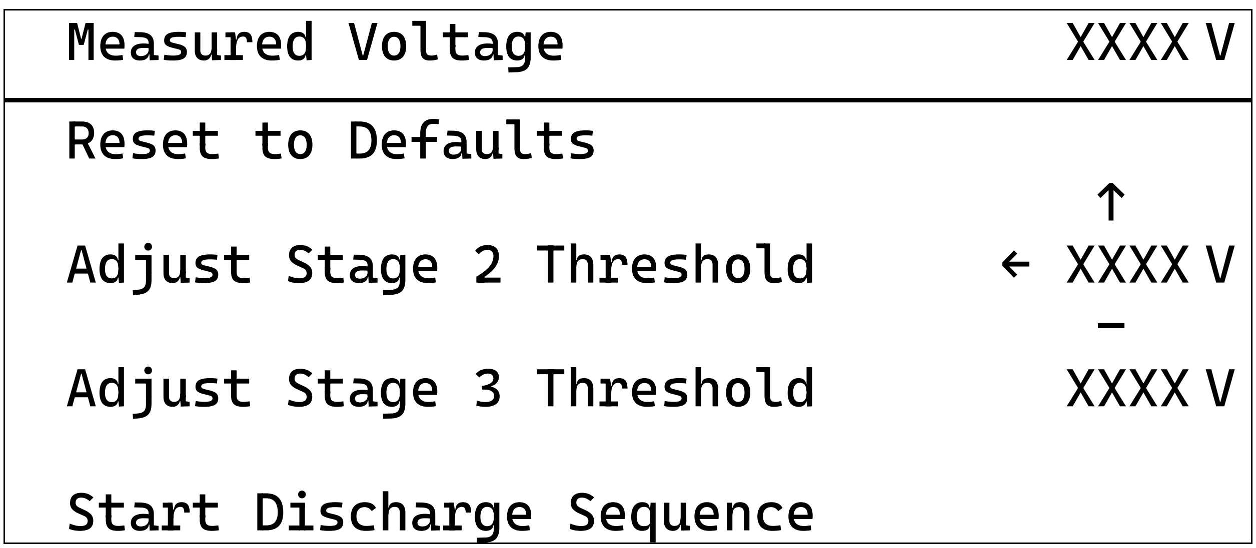


Figure 23: Wireframe Diagram of Setpoint Adjustment

7.1.3 - Discharge Sequence

The discharge sequence will have a single screen that displays important information to the user, such as the current stage, voltage difference across the discharge network, time elapsed since the start of the discharge sequence, real-time temperature of the heatsink for the resistor network, and a graph of the capacitor bank over time. Additionally, the user can use the select button to cancel the discharge in case they need to stop the sequence. Below is a wireframe mockup of the contents displayed during the discharge sequence.

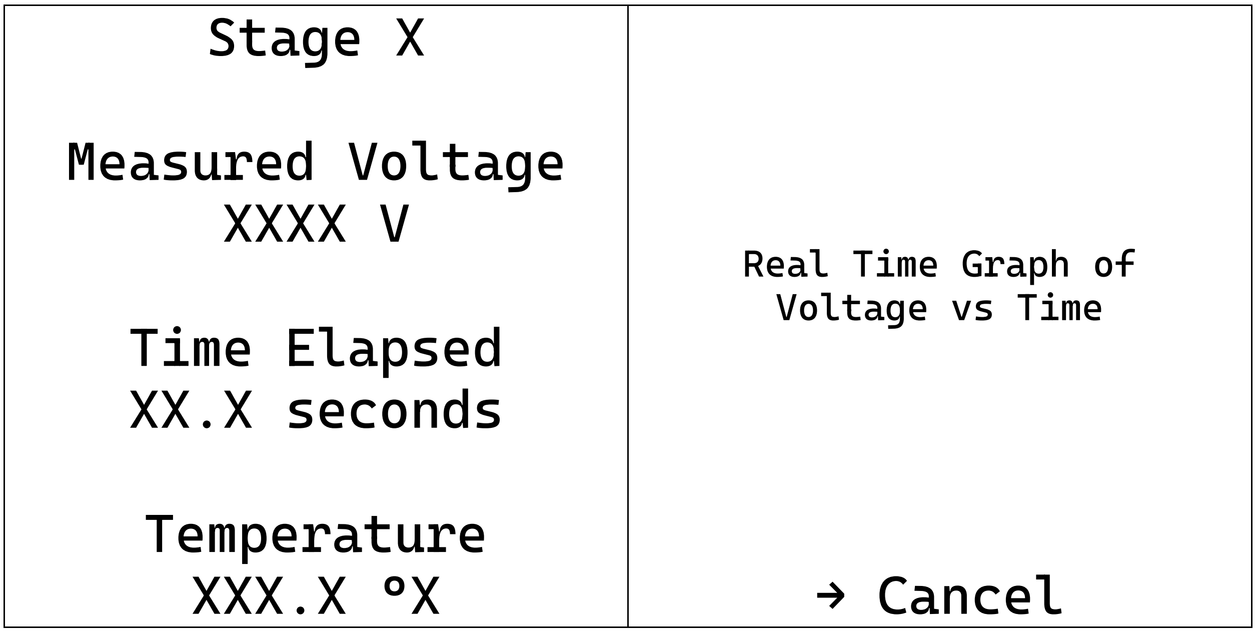


Figure 24: Wireframe Diagram of Discharge Sequence UI

7.1.4 - Completion Screens

The discharge sequence can automatically enter the two following screens, the first when the discharge sequence is completed safely and the remaining voltage does not exceed $10V$ across the discharge network. This screen is very similar to the interface for the discharge sequence but instead will indicate to the user that the discharge sequence has been completed. It will keep the graph of voltage over time, but it will no longer be real time, instead it will be generated from the data collected during the discharge phase. Readouts of the measured voltage and heatsink temperature will still be updated in real time, but the time elapsed will also be stopped once the voltage is under the safety threshold.

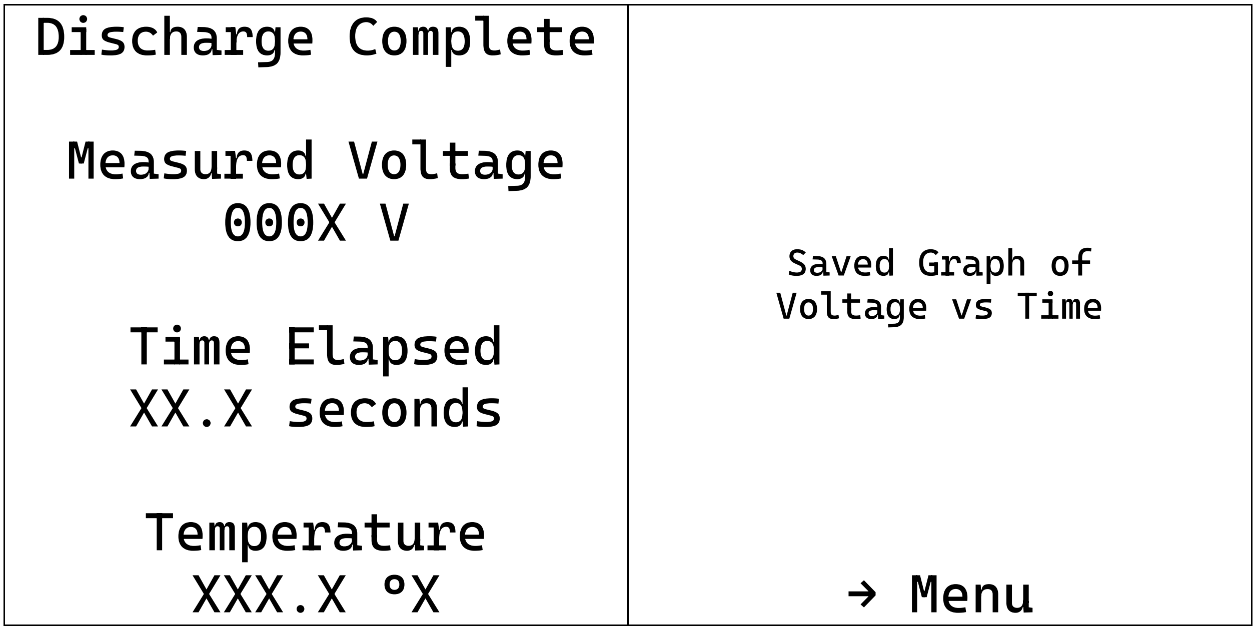


Figure 25: Wireframe Diagram of Safe Condition Screen

The other automatic end of the discharge phase occurs when the microcontroller detects an unsafe condition, such as the voltage not decreasing after relays have been signaled to close, an unexpectedly rapid drop of the voltage, or the heatsink temperature exceeding safe values. This screen will display a short list of possible causes along with a lookup code for further information. The user can then use the select button to dismiss the warning and return to the configuration phase.

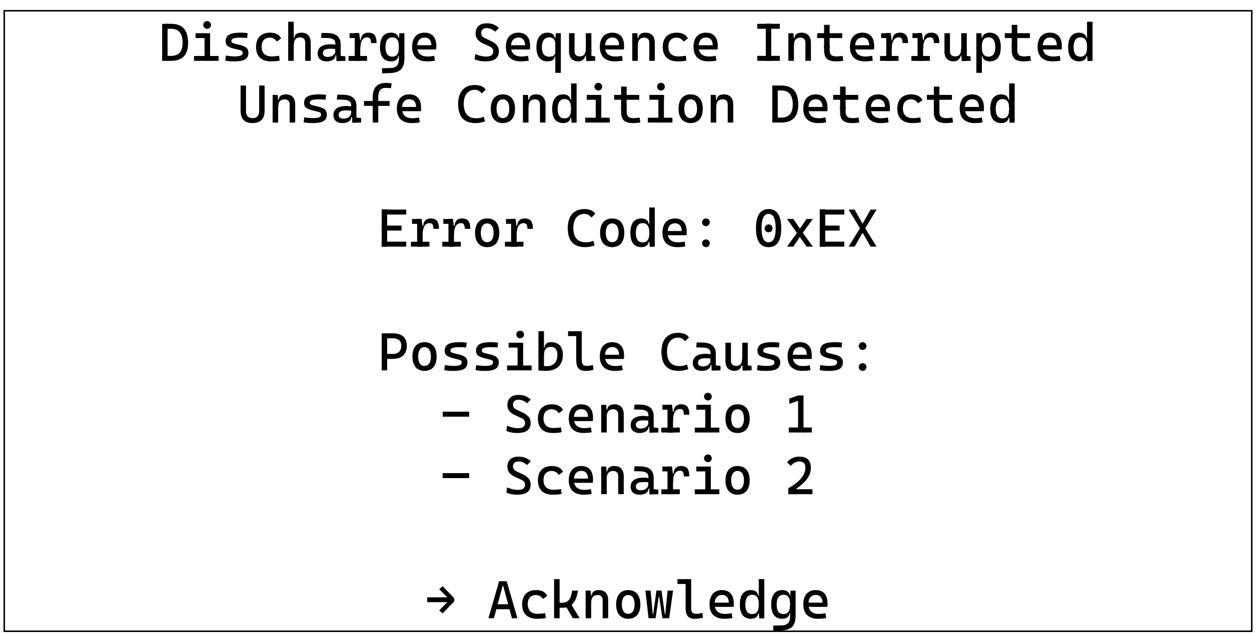


Figure 26: Wireframe Diagram of Unsafe Condition Screen

7.1.5 - Indicator LEDs

Each of the five indicator LEDs will have a unique color that represents the status of the current state of the system. For the sake of simplicity, none of the indicator LEDs should have blinking patterns, instead they will represent a true or false condition of their respective values. Per project requirements, three of the LEDs indicate which of the discharge stages are active, while a fourth will be activated when the system has been safely discharged. Additionally, there will be a fifth LED to indicate the system is powered and properly configured. As such, the fifth LED should be connected to a general-purpose output pin rather than at the voltage source of the microcontroller. This will ensure that the LED will not be turned on until the system has completed its I/O configuration.

Table 29: Indicator LED Definitions

Description	**Color**	**Active Condition**
1st Stage	Red	The relay connected to the 1st discharge subnetwork is active.
2nd Stage	Yellow	The relay connected to the 2nd discharge subnetwork is active.
3rd Stage	White	The relay connected to the 3rd discharge subnetwork is active.
Complete	Green	Safe completion with $10V$ or less across the discharge circuit.
Power	Blue	Device is powered on and microcontroller is running the program.

7.2 - State Flow

From a high-level overview, there are three main states which the program will need to cycle through; the configuration phase, where the user connects the device to the bank of capacitors and tweaks the voltage threshold setpoints if necessary; the discharge phase, where the device will go through the configured sequence of discharge stage activations, activating each by comparing the observed value of the scaled-down voltage against the setpoints provided; and finally the completion phase, which holds all relays in the discharge network closed, to ensure the connected capacitors remain at a safe voltage, until the device is either powered off or reset to the configuration phase.

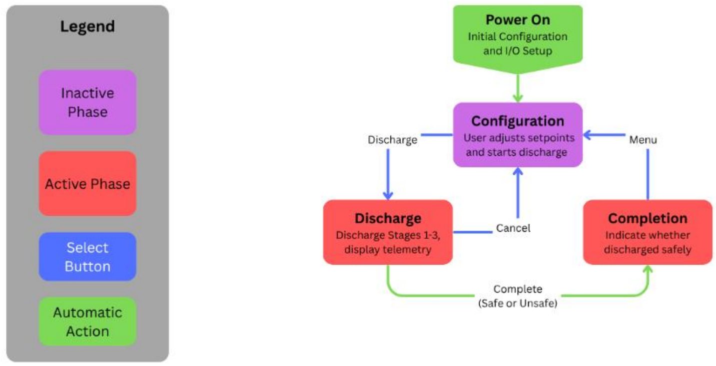


Figure 27: Overview of Software Phases

Each of the three main phases have their own subroutines, such as the three distinct discharge stages defined by the project requirements that comprise the discharge phase. Some of these states are progressed through automatically, including the discharge stages, while others must receive user input to enter the stage, like when adjusting a voltage threshold setpoint or when switching between the configuration phase and first discharge stage.

7.2.1 - Power On

Once the microcontroller is powered on, the program will start by configuring the internal clocks, general-purpose I/O pull-up and pull-down resistors, mapping relevant pins as input versus output, and other relevant actions to ensure the system is able to take input from and communicate with the user. After the initial setup is complete, the system will enter the Configuration Phase with the default voltage thresholds as the initial values.

7.2.2 - Configuration Phase

While in the configuration phase, the program will display the user with a menu presenting the stored voltage thresholds for each discharge stage, along with the option to adjust the values (within a safe limit) to change the profile of the sequence. Additionally, the user will have the option to reset any changes made to the default values. Finally, when the user is ready, they can start the discharge sequence. Even though the user can adjust the setpoints, it is not required for them to do so before starting the discharge, as the program should be initialized with default values. None of the relays should be active during the configuration phase, and the program will ensure the corresponding output pins are off when in any state within the configuration phase.

Figure 28: Configuration State Diagram

7.2.3 - Discharge Phase

Once the user selects the option to start the discharge sequence, the system will enter the discharge phase. This will start by closing the relay connected to the first phase of the discharge network, corresponding to the highest equivalent resistance. After which, the program will remain in the first discharge stage until the measured voltage is below the voltage threshold for the second stage to start. Then, the microcontroller will activate the second relay in the discharge network while holding the first relay to enter the second discharge stage.

Like with the first stage, the sampled voltage will be compared to the threshold setpoint, which will be activated when it drops below the value provided by the user. While the first two relays continue to hold their discharge subnetworks closed, the third relay will then be activated to start the third and final stage of the discharge sequence. Finally, when the measurement indicates the remaining charge in the capacitors is less than ten volts, the discharge sequence is considered complete and will continue into the safe state of the completion phase of the program.

At any point during the discharge stage, if the microcontroller determines that there is an unsafe condition within the discharge network, it will turn off all the relays and enter the unsafe state of the completion phase to prevent damage to the system or harm to the user. A few examples of detected conditions that would cause the system to stop the discharge would include: if the measured voltage is less than ten volts when the discharge sequence is activated, which could indicate that the capacitor is not fully connected or the analog-analog converter may be damaged; or if the measured voltage remains constant while the discharge stage is active, which could indicate that the relay or another connection within the subnetwork is damaged; or a sudden drop in voltage, which could indicate the connectors for the capacitor were disconnected, or a possible ground fault occurring.

During the discharge phase, the program will use both the display and several indicator LEDs to display the current discharge stage to the user. The indicator LEDs will be tied to the signals for their corresponding relay and will light up to indicate that the discharge stage has been activated. At the same time, readings from the voltage and temperature sensors will be displayed along with other helpful information on the display so the user can have more information that just which stages are activated at any given time. Additionally, the user can use the select button to cancel the discharge at any of the three stages.

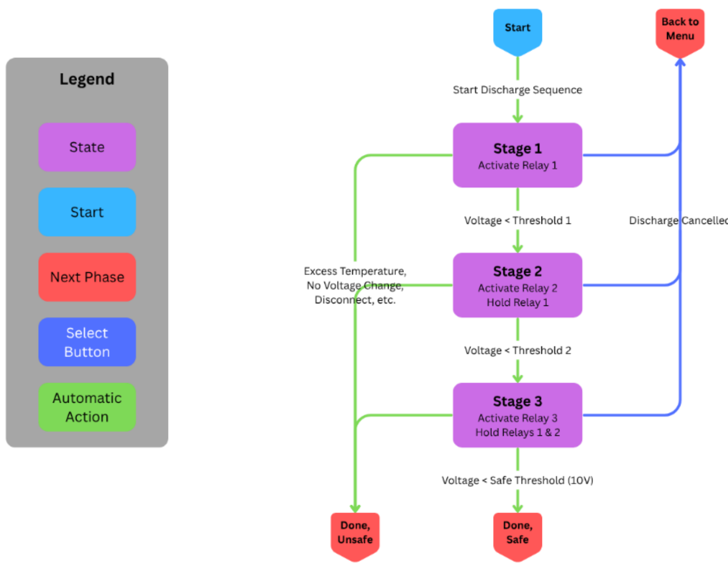


Figure 29: Discharge State Diagram

7.2.4 - Completion Phase

As mentioned in the discussion on the discharge phase, the completion phase has two distinct states: safe and unsafe. The safe state will indicate to the user that the discharge sequence has been safely completed and that the remaining charge in the capacitors is less than ten volts between the terminals. During the safe state, all relays should be held closed to ensure the capacitors will be fully discharged while the device is connected. When the user presses the select button, the relays will be reset, and the program will return to the configuration phase so the device can be used to discharge another bank of capacitors.

On the other hand, the unsafe state will stop powering all relays that were previously activated to ensure all subnetworks in the discharge circuit remain open until the issue is resolved. While the program is in this state, it will display a prominent warning on the display and require the user to acknowledge the cause of the unsafe state before returning to the configuration phase.

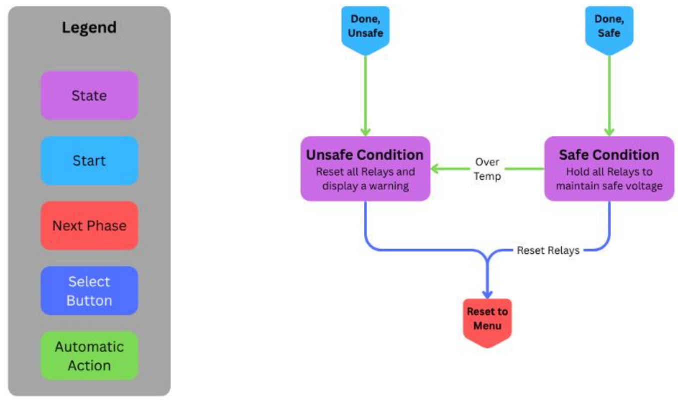


Figure 30: Completion State Diagram

7.3 - Background Tasks

While changes in the program's state will be controlled using interrupts generated by user input or built-in timers, there are a few subroutines that need to be handled on regular intervals to ensure the program receives the latest data from its sensors and communicates that data back to the user. These background tasks will include measuring the scaled voltage to determine the remaining voltage across the capacitor, communicating with other devices using SPI, and the proper handling of any interruptions or exceptions that occur during the program's runtime.

7.3.1 - Voltage Reading

To determine the capacitor bank's voltage at any given time, the microcontroller needs to continuously sample the scaled analog input provided by the sensing circuitry. This is often performed using timer-generated interrupt-based polling. While this is a viable option in many scenarios including this project, there are a few analog integration features provided by the STM32 microcontroller that simplify this process.

One of these features is that the ADC operates on a different clock signal than the microcontroller's system clock, allowing the sampling rate to be independent of the microcontroller. Another useful feature provided by the STM32G4 family of microcontrollers is the ability to write ADC measurements directly to a specified address using the built-in direct memory access controller. This removes the requirement of a dedicated timer and interrupts in favor of having the latest measurement already stored in a volatile global variable, with only the slight cost of a larger initial setup phase.

7.3.1.1 Hardware Oversampling

The selected STM32 microcontroller includes an optional feature allowing the built-in ADC to read at up to a 16-bit resolution with the trade-off of a lower polling rate compared to the 12-bit default. This result is achieved by passing multiple samples of data through the digital signal processing module and applying a low-pass filter to reduce the noisiness of the measurement. Use of this feature can reduce the maximum sampling frequency from $4M$ Samples per second down to $156k$ Samples per second, depending on the configured amount of oversampling [84].

However, even the lowest effective sampling rate when using maximum oversampling $(156kHz)$ is well over the $50Hz$ rate for voltage sampling identified in the project's specifications. Besides the reduced variance in voltage readings that reduce the chance of noise-induced early relay activation, utilizing this feature also provides the benefit of higher resolution readings, allowing the LSB to represent 0.0458 Volts at 16-bit readings compared to 0.732 Volts at the 12-bit LSB.

7.3.2 - Communication

Many embedded systems utilize communication protocols to connect multiple devices responsible for specialized duties, such as the RTD for temperature sensing and display for user interaction in this project. While there are many common protocols for varying devices and applications, the two submodules managed by the microcontroller will both communicate using SPI, which requires synchronization between devices.

The SPI protocol allows for both bus and daisy chain configurations in systems that rely on a large number of devices to be interconnected, but because the microcontroller we selected has an abundance of SPI-capable GPIO pins, it is not necessary for the RTD and display to share a connection as there are enough pins for each device to receive their own dedicated connection.

7.3.2.1 Display Controller by SPI

The selected display is equipped with its own microcontroller that can handle a vast majority of the graphics-related computation, allowing the main microcontroller to preserve its resources for other tasks that may require a large amount of processing power or quick responses. While the traditional option of writing a frame buffer is still available, a major consideration during the component selection for the display was its ability to receive a library of commands over SPI [85].

When the program's state is changed, program should command the display to present the user with the relevant information discussed in the User Interface section. This would include issuing a command to reset the contents on screen, followed by state-specific commands to present the user with data or control options. When the program is in the discharge phase the display should provide a secondary indicator of which stage is active. Additionally, the screen should have other helpful information such as the voltage measurement, time elapsed since the start of the discharge sequence, a graph of voltage over time, etc. Finally, during the completion phase, the display should indicate whether the capacitors were discharged to a safe voltage or alert the user of the cause if there is an unsafe condition.

To ensure the display updates on a regular interval, one of the microcontroller's internal timers should be dedicated to generating an interruption that will run a subroutine to update the display with the latest measured data. However, because the refresh rate is very low compared to the microcontroller's main clock, nor does it require a high level of precision, it can be configured to run on the STM32's built-in low-speed $(32\ kHz)$ and lowest precision $(\pm 5\%)$ capacitor oscillator [86]. Another method that can improve the display's response time is triggering the display interrupt after each state change to ensure the information provided to the user is up to date.

7.3.2.2 RTD Polling by SPI

For the program to receive the latest temperature data from the discharge network heatsink, another timer needs to be dedicated to polling the RTD using SPI.

7.3.3 - Push Button Interrupts

Interruption-based user input handling is one of the most common ways to balance responsiveness with low resource overheads, especially in embedded systems. As such, the program running on the microcontroller will be implemented to use two separate handlers for when the user interacts with the push buttons to control the system. The select button will have its own dedicated interrupt handler, as it will be the primary method for the user to initiate a state change. The secondary interrupt handler is for both directional inputs, as having both the up and down button pressed at the same time should be ignored.

When any button is pressed, the program will add a short duration $(\sim 50ms)$ a dedicated timer linked to the built-in crystal oscillator. This first timer will indicate the button is in its debounce period, where measuring the push button input will yield inconsistent results. Once this timer expires, it will generate another interrupt to handle the input. If the button pressed is the select button, the program will always advance to its next user input state. However, if the input is one of the directional buttons, the program will first check that it is in the configuration phase.

When in the configuration menu, the selected menu item or voltage threshold will be updated to the next allowed value in the input direction. For example, pressing up while a threshold was selected would increase the saved threshold value to the next increment or set it to the maximum allowed value, whichever is lesser. After the update is processed, a longer timer $(\sim 500ms)$ will be scheduled, and if the button is still depressed when it expires, the program will register the action as a button hold, and in the previous example, would start increasing the value by larger increments, limited to the maximum allowed value. If the current state is not in the configuration phase, the directional input will be ignored.

Chapter 10: Administrative Content

10.1 - Project Milestones

These milestones are meant to keep the group on track and enable adequate preparation for the numerous tasks that need to be completed in both Senior Design 1 and 2. These include tasks related to documentation, design, manufacturing, and testing.

Table 30: Senior Design 1 Project Documentation Milestones

Start Date	End Date	Item
8/18/25	8/22/25	Project idea and group formation
8/25/25	9/5/25	Divide and Conquer Document
9/8/25	9/12/25	Divide and conquer revisions
9/15/25	10/31/25	80-page milestone
10/20/25	11/7/25	Overall revision of report
10/20/25	11/18/25	120-page milestone (these two items can be done simultaneously)

Table 31: Senior Design 1 Project Design Milestones

Start Date	End Date	Item
9/15/2025	10/1/2025	Research and System definition
10/3/25	10/19/25	Individual System design and component selection
10/20/25	10/31/25	Schematic Development and Component Ordering
11/1/25	11/17/25	Breadboard experimentation and PCB Design
11/17/25	11/25/25	Finalization of PCB design/demo video

Table 32: Senior Design 2 Project Milestones

Start Date	End Date	Item
12/2/25	12/17/25	PCB ordering
01/13/26	02/01/26	PCB prototype design
01/13/26	02/01/26	Integrate and complete software code
02/01/26	02/15/26	PCB assembly/System testing
02/15/26	03/01/26	Buffer for solutions (If things go wrong, a period to account for assembly of things or to reorder parts is essential)
03/01/26	03/20/26	PCB assembly part 2 and testing of prototype
03/23/26	04/14/26	Working prototype
01/13/26	04/20/26	Final Documentation (secondary activity throughout semester)
01/13/26	04/20/26	Calculations for high voltage design, along with comparisons between high level voltage and low level, and high- level voltage BOM

10.2 - Work Distribution

To meet the specified project milestones under the limited amount of time present within the senior design course, an effective distribution of major design tasks is required. As the features and functionalities of the project evolved, particular subsystems also grew and became clearer. These subsystems eventually became the main way in which work was divided between team members. To avoid team members from becoming too isolated, however, a primary and secondary person was assigned to each subsystem. This provides one form of assistance and collaboration in the design process. Additionally, the entire team meets twice a week to update each other on progress, struggles, and potential concerns/conflicts with the design process. This provides a second form of collaboration between team members.

Table 33: Work Distribution Table

Subsystem	Primary	Secondary	Responsibilities
Sensing and Isolation	Kealan Frost	Will Serface	Sensor research and selections
			Sensor circuit designs
			Sensor, MCU, and relay integration
			Isolation from high voltage
Discharge	Javier Lopez-Marrero	Kealan Frost	High power resistor research and selection
			Relay research and selection
			Discharge network design
			Relay and MCU integration
Computing	Will Serface	Zeeshan Asif	MCU research and selection
			Display and I/O research and selection
			Embedded Programming
Power	Zeeshan Asif	Javier Lopez-Marrero	External power research and selection
			Regulator designs
			Capacitor charging circuit design

The only items not covered in the above distribution are the PCB design and general device testing. Since both of these items bring every subsystem together, the team will work as one to complete these tasks together. Cloud based PCB design software such as EAGLE makes collaboration between team members possible within a shareable project file. Additionally, group lab sessions will be held to adequately test and troubleshoot the system.

10.3 - Project Budget and Bill of Materials

This project is sponsored by NextEra Energy. While an exact dollar budget has not yet been provided, we can reasonably estimate the cost of the project and the necessary budget. To accomplish this, we have listed an example BOM containing general parts necessary for a robust design, meeting all required specifications while being mindful of the costs. This involved selecting typical prices for expected components and accounting for any contingencies such as design updates, issues, component failures, and price changes by leaving some flexibility in the estimated budget. This should ensure that, even now, we have a realistic and reliable estimate of the total budget needed to complete this project despite not having yet undergone a component selection process.

Table 34: Prototype BOM

Component	Model	Unit Price	Quantity	Total
Microcontroller	STM32G431RBT6	$ 5.60	1	$ 5.60
Display	NHD-5.0-800480FT-CTXL-T	$ 95.77	1	$ 95.77
Display Header	SBH11-PBPC-D10-ST-BK	$ 0.41	1	$ 0.41
Buttons	MX1A-E1NW Cherry MX Blue Pushbutton Switch	$ 1.25	3	$ 3.75
LEDs	CHANZON 0805 SMD LED	$ 6.99	1	$ 6.99
3.3V Regulator	LM2576SX-3.3/NOPB	$ 3.86	1	$ 3.86
5V Regulator	LM2576SX-5.0/NOPB	$ 3.86	1	$ 3.86
Power Adapter	Desktop AC Power Adapter - 24 VDC Switching Power Supply	$ 49.99	1	$ 49.99
Discharge Resistors	TE HSC100 Series	$ 17.83	12	$ 213.96
Relays	P115 CDA	$ 108.36	3	$ 325.08
High Voltage Wire	ROWE High Voltage Lead Wire, 22AWG, 5kV, 25ft	$ 20.66	1	$ 20.66
Aluminum Chassis	McMaster Carr, 1ft by 2ft, 1/4 Inch Thick, 6061 Aluminum	$ 58.10	1	$ 58.10
M3 Ring Terminals	A106341-ND	$ 0.39	12	$ 4.68
M4 Ring Terminals	BU-190540054	$ 0.21	12	$ 2.52
RTD	TT4-PT1000B-T125-M5-500	$ 7.15	1	$ 7.15
RTD to Digital Converter	MAX31865AAP+	$ 7.84	1	$ 7.84
Relay Flyback Diode	P6KE47CA-E3/54	$ 0.56	3	$ 1.68
NMOS Transistor	AO3400A	$ 0.46	3	$ 1.38
Screw Terminals	691137710002	$ 0.36	5	$ 1.80
Voltage Divider Resistors	TNPV12101M50BEEN	$ 1.98	10	$ 19.80
Isolation Amplifier IC	AMC3330QDWERQ1	$ 7.89	1	$ 7.89
Dual Op Amp IC	TLV2313QDRQ1	$ 1.14	1	$ 1.14
Voltage Reference IC	REF2033QDDCRQ1	$ 3.72	1	$ 3.72
Control PCB	-	$ 200.00	1	$ 200.00
Tax, Tarrif, and Shipping (15%)	-	-	-	$ 157.00
Margin (30%)	-	-	-	$ 360.00
			Total:	$ 1,564.63

Based on the table above, our estimate as to what parts may go into this project, we are coming up with an estimate of $1,564.63. This includes an additional 15% margin added to the cost to cover potential taxes, tariffs, and shipping. Another 30% is also added on top of that to account for any extra materials needed, revisions, part failures, or change of scope/features/functionality.

Appendix A: References

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Appendix B: Copyright Permissions

Appendix C: Data Sheets

Appendix D: Software Code

Appendix E: AI/LLM Prompts and Responses

[1a] **Case Study 1 Prompt:** "Give me a description of various resistor technologies, how they are made, how common performance specifications for them compare, and their common use cases. Also list the sources you used for this research"

[1b] Case Study 1 ChatGPT Copied Output:
1. Introduction
Resistors are passive components that limit or regulate electrical current. Their performance depends heavily on the material and manufacturing technology used. This document summarizes major resistor technologies, their construction, performance characteristics, and common applications.

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2. Resistor Technologies Summary

Type	Construction	Typical Specs / Performance	Common Uses
Carbon Composition	Mix of carbon and ceramic binder pressed into a rod; leads attached.	Tolerance ±5–20%; TCR ≈ 2000–5000 ppm/°C; high noise; poor stability.	Low-cost general circuits, surge-resistant applications.
Carbon Film	Carbon film on ceramic substrate; spiral-trimmed for value.	±1–5%; TCR ≈ 200–500 ppm/°C; moderate noise.	General electronics, moderate precision needs.
Thick Film (SMD)	Resistive paste printed on ceramic and fired.	±1–5%; TCR ≈ 50–300 ppm/°C; moderate drift, higher noise than thin film.	Standard SMD chip resistors in consumer devices.
Metal Film	Thin metallic film (NiCr, etc.) sputtered onto ceramic, laser-trimmed.	±0.1–1%; TCR ≈ 5–50 ppm/°C; low noise; stable.	Precision analog, audio, instrumentation.
Metal-Oxide Film	Metal-oxide (e.g. SnO_2) film on ceramic; spiral-trimmed.	±1–2%; TCR ≈ 50–200 ppm/°C; better heat/surge handling than metal film.	Industrial, high-temp, power circuits.
Wire-Wound	Resistive wire wound on ceramic core; often coated or heat-sunk.	±0.1–1%; TCR depends on alloy (10–50 ppm/°C); very high power; low noise; may be inductive.	Power resistors, current shunts, precision standards.
Metal Foil / Bulk Alloy	Metal foil bonded to substrate and laser-trimmed.	±0.005–0.01%; TCR < 2 ppm/°C; extremely low noise; best long-term stability.	Precision instrumentation, calibration, metrology.

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3. Key Specification Comparison

Spec	Definition	Typical Range (Across Technologies)
Tolerance	Deviation from nominal resistance.	±20% (carbon comp) → ±0.001% (foil).

Spec	Definition	Typical Range (Across Technologies)
TCR	Change in resistance per °C (ppm/°C).	5000 ppm (carbon comp) → < 1 ppm (foil).
Noise	Excess noise beyond thermal noise.	High (carbon) → very low (metal/foil).
Stability / Drift	Change over time/load.	Poor (carbon) → excellent (foil/wire-wound).
Power Rating	Continuous dissipation capability.	< 0.25 W (SMD film) → > 100 W (wire-wound).
Surge Handling	Short-term overload tolerance.	Best: wire-wound, metal-oxide; Worst: thin/thick-film.
Parasitics	Inductance/capacitance at HF.	Worst: wire-wound; Best: foil/film.

4. Technology Comparison Summary

Technology	Precision	Temp Stability	Noise	Power	Cost	Frequency Suitability
Carbon Composition	Low	Poor	High	Medium	Low	Low
Carbon Film	Medium	Fair	Medium	Medium	Low	Fair
Thick Film	Medium	Fair	Medium	Low	Very Low	Moderate
Metal Film	High	Good	Low	Medium	Medium	High
Metal-Oxide Film	Medium	Good	Medium	High	Medium	Moderate
Wire-Wound	High	Very Good	Very Low	Very High	High	Low (inductive)
Metal Foil	Very High	Excellent	Very Low	Medium	Very High	Excellent

5. Manufacturing Overview

- Carbon Composition: Carbon and binder mixed, molded, and baked.
- Film Types: Thin or thick resistive layer deposited on ceramic, then laser-trimmed.
- Metal-Oxide Film: Similar to metal film but with oxide materials, giving better heat resistance.
- Wire-Wound: Resistive alloy wire wound on a core, sometimes bifilar for low inductance.
- Foil / Bulk Alloy: Foil bonded to a substrate and trimmed; used for metrology-grade stability.

6. Application Guidelines

Application	Recommended Technology
Consumer Electronics	Thick Film / Carbon Film
Audio / Analog Circuits	Metal Film
Precision Measurement	Metal Foil / Bulk Alloy
Power / Load Resistors	Wire-Wound
High-Temperature Environments	Metal-Oxide Film

Application	Recommended Technology
High-Frequency Circuits	Thin / Metal Film, Foil (low inductance)

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7. Typical Performance Examples

Example	Tolerance	TCR (ppm/°C)	Power (W)
Standard Metal Film	±1%	±25	0.25
Precision Thin Film	±0.01%	±5	0.125
Carbon Composition	±10%	±2000	0.5
Wire-Wound Power	±1%	±20	50
Foil Precision	±0.005%	±0.2	0.1

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8. Trade-Off Overview

When choosing resistor types:

- Precision & Stability: Foil or metal film.
- Power: Wire-wound or metal-oxide.
- Cost & Compactness: Thick film.
- High Temperature or Harsh Use: Metal-oxide or wire-wound.
- Low Noise / High Frequency: Thin film or foil.

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[1b] Case Study 1 Copliot Copied Output:
Resistor technologies vary widely in construction, performance, and application. Here's a breakdown of the most common types, how they're made, how they compare, and where they're used.

🛠️ Common Resistor Technologies & How They're Made

Type	Construction	Manufacturing Notes
Carbon Composition	Mix of carbon powder and binder molded into a cylinder	Oldest type; simple and cheap but noisy and unstable
Carbon Film	Carbon layer deposited on ceramic rod	Laser-trimmed for resistance; better stability than composition
Metal Film	Thin metal layer (e.g., nickel-chromium) on ceramic substrate	Precision trimming allows tight tolerance and low noise
Metal Oxide Film	Tin oxide film on ceramic	Higher temperature and voltage tolerance than metal film
Thick Film	Screen-printed resistive paste (often ruthenium oxide) on ceramic	Common in surface-mount devices (SMD); cost-effective for mass production
Thin Film	Vacuum-deposited metal film on ceramic	High precision, low TCR (temperature coefficient of resistance), stable over time
Wirewound	Resistive wire (e.g., nichrome) wound around a ceramic or fiberglass core	High power handling; inductive unless specially designed
Foil (Bulk Metal)	Etched metal foil bonded to a substrate	Ultra-precise, extremely low TCR and noise; expensive

📊 Performance Comparison

Type	Tolerance	TCR (ppm/°C)	Noise	Power Rating	Stability
Carbon Composition	±5–20%	±1000+	High	Moderate	Poor
Carbon Film	±2–5%	±200–500	Moderate	Low–Moderate	Fair
Metal Film	±0.1–1%	±25–100	Low	Low–Moderate	Good
Metal Oxide Film	±1–5%	±300–500	Moderate	Moderate	Good
Thick Film	±1–5%	±100–300	Moderate	Low–Moderate	Fair
Thin Film	±0.01–1%	±5–50	Very Low	Low	Excellent
Wirewound	±0.1–5%	±5–50	Very Low	High	Excellent
Foil (Bulk Metal)	±0.005–0.1%	±0.2–2	Extremely Low	Low–Moderate	Exceptional

⚙️ Common Use Cases

- Carbon Composition: Vintage electronics, surge protection (due to energy absorption)
- Carbon Film: General-purpose consumer electronics
- Metal Film: Precision analog circuits, audio equipment, instrumentation
- Metal Oxide Film: Power supplies, automotive, high-temp environments
- Thick Film: Mass-produced SMD circuits, consumer electronics
- Thin Film: High-precision applications, medical devices, aerospace
- Wirewound: Power resistors, motor drives, high-current applications

- Foil: Metrology, high-end instrumentation, aerospace, military

📚 Sources

1. Passive Components Blog – Resistor Types and Construction
2. Kynix Electronics – Resistor Types and Their Applications (2025)
3. TheLinuxCode – Understanding Carbon, Film, and Composition Resistors
4. SEI Electronics – Nichrome vs. Tantalum Nitride Comparison
5. Altera Price – In-Depth Analysis of Resistor Technologies

If you're designing a circuit or selecting components, I can help you choose the right resistor type based on your specific needs—just let me know your constraints or application!

[1c] Case Study 1 Gemini Copied Output:

I've put together a research plan. If you need to update it in any way, let me know.

Resistor Technologies: A Comprehensive Overview

Research Websites

(1) Systematically define and describe the major fixed resistor technologies, including Carbon Composition, Carbon Film, Metal Film (Thin Film), Thick Film (SMD/Chip), and Wirewound resistors.
(2) Investigate the general manufacturing processes for Carbon Composition, Carbon Film, and Metal Film resistors, focusing on the differences in how the resistive element is created and trimmed.
(3) Investigate the manufacturing processes for Wirewound resistors and Surface Mount Device...

More

Analyze Results

Create Report

Ready in a few mins

Edit plan | Start research

Resistor Technologies: A Comprehensive Overview | Create | ×

Researched 45 websites

In researching your report, Gemini searches the web and browses content from relevant websites on your behalf.

- **circuitmasterclass.com** Carbon Film Resistor – Detailed Explanation - Circuit Masterclass
- **vishay.com** Manufacturing Process for Fixed Film Resistors - Vishay
- **circuitmasterclass.com** Metal Film Resistor – Construction and Applications - Circuit Masterclass
- **xy-resistor.com** Film Resistor : Construction, Working, Types and Its Applications
- **electronics-tutorials.ws**
- **vpgfoilresistors.com** Reading Between the Lines in Resistor Datasheets-FAAG-63517
- **newark.com** Locked in resistance: Exploring the world of fixed value resistors - Newark Electronics
- **circuitschools.com** FIXED RESISTOR: Guide to Identification, Types & Applications - Circuit Schools
- **blikai.com** Wirewound Resistor: An In-Depth Overview - Blikai
- **madpcb.com** Thick Film Resistor(s): Surface Mounting Device (SMD) | MADPCB
- **en.wikipedia.org** Thick-film technology - Wikipedia
- **susumu.co.jp** 2.Manufacturing methods and characteristics of thin film resistors | Susumu Deutschland GmbH
- **korvustech.com** Thin Film Resistors | A Deep Dive - Korvus Technology

[2a] **Case Study 2 Prompt:** "Explain to me the process you would go through, along with relevant scientific theory, for estimating the temperature rise in a TE HSC100 series resistor (datasheet attached) if it dissipated an average power of 10W over 30 seconds."

[2b] Case Study 2 ChatGPT Copied Output:

- 1) Physical and Conceptual Model

Step 1: Lumped Thermal Model (RC Analogy)
The resistor and its aluminum housing (and any heatsink it's mounted to) can be modeled as a single thermal capacitance, denoted *Cth* (in joules per kelvin), connected to ambient air through a thermal resistance *Rth* (in kelvins per watt).

- The thermal capacitance *Cth* equals the mass *m* of the body multiplied by the specific heat capacity *cp*.
  (That is, Cth = m × cp.)
- The thermal resistance *Rth* describes how easily heat escapes to ambient air.

This simple "RC" model is valid when the temperature is fairly uniform through the resistor body or when we only need an average body temperature.
Step 2: Governing Transient Equation
When constant power *P* is dissipated for a time *t*, the temperature rise above ambient, written as delta-T(t), is given by:
delta-T(t) = P × Rth × [1 - exp(-t / tau)],
where *tau* (the thermal time constant) equals Rth × Cth.
The temperature rise will eventually reach the steady-state value delta-Tss = P × Rth once enough time has passed.
Step 3: Why This Model Works for a 30-Second Event
A 30-second pulse is usually short compared to the thermal time constant of a metal-housed resistor and its heatsink. Therefore, the resistor temperature typically does not reach steady state, and transient heating dominates.

- 2) Data Needed and Where to Get It

You need the following inputs:

- **Thermal resistance (Rth)**: found or inferred from the TE datasheet for the HSC100. If not directly listed, it can be estimated as Rth = (Allowed temperature rise) / (Rated power).
- **Thermal capacitance (Cth)**: estimated as the product of the mass of the resistor (or housing) and the specific heat capacity of aluminum, which is about 900 joules per kilogram per kelvin.
- **Mounting details**: whether the resistor is attached to a standard heatsink, and whether thermal compound or insulation is used. These factors strongly affect Rth.
- **Ambient temperature**: usually assumed to be around 25 degrees Celsius unless otherwise specified.

The datasheet includes pulse overload and surface temperature rise curves that allow a more precise inference of thermal performance.

- 3) Step-by-Step Estimation Procedure

1. Identify whether the resistor is used with a heatsink or free in air.

2. Obtain or estimate the steady-state thermal resistance Rth from the datasheet or by measurement.
3. Estimate the thermal capacitance using the formula Cth = m × cp, where m is the mass of the resistor or housing.
4. Compute the thermal time constant tau = Rth × Cth.
5. Compute the temperature rise after 30 seconds using the formula delta-T = P × Rth × [1 - exp(-30 / tau)].
6. Compare your results to the datasheet's overload and pulse graphs to ensure consistency.
7. Validate through measurement if needed.

- 4) Worked Example with Assumed Values

We will calculate temperature rise for a 10-watt average dissipation over 30 seconds using several reasonable assumptions.

- Common Assumptions
- Power = 10 watts
- Specific heat capacity of aluminum = 900 joules per kilogram per kelvin
- Ambient temperature = 25 degrees Celsius

We will consider two different masses and two different thermal resistances to show the sensitivity of the results.

Case A: Good heatsink and large mass

- Thermal resistance Rth = 1 kelvin per watt
- Mass m = 0.20 kilograms
- Thermal capacitance Cth = 0.20 × 900 = 180 joules per kelvin
- Thermal time constant tau = 1 × 180 = 180 seconds
- Steady-state temperature rise delta-Tss = 10 × 1 = 10 degrees Celsius
- Transient rise after 30 seconds = 10 × (1 - exp(-30 / 180)) ≈ 1.5 degrees Celsius

Case B: No heatsink but large mass

- Rth = 5 kelvins per watt
- Cth = 180 joules per kelvin
- tau = 5 × 180 = 900 seconds
- delta-Tss = 10 × 5 = 50 degrees Celsius
- delta-T at 30 seconds = 50 × (1 - exp(-30 / 900)) ≈ 1.6 degrees Celsius

Case C: No heatsink and small effective mass

- Rth = 5 kelvins per watt
- Mass = 0.02 kilograms
- Cth = 0.02 × 900 = 18 joules per kelvin
- tau = 5 × 18 = 90 seconds
- delta-Tss = 10 × 5 = 50 degrees Celsius
- delta-T at 30 seconds = 50 × (1 - exp(-30 / 90)) ≈ 14.2 degrees Celsius

Case D: With heatsink and small effective mass

- Rth = 1 kelvin per watt
- Mass = 0.02 kilograms
- Cth = 18 joules per kelvin
- tau = 1 × 18 = 18 seconds
- delta-Tss = 10 × 1 = 10 degrees Celsius
- delta-T at 30 seconds = 10 × (1 - exp(-30 / 18)) ≈ 8.1 degrees Celsius

---

- 5) Interpretation of Results

For a 10-watt, 30-second pulse, the temperature rise depends strongly on both the thermal mass and thermal resistance:

- If the resistor is well-heatsinked and massive, the temperature rise is only about 1 to 2 degrees Celsius.
- If the resistor is poorly cooled or has little effective thermal mass, the temperature rise may be around 8 to 15 degrees Celsius.
- If the same 10 watts were applied indefinitely, the steady-state rise would approach P × Rth (for example, 50 degrees Celsius with Rth = 5 kelvins per watt).

- 6) Practical Recommendations
- Use the datasheet's "Pulse and Overload" curves to verify that a 10-watt, 30-second load falls within safe limits.
- Measure the real resistor temperature during a test run to confirm your assumptions for Rth and Cth.
- Improve thermal contact with a flat mounting surface, proper torque, and thermal compound.
- Always ensure that the resistor surface temperature remains below its rated limit, even during transient pulses.

- 7) Summary

To estimate the temperature rise for a TE HSC100 resistor dissipating 10 watts for 30 seconds:

1. Obtain Rth and Cth.
2. Compute tau = Rth × Cth.
3. Compute delta-T = P × Rth × [1 - exp(-t / tau)].
4. Check results against datasheet pulse ratings.

In practical terms, for 10 watts over 30 seconds, the temperature rise will typically be a few degrees Celsius for well-mounted resistors or up to about 15 degrees Celsius for less ideal cooling.

[2c] Case Study 2 Copilot Copied Output:
Overview of process

1. Gather required datasheet parameters and geometric data for the HSC100.
2. Build a thermal model treating the resistor housing and heatsink as a lumped thermal mass coupled to ambient through a thermal resistance.
3. Compute steady-state temperature rise as DeltaTss = P * Rth.
4. Estimate the thermal capacitance Cth of the aluminium assembly.
5. Compute the thermal time constant tau = Rth * Cth and the transient temperature rise after t = 30 s using the first-order lumped-capacitance response.
6. Report result and list assumptions and uncertainty sources.

Datasheet parameters and constants used

- Standard heatsink area for HSC100: 99,500 mm2 which is 0.0995 m2.
- Housing thickness used for mass estimate: 3 mm which is 0.003 m.
- Dissipated power: 10 W for duration 30 s.
- Aluminium density rho = 2700 kg/m3.
- Aluminium specific heat c = 900 J/(kg·K).
- Natural convection heat transfer coefficient h assumed = 5 W/(m2·K).
- Contact/interface thermal resistance assumed Rth_contact = 0.2 K/W.

Step 1 — Estimate thermal resistance Rth

- Convective thermal resistance Rth_conv = 1 / (h * A).
- With h = 5 and A = 0.0995, Rth_conv = 1 / (5 * 0.0995) = 2.01005 K/W (approx 2.01 K/W).
- Add contact resistance Rth_contact = 0.2 K/W.
- Total thermal resistance Rth_total = Rth_conv + Rth_contact = 2.01 + 0.2 = 2.21 K/W (rounded 2.2 K/W).

Step 2 — Steady-state temperature rise

- DeltaTss = P * Rth_total.
- With P = 10 W and Rth_total = 2.21 K/W, DeltaTss = 10 * 2.21 = 22.1 °C (approx 22 °C above ambient).

Step 3 — Estimate thermal capacitance Cth

- Heatsink volume V = area * thickness = 0.0995 m2 * 0.003 m = 0.0002985 m3.
- Mass m = rho * V = 2700 kg/m3 * 0.0002985 m3 = 0.80595 kg (approx 0.806 kg).
- Thermal capacitance Cth = m * c = 0.80595 kg * 900 J/(kg·K) = 725.355 J/K (approx 725 J/K).

Step 4 — Thermal time constant tau and transient rise at 30 seconds

- Time constant tau = Rth_total * Cth = 2.21 K/W * 725.355 J/K = 1603.0 s (approx 1600 s).
- First-order transient response DeltaT(t) = DeltaTss * (1 - exp(-t / tau)).
- For t = 30 s, exponent = -30 / 1603.0 = -0.01872; exp(exponent) = 0.98145.
- Fractional rise = 1 - 0.98145 = 0.01855.
- DeltaT(30 s) = 22.1 °C * 0.01855 = 0.410 °C (approx 0.41 °C above ambient).

Final numeric summary

- Steady-state temperature rise at 10 W: 22.1 °C above ambient (rounded 22 °C).
- Temperature rise after 30 seconds of continuous 10 W dissipation: 0.41 °C above ambient (rounded 0.4 °C).

Key assumptions and uncertainty sources

- Convection coefficient h assumed 5 W/(m2·K); real h depends on orientation, proximity of other components, and airflow. Forced convection reduces Rth significantly.
- Contact/interface resistance assumed 0.2 K/W; poor mounting or missing thermal compound increases Rth.
- Lumped-capacitance model assumes uniform temperature within the aluminium mass; in reality the resistor element and leads can be hotter than the housing surface.
- Mass estimate used heatsink area and a uniform thickness of 3 mm; actual effective thermal mass may be larger if internal components or additional mounting hardware contribute.
- Datasheet experimental derating and surface-temperature graphs can provide more accurate Rth and transient behavior if read directly or requested from TE.

Practical recommendation

- Use these numbers for quick screening calculations.
- For design-critical work, measure temperature on the actual mounted HSC100 under intended ambient and airflow or obtain TE’s application-specific thermal data for the chosen mounting and environment.

[2d] Case Study 2 Gemini Copied Output:

🌡️ Estimating Temperature Rise for the HSC100 Resistor

To estimate the temperature rise in a TE HSC100 series resistor that dissipates an average power of **ten watts** ($10\ \text{W}$) over a duration of **thirty seconds** ($30\ \text{s}$), the process involves analyzing the event's safety using a transient check, and then estimating the temperature rise using the steady-state thermal graph provided in the datasheet.

1. Scientific Theory: Thermal Analysis

The dissipation of power over a short period like **thirty seconds** is a **transient thermal event**. However, because the applied power (**ten watts**) is a small fraction of the resistor's continuous rating, the final temperature rise will be close to the **steady-state** (continuous) rise for that power level.

- **Transient Analysis (Safety Check):** This is governed by the resistor's **thermal capacitance** (its ability to store heat) and is visualized in the **Power Overload** graph.
- **Steady-State Analysis (Temperature Estimation):** This is governed by the **thermal resistance** between the resistor's element and the heatsink, and is visualized in the **Surface Temperature Rise** graph.

---

2. Step-by-Step Estimation Process

Step A: Transient Power Check (Safety and Context)

First, determine how the **ten watts** compares to the component's maximum rated continuous power.

- **Rated Power (with standard heatsink):** The HSC100 is rated for **one hundred watts** ($100\ \text{W}$).
- **Multiples of Rated Power:**

$$\text{Multiples} = \frac{\text{Actual Power}}{\text{Rated Power}} = \frac{\text{ten watts}}{\text{one hundred watts}} = \text{zero point one}$$

- **Using the Power Overload Graph (Page Three, Bottom Left):**
  - The graph plots overloads (multiples of **five** to **thirty** times the rated power) against duration.
  - Since the actual power is only **zero point one** times the rated power, it is significantly **below** the minimum overload condition shown. The resistor is safely operating at only **one-tenth** of its maximum capacity, making a $30\ \text{s}$ duration a very benign event.

Step B: Steady-State Temperature Estimation

Since the power is low and the duration is relatively long, the temperature rise will closely follow the continuous power curve.

- **Using the Surface Temperature Rise Graph (Page Three, Bottom Right):**
  1. Locate **ten watts** on the x-axis (*Power Dissipation (Watts)*).
  2. Trace a vertical line up to the curve corresponding to the HSC100 resistor.
  3. Trace a horizontal line from this intersection point to the y-axis (*Surface Temp. Rise* ($^\circ C$)).
  4. The intersection point for HSC100 at ten watts is very low, visually falling between zero and twenty degrees Celsius.

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3. Conclusion

The estimated **surface temperature rise** for the HSC100 resistor dissipating **ten watts** for **thirty seconds** on a standard heatsink is very low, approximately **five degrees Celsius ($5^\circ C$) to ten degrees Celsius ($10^\circ C$)**.

Would you like me to find the **Standard heatsink area** for the HSC100 resistor in square millimeters?

Sources

[3a] **Case Study 3 prompt: "**types of regulators to use in a capacitor discharge project"
[3b] Case Study 3 ChatGpt output: 1. Switching (Buck / Step-Down) Regulators
Use when: You need to charge a capacitor bank from a higher DC voltage efficiently.

- **Why:** Buck converters are ideal for efficiently stepping down voltage from, say, a 24 V DC input to a lower voltage (e.g., 12 V or 5 V) for the control circuitry or gate drivers.
- Examples:
  - **LM2576 / LM2596** (Fixed 3.3 V, 5 V, 12 V options, 3 A output)
  - **TPS5430** (5 A switching regulator from Texas Instruments)
- **Efficiency:** 80–95%, low heat.
- **Typical use:** Powering microcontrollers, trigger circuits, MOSFET gates, sensors.

⚙️ 2. Boost (Step-Up) Regulators
Use when: You need to charge capacitors to a higher voltage than your supply (e.g., from a 12 V source up to 48 V or 100 V).

- **Why:** A capacitor discharge circuit often needs a higher charge voltage for a strong pulse discharge.
- Examples:
  - **LT3750 / LT3751** – specifically designed for **capacitor charging** up to hundreds of volts.
  - **XL6009 / LM3478** – general-purpose boost converters.
- Efficiency: 85–95%.
- **Notes:** Include current limiting and feedback control to avoid capacitor overcharging.

⚙️ 3. Linear Regulators (LDOs)
Use when: You need a **clean, low-noise** power rail for sensitive analog or timing circuits.

- **Why:** In capacitor discharge systems, the control circuit may include op-amps, comparators, or microcontrollers that benefit from noise-free supply.
- Examples:
  - **LM7805 / LM7812** for basic fixed-voltage regulation.
  - **LT1763** for precision, low-noise applications.
- **Efficiency:** Lower (50–70%), but simple and stable.

⚙️ 4. Constant-Current Regulators
Use when: You want to control the charging current to the capacitor.

- **Why:** Prevents damaging surge currents that can over-stress components or power sources.
- Examples:
  - LM317 configured as a constant-current source.
  - **Dedicated LED driver ICs** like **LT3474** can also be used for constant-current charging.
- **Benefit:** Smooth, controlled charge curve to capacitor.

⚙️ 5. Specialized Capacitor-Charger ICs
Use when: The design centers around **high-voltage capacitor charging and controlled discharge** (e.g., flash, pulse, or coil-gun circuits).

- Examples:

  - **LT3750 / LT3751 (Analog Devices)** – dedicated ICs for charging large capacitors to high voltage with built-in current sensing and shutdown.
  - **MIC3172 / MAX1771** – compact boost controllers.
- **Advantage:** Simplified control, built-in safety, high power handling.

⚙️ Recommended Setup Example

If your project uses a **24 V DC input**, and your discharge circuit needs:

- 5 V control logic → use a Buck converter (LM2576-5.0).
- 48 V capacitor bank charge → use a Boost converter (LT3750).
- Stable reference voltage for sensing → use an LDO (LM7805 or LT1763).
- Current limit protection → add a constant-current circuit using LM317.

[3c] Case Study 3 CoPilot Output

For a capacitor discharge project, the most suitable types of voltage regulators are typically linear regulators, switching regulators, and programmable regulators—each offering distinct advantages depending on your design goals.

Here's a breakdown of the most relevant regulator types and how they fit into capacitor discharge applications:

Common Regulator Types for Capacitor Discharge Projects

1. Linear Voltage Regulators

- **Examples**: LM317, 7805, 7812
- **Best for**: Low-noise applications, simple designs
- Pros:
  - Easy to use and inexpensive
  - Provide clean, stable output
- Cons:
  - Inefficient for high current or large voltage drops (dissipate excess energy as heat)

2. Switching Voltage Regulators

- **Examples**: Buck (step-down), Boost (step-up), Buck-Boost
- **Best for**: Efficient power conversion, battery-powered or high-current systems
- Pros:
  - High efficiency (up to 90%+)
  - Can step voltage up or down
- Cons:
  - More complex design
  - Can introduce switching noise (requires good filtering)

3. Programmable Regulators

- **Examples**: Digital potentiometer-controlled regulators, microcontroller-based control
- **Best for**: Projects needing variable output voltage or controlled discharge profiles
- Pros:
  - Adjustable output
  - Can be integrated with sensors or feedback loops
- Cons:
  - Requires programming and additional circuitry

4. Induction and Step-Type Regulators

- **Used in**: Larger-scale or industrial capacitor banks (e.g., substations)

- Pros:
  - Handle high power levels
  - Suitable for reactive power compensation
- Cons:
  - Not practical for small-scale electronics projects

When choosing a regulator, consider:

- **Discharge voltage range**: Does your capacitor discharge from a high voltage that needs stepping down?
- **Load requirements**: What current does your load draw during discharge?
- **Efficiency vs simplicity**: Linear regulators are simple but waste energy; switching regulators are efficient but complex.
- **Noise sensitivity**: Audio or analog circuits may require low-noise linear regulators.

If you're working with high-speed switching or pulsed loads, capacitor selection also becomes critical. Use **low-ESR capacitors** like ceramic or film types to support fast current delivery and minimize losses.

Would you like help designing a specific regulator circuit for your project? I can walk you through component selection or simulate a discharge curve.

[3d] Case Study 3 Google Gemini Output

That's a great question, especially since a capacitor discharge can have a **wide and rapidly falling voltage**—a challenging input for a regulator!

The best type of regulator for your capacitor discharge project depends on your specific needs, primarily the **input voltage range** (from the capacitor) and the **required output voltage**.

Here are the main types of regulators and which ones are typically suited for a capacitor discharge scenario:

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1. Switching Regulators (DC-DC Converters)

These are generally the **best choice** because of their high efficiency and ability to handle a varying input voltage, especially as the capacitor discharges.[1]

Type	Function	Why it's useful for Capacitor Discharge
Buck Regulator (Step-Down)	Output voltage is always **lower** than the input.	Good if the fully charged capacitor voltage is high and you only need a lower output. The high efficiency is key.
Boost Regulator (Step-Up)	Output voltage is always **higher** than the input.	Useful if you need a higher regulated voltage than the capacitor's voltage *after* it has discharged somewhat (e.g., boosting a 2V supercapacitor up to 3.3V).
Buck-Boost Regulator	Output voltage can be **lower or higher** than the input.	**Most versatile** for capacitor discharge. It maintains a constant output voltage as the capacitor voltage drops from above to below the required output. **Highly recommended** if the capacitor voltage swings widely.

Key Advantages:

- **High Efficiency:** Often 85% to over 95%, meaning less power is wasted as heat, which is critical when drawing limited energy from a capacitor.
- **Flexibility:** Can step up, step down, or both (Buck-Boost).[2]

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2. Linear Regulators

These are simpler and quieter but less efficient, which can be a major issue when using a capacitor as your primary energy source.

Type	Function	Why it's useful for Capacitor Discharge
Low-Dropout Regulator (LDO)	Output voltage is always **lower** than the input, but it can maintain regulation even when the input voltage is *very close* to the output voltage (low "dropout" voltage).	Best linear option. It maximizes the usable energy from the capacitor because it can continue regulating until the capacitor voltage drops almost to the output voltage level.
Standard Linear Regulator (e.g., 78xx series)	Output voltage is always **lower** than the input, requiring a significant voltage difference (e.g., 2V-3V) between input and output.	**Generally not recommended.** The poor efficiency (wasted energy = $(V_{IN} - V_{OUT}) \times I_{LOAD}$) and high dropout voltage will quickly waste the capacitor's stored energy and drastically limit the usable range of the discharge.

Key Advantages:

- **Low Noise:** Excellent for noise-sensitive circuits (e.g., radio, audio).
- **Simplicity:** Fewer external components are required.

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3. Zener Diode/Shunt Regulator (Passive)

While technically a regulator, this is typically only used for very low-power, simple reference voltage circuits, and **not** for powering a load from a capacitor discharge.

- It regulates by shunting (diverting) excess current to ground. If the capacitor voltage drops, it simply stops regulating. Its inefficiency makes it unsuitable for energy-limited applications like a capacitor discharge.

💡 Recommendation and Next Steps

For most capacitor discharge projects where **efficiency and maximizing run-time** are important:

1. **Use a Buck-Boost Switching Regulator (DC-DC Converter).** This gives you the best efficiency and the ability to maintain a constant output over the capacitor's entire discharge range (high voltage to low voltage).
2. If the capacitor voltage will *always* be close to and slightly higher than the required output: An LDO (Low-Dropout Regulator) is a simple, low-noise option, but you'll still lose more energy than with a switching regulator.

To help you choose a specific part number, would you like me to find some examples of **Buck-Boost DC-DC converters** suitable for a specific set of parameters, such as a **target output voltage (e.g., 5V or 3.3V)** and **maximum current**?

[4a]- “ within the power subsystem of my capacitor discharge project, what other features should I add besides the regulator and external power”

[4b]- Case Study 4 Google Gemini Output

Safety and Discharge Control

These components are critical, especially if you are working with large or high-voltage capacitors, as they directly manage the rapid energy release.

Feature	Purpose and Why It's Needed
Bleeder Resistor	A high-value resistor connected **permanently in parallel** with the capacitor. It slowly drains the stored charge when the main power is disconnected.
High-Current Switch/Contactor	A fast-acting, high-power switch (like a **MOSFET, IGBT, or SCR**) placed between the capacitor and the load circuit.
Current Limiter / Fuse	A fuse or circuit breaker on the main power input, and potentially a fast-acting current limiter within the discharge path itself.

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2. 📊 Monitoring and Feedback

The unique challenge of a capacitor discharge is the constantly falling voltage, making monitoring essential for performance and reliability.

Feature	Purpose and Why It's Needed
Voltage Monitoring Circuit	A simple circuit (often a voltage divider) that feeds the capacitor voltage to a microcontroller (MCU).
Over-Voltage Protection (OVP)	A circuit that monitors the capacitor voltage and disconnects the charger once the voltage hits a safe maximum limit.
LED Indicators	Simple LEDs for status.

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3. 🔌 Charging and External Power Interface

You mentioned external power; these features optimize how that power is used to charge the capacitor.

Feature	Purpose and Why It's Needed
Charging Circuit/Converter	A dedicated circuit (often a **current-limited source**) to safely charge the capacitor from your external power.
Input Isolation/Reverse Polarity Protection	A diode (or a MOSFET in a smarter circuit) on the main power input.

[4c] – Case Study 4 ChatGpt Output

Essential protections & safety

- **Input fuse / circuit breaker** — slow-blow or fast depending on inrush and fault type.
- **Inrush limiter / NTC or soft-start** — protects supply and prevents contactor tripping when capacitors charge.
- **Precharge / current-limit resistor + relay/contactor** — prevents huge charging surge into the empty capacitor bank; use a relay/contact to bypass the precharge resistor after charging.
- **Bleeder (discharge) resistor** — slowly drains capacitors to safe voltage when powered off; add a mechanical shunt that shorts for fast discharge only when testing.
- **Over-voltage, over-current, over-temperature shutdown** — hardware comparator/MCU logic trips a disable signal to the charger/MOSFETs.

- **Crowbar / TVS / MOV / surge protection** — transient protection for spikes from AC mains or inductive loads.
- **Isolation & earth-grounding** — ensure chassis, measurement circuits, and operator safety are correctly grounded and isolated where needed.

Charging & energy control

- **Controlled charge algorithm** — current-limited charging (constant current then constant voltage or stop at set voltage) with monitoring.
- **Charge current sensing** — low-ohm sense resistor + differential amplifier or isolated current sensor (Hall effect) for control & protection.
- **Charge/discharge enable logic** — a clearly defined enable/arm sequence (interlocks + status LEDs) to avoid accidental firing.
- **Reverse-polarity protection** — for battery/supply connections.

Discharge control & switching

- **High-current switch/MOSFET or IGBT with gate driver** — sized for pulse current and dV/dt; include a proper gate driver, dead-time control, and gate resistors.
- **Snubbers / RC or RCD snubber networks** — clamp voltage overshoot from switching and protect the switch.
- **Current sensing in discharge path** — fast sense for monitoring and for over-current cutout.
- **Soft / staged discharge (if applicable)** — multiple stages or parallel switches to control discharge profile or share stress.

Sensing, measurement & telemetry

- **Voltage sensing on each capacitor bank** — for safety, balancing, and logging. If multiple cells, sense cell-level voltages.
- Temperature sensors (thermistors/RTDs/thermocouples) on capacitors, MOSFETs, inductors, and enclosure.
- **Accurate current measurement** — shunt + ADC or Hall sensor; ensure bandwidth covers discharge pulse.
- **Isolated ADCs or isolated measurement front-end** if measurements cross different potential domains.
- **Status indicators & meters** — voltmeter, ammeter, LEDs for armed/charged/error states.
- **Data logging / telemetry** — log charge/discharge cycles, peak currents, temps, and faults for debugging and lifetime analysis.

Balancing & longevity (for multi-cell packs)

- **Cell balancing (active or passive)** for multi-cell Li or supercap packs.
- **Battery Management System (BMS)** if using batteries — pack voltage, cell balancing, thermal, and safety cutouts.

EMI / EMC and layout

- **Input EMI filter** (common-mode choke + capacitors) and output filtering to meet emissions and prevent interference with control electronics.
- **Good PCB layout**: separate power and signal grounds, short high-current traces, wide copper, proper thermal vias and busbars for high currents.
- **Shielding and cable routing** to reduce radiated emissions and avoid noise coupling into sensors.

Thermal management & mechanical

- **Heatsinks, forced air / fan control** and thermal cutouts for MOSFETs/regulators/inductors.
- **Thermal pads / insulating hardware** and airflow channels in enclosure.
- **Robust connectors & cable gauge** sized for pulse current (use rated connectors and measure derating for pulse duty).
- **Clear labeling and safe enclosure** with interlock switches that cut main power when opened.

User interface & safe operation

- **Arm/Disarm sequence with physical confirmation** (e.g., key switch or two-button safety) to avoid accidental discharge.
- **Visible indicators** for charged state and fault conditions.
- **Enable lockout on faults** and auto-retry logic only after manual reset (for safety).
- **Emergency stop** that immediately isolates the discharge path.

Testing, calibration & diagnostics

- **Test points** for voltage, current, and gate drive waveforms.
- **Self-test routines** in firmware to check sensors, ADCs, and relays before allowing charge.
- **Built-in diagnostics & fault logging** to store the last error condition and parameter values.

Firmware & control features

- Watchdog and safe-state on MCU failure (drive gates low, open relays).
- **State machine**: clearly defined states (Power-off → Precharge → Charged/Armed → Discharge → Fault).
- **Rate limiting and interlocks** in software for repeated pulses (duty cycle control, cooldown times).
- **Remote control / comms (optional)** — serial, CAN, USB, or wireless with authentication and safe-operation rules.

Documentation & compliance

- **Schematic-level safety notes** and clearly written operating procedures.
- **BOM with derated component selections** (components rated for higher voltage/current/temperature than expected).
- **Regulatory checks** (if the device will be used publicly): basic EMC and safety rules, high-voltage handling procedures, and labeling.

[4d]- Case Study 4 CoPilot Output

Active Discharge Circuitry

- **Purpose**: Ensures capacitors safely discharge when power is removed.
- Components:
  - *Power MOSFETs*: Enable controlled discharge paths.
  - *Discharge resistors*: Premounted modules improve reliability.
  - *Gate resistors and optocouplers*: Provide isolation and control.

🔒 Protection Features

- **Overvoltage Protection**: Prevents damage from voltage spikes.
- **Reverse Polarity Protection**: Safeguards against incorrect power connections.
- **Current Limiting**: Avoids excessive current draw during charging/discharging.

📊 Monitoring and Feedback

- **Voltage and Current Sensors**: Track capacitor charge/discharge status.
- **Microcontroller Interface**: Enables real-time data logging and control.

- **Status LEDs or Display**: Visual indicators for system health and capacitor state.

🔁 Switching and Control

- **Relay or Transistor Switching**: Allows staged capacitor bank discharge.
- Programmable Logic (e.g., FPGA or MCU): Automates timing and sequencing.

🧯 Safety Enhancements

- **Bleeder Resistors**: Passive discharge when active circuitry fails.
- **Thermal Management**: Heatsinks or fans for dissipating energy safely.
- **Isolation Barriers**: Protect users and sensitive components from high voltage.

🧠 Smart Features (Optional)

- **Auto-discharge on power-off**: Prevents residual voltage hazards.
- **Self-test routines**: Verifies system integrity before operation.
- **Remote control or telemetry**: Useful for industrial or remote applications.

[5a] **Case Study 5 Prompt:** what are some common applications of the serial peripheral interface?

[5b] **Case Study 5 Gemini Output:**

Common applications of the Serial Peripheral Interface (SPI) include connecting microcontrollers to various peripherals like **sensors** (temperature, accelerometer), **memory devices** (flash, EEPROM, SD cards), and **displays** (LCD, OLED) in embedded systems, Internet of Things (IoT) devices, and wireless communication modules. It is also used for motor control, audio codecs, and for high-speed data transfer between microcontrollers and wireless modules like Wi-Fi and Bluetooth.

Embedded systems

- **Sensors:** Communicating with sensors such as temperature, pressure, light, accelerometers, and gyroscopes to gather environmental and motion data.
- **Memory:** Interfacing with flash memory, EEPROM, and other storage devices for data storage and retrieval.
- **Actuators:** Controlling devices like motors and servos in applications such as robotics and industrial automation.
- **Audio:** Connecting to audio chips, including digital-to-analog converters (DACs) and audio codecs.

Internet of Things (IoT)

- **Environmental monitoring:** Connecting to sensors for smart home and industrial applications, like tracking temperature, humidity, and air quality.
- **Connectivity:** Linking microcontrollers to wireless modules for Wi-Fi and Bluetooth communication, enabling high-speed data transfer.

Displays and other peripherals

- **Graphical displays:** Driving and communicating with OLED, LCD, and e-paper screens.
- **Data converters:** Interfacing with analog-to-digital (ADC) and digital-to-analog (DAC) converters.
- **Real-time clocks (RTCs):** Communicating with real-time clock ICs.
- **Expansion:** Connecting to devices like shift registers for I/O expansion.

[5c] Case Study 5 Copilot Output:

Serial Peripheral Interface (SPI) is commonly used in embedded systems to connect microcontrollers with peripheral devices like sensors, displays, and memory modules.
Here are some of the most frequent and practical applications of SPI:

Chapter 12: 🧠 Embedded Systems & Microcontrollers

- **Microcontroller-to-peripheral communication**: SPI is ideal for connecting microcontrollers to devices like EEPROMs, ADCs (Analog-to-Digital Converters), DACs (Digital-to-Analog Converters), and RTCs (Real-Time Clocks) GeeksForGeeks.
- **Inter-microcontroller communication**: It enables fast data exchange between multiple microcontrollers in a master-slave configuration Wikipedia.

Chapter 13: 📟 Display Interfaces

- **LCD and OLED displays**: SPI is often used to drive graphical displays in embedded devices due to its high-speed data transfer capabilities Electronics Hub.

Chapter 14: 🎧 Audio and Sensor Modules

- **Audio ICs**: Many audio chips use SPI for configuration and control.
- **Sensors**: SPI is used to interface with sensors like temperature, pressure, and motion sensors for real-time data acquisition Electronics Hub.

Chapter 15: 💾 Memory Devices

- **Flash memory and EEPROMs**: SPI is a popular protocol for accessing non-volatile memory in embedded systems, especially in bootloaders and firmware storage Electronics Hub.
- **SD and MMC cards**: SPI mode is supported by many memory cards for simple and low-cost interfacing Electronics Hub.

Chapter 16: 🧩 Industrial and Consumer Electronics

- **Industrial control systems**: SPI is used in PLCs and other automation systems for fast and reliable communication between control units and sensors.
- **Consumer electronics**: Devices like smartwatches, fitness trackers, and digital cameras often use SPI internally for component communication Spiceworks.

Chapter 17: ⚙️ Why SPI Is Preferred

- **High speed**: Faster than I²C for short-distance communication.
- **Full-duplex**: Can send and receive data simultaneously.
- **Simple hardware**: Requires fewer pins than parallel communication.

If you're working on a project involving microcontrollers or embedded systems, SPI is a go-to protocol for efficient and reliable communication. Want help choosing between SPI and I²C for a specific application?