Microcontroller-based Capacitor Discharge Circuit with Configurable Setpoints

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Table of Contents

List of Tables

List of Figures

Chapter 2: Project Description

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 ± 20 %
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.

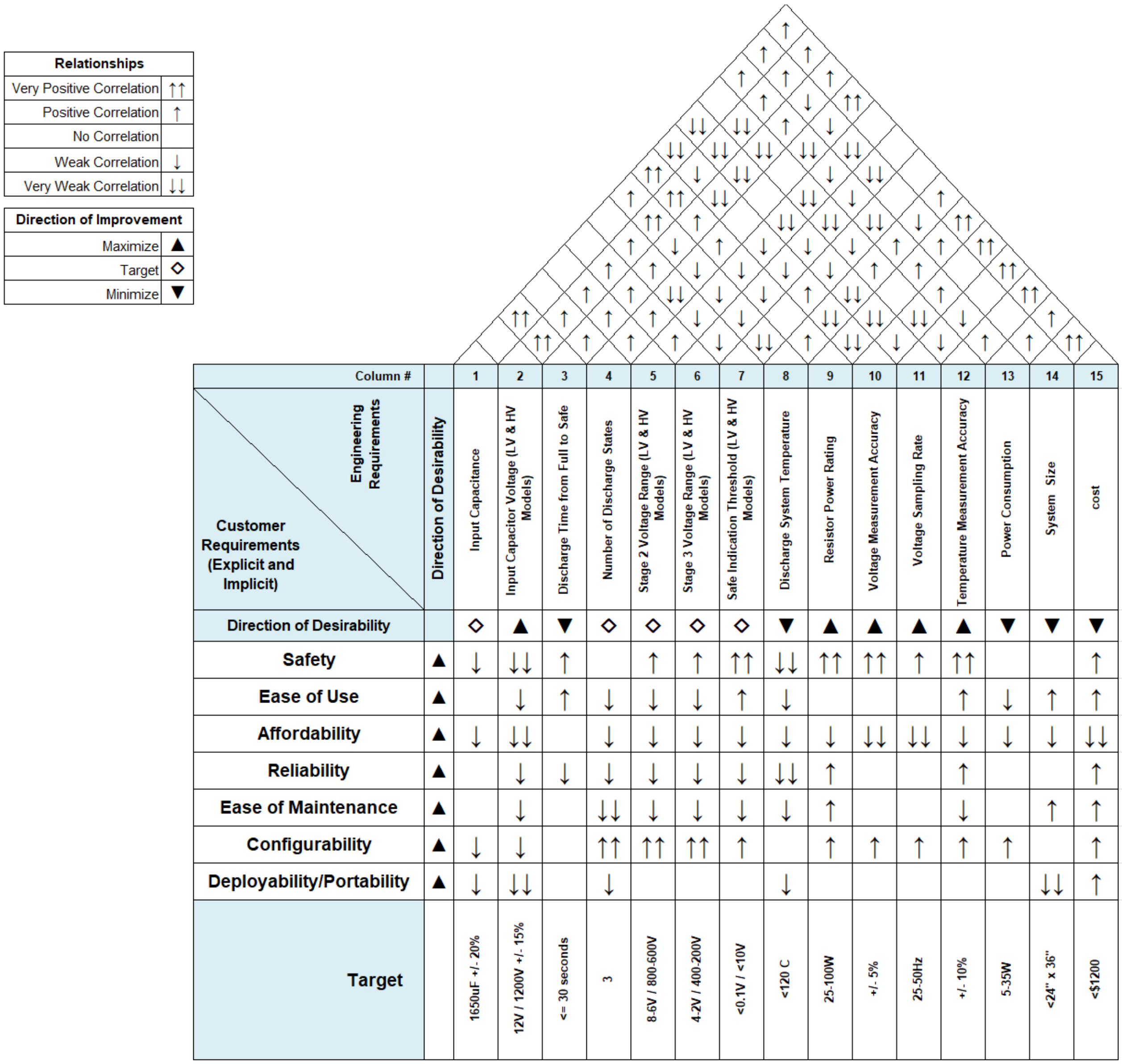

Figure 1: House of Quality

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.

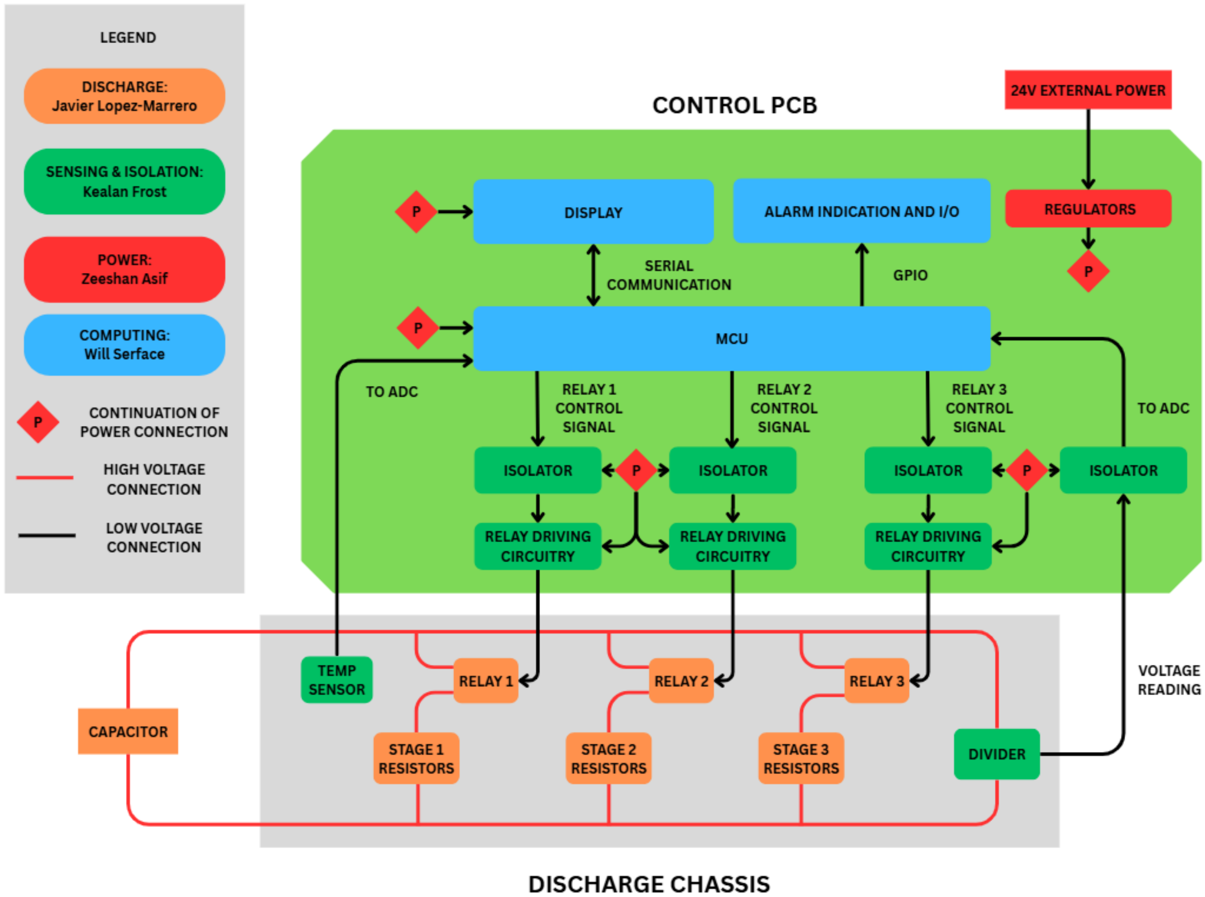

Figure 2: Hardware Diagram

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.

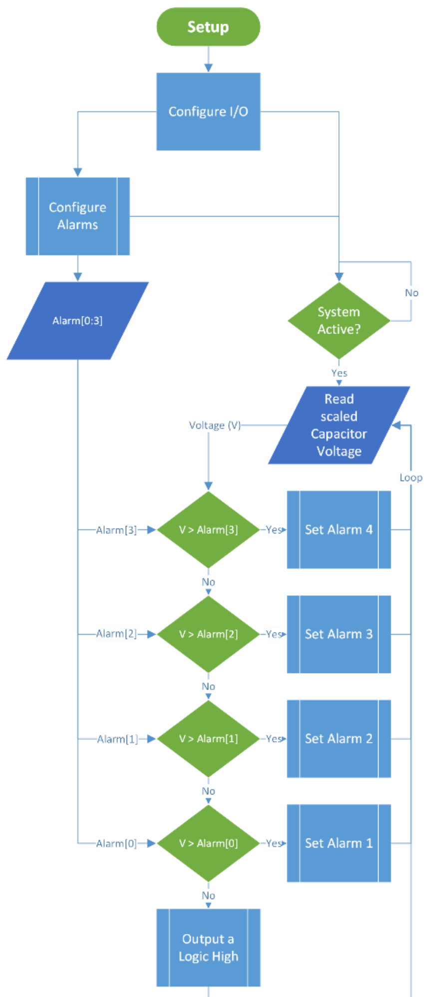

Figure 3: Software Flowchart

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 3: 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 4: 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 5: 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 6: 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 the parts necessary for a robust design, meeting all required specifications while being mindful of the costs. This involved carefully selecting the components to avoid unnecessary expenses. We also need to account 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.

Table 7: Prototype BOM

Component	Typical Unit Price	Quantity	Total
Controller and UI			
Microcontroller	$6.13	1	$6.13
Display	$12.99	1	$12.99
Rotary Encoder	$2.40	2	$4.80
Button	$1.00	5	$5.00
Lights	$3.72	4	$14.88
Device Power Supply			
DC Power Brick	$36.86	1	$36.86
DC Jack	$0.33	1	$0.33
5V Regulator	$5.00	1	$5.00
3.3V Regulator	$5.00	1	$5.00
12V Regulator	$5.00	1	$5.00
Sensing & Isolation			
ADC	$3.87	1	$3.87
Voltage Divider	$2.20	1	$2.20
Thermistor	$0.57	2	$0.57
	$4.57	4	$18.28
Discharge Stages			
Power Resistors	$17.02	11	$187.22
Relays/Contactors	$108.36	4	$433.44
Capacitor Connectors	$14.99	1	$14.99
Wire (50ft)	$35.56	1	$35.56
Aluminum Mounting Plate / Heatsink (2ft x 2ft)	$89.43	1	$89.43
PCBs and Assembly			

Main PCB	$240	2	$480
Assembly Consumable	$30	1	$30
Enclosure	$45	1	$45
Hardware	$10	1	$10
Total:			$1,451.12

Based on the table above, our estimate as to what parts may go into this project, we are coming up with an estimate of $1,451.12. An additional 15% will be added to the cost to cover tax and shipping, alongside another 35% to account for any extra materials needed, revisions, part failures, or change of scope/features/functionality. This brings the current estimate of our budget for this project to $2,176.68.