Smart Assessing Breaker for Residential Estates (SABRE)

Initial Divide and Conquer Document
EEL4914 - Senior Design I

University of Central Florida
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Chapter 1 – Abstract

The modern conventional breaker first came into residential use in the 1950s-1960s with their conventional approach of using bimetal strips which use the basic understanding of how certain metals behave under extreme temperatures to bend the strip and trip to trip the breaker being established long before this in the 1920s. In this period, the thermal magnetic component of the breaker was introduced. It used a concise understanding of electromagnetism to trip the breaker whenever a certain threshold of current had been reached. These two components within the breaker have not been updated since then, meaning they have not been in touch in the past 60 years. To keep up with the demands of continuously changing technology, the SABRE smart breaker was developed in partnership with Grid Interactive Things Inc. The SABRE smart breaker uses modern sensors and electrical principles to provide a more efficient and safe means to properly protect residential electrical systems while also providing readily available data from anywhere in the world so long as access to Wi-Fi is available. It is designed to allow the user to trip the breaker remotely or on its own accord, provide live readings of energy usage in the website, and provide intel on any disturbances allowing the user to determine if their system is compromised or could be in the in the future.

The SABRE smart breaker system opeartes in a simlar manner to that of a protective relay in substations. The smart breaker takes an input signal and scales it down via a step-down transformer. The scaled-down siganl is then read by one of two sensors: a hall effect sensor to detect sudden spikes in voltage and a Rigowski coil to for fault current detection. Both sensors communicate with an ESP32 microcontroller board to process the signal and determine its correctness. The microcontroller will use phasor mathematics to determine the error percentage to which it will then inform the user of via the website. The microcontroller has a connected antenna capable of communicating through Wi-Fi signals at distances of up to 50 meters.

Due to the sizing constraints of the project enforced by the University of Central Florida for safety purposes, the SABRE smart breaker will operate at 25 volts and 5 amperes. As a result, a smaller scale current blocking mechanism was employed with a solid-state relay interconnected between the microcontroller and sensors. Any potential disturbances found within the input signal by the sensors will then be determined by the microcontroller to which it will decide whether the solid-state relay should be activated to prevent current from reaching the load potentially damaging the circuit.

This document describes the design process of the SABRE smart breaker including the fundamental theories, technical applications, rationale behind each selection, and implementation process. Furthermore, this document details the software implementation, hardware schematics, standards, and codes used when designing the system, and administrative considerations. Final conclusions for future improvements are presented, along with an appendix that contains technical references and permissions.

Chapter 2 - Project Description

2.1 Background and Motivation

Electricity is everywhere in the modern world. In North America the rating at which an outlet operates at is 60 Hz, 120 VAC and a maximum of 20 Amps According to the National Electrical Manufacturer's Association (NEMA) [17]. Power at this level is enough to not only kill a person by itself but if improperly regulated, could burn down an entire building hurting or possibly killing anyone inside. When electricity such a high voltage/amperage is implemented into nearly every home in the country, safety implements have to be in place. In comes the modern breaker. A device that not only protects the circuitry inside your home from receiving irreparable damage but also prevents intense heat from generating inside the wirings that can cause potential fires. However, the breaker is rather simple in its design, as such the breaker itself is prone to damage with repeated use and if left unchecked can cause shortages and faults leading to circuit damage, insulation burns, and even fires [14]. Furthermore with the modern digitizing age, there is an increasing demand on every electrical grid in the world requiring an upgrade to the old. With the Smart Assessing Breaker for Residential Estates (SABRE), these issues can be a thing of the past.

The Smart 1 Phase Breaker for Residential Buildings looks to act as a low power prototype for a future full scale Smart Breaker that can optimize the conventional breaker by providing real-time monitoring and control of energy consumption of power within the home. The prototype also allows for a smarter way to trip power rather than causing strain on the mechanical aspect of a conventional breaker by including a Microcontroller device into the hardware making the breaker more reliant on circuitry giving it a safer, more reliable, and fast acting breaking than traditional means [5]. With a built-in antenna, the prototype also provides all this information to the user at any place in the world as long as it is connected to Wi-Fi, which allows the user to check in on any irregularities while they are away from home, allowing them to remotely trip the breaker in case of a potential hazard predicted by the app [1].

Throughout the past 70 years, overall electricity consumption has increased 14 fold in residential homes, consuming 1.42T kWh of electricity in 2022 alone. This includes a doubling in Miscellaneous Electrical Loads (MEL) over roughly the past 50 years, which is a measurement of power consumption that excludes systems that are a part of the building's main function such as HVAC and lighting. These MELs do include devices such as computers, consoles, televisions and other digital devices that have increasingly become something of a standard within homes across the United States [13]. These are just consumption statistics relating to residential buildings, without factoring in elements such as new large scale data centers which are being invested into more and more by commercial ventures and consume even more electricity than residential areas. In essence, society as a whole is reliant on electricity, and any way to minimize the consumption should be a necessity. This inspired our team to implement a solution on an individual level to reduce energy consumption from a ground up approach, if everybody is reducing their energy consumption, the overall strain on the grid can be managed more effectively, and have a significant reduction in electricity consumed. The Smart 1 Phase Breaker for Residential Buildings design is sponsored by Dr. Qun Zhou from the University of Central Florida, who has previously supported projects relating to minimizing energy consumption. Specifically, in a previous year, she sponsored a team that implemented a smart water heater that was designed to improve energy efficiency and manual control over the usage via wireless communication through a web-app service. To expand on this idea Dr. Zhou has tasked our team to design a Smart Circuit Breaker that innovates the conventional functionality of today's breakers by directly managing and optimizing power usage at the branch circuit level. Dr. Zhou also emphasized the potential market applications of this work through her collaboration with Grid Interactive Things Inc., which will serve as the intended customer for this project.

2.2 Goals & Objectives

The primary objective of this project is to develop a functional Smart Circuit Breaker capable of remotely monitoring power consumption in real time. The system will provide live power readings, incorporate protection features to safeguard the electrical system, and enable direct communication to enhance safety, efficiency, and user control in both residential and commercial applications.

For safety and demonstration purposes, the project will be implemented at a reduced scale, operating at 24 VAC and 5 A.

2.2.1. Goals

2.2.1.1 Basic Goals

- Build a Smart Circuit Breaker capable of protecting against overcurrent, short circuit, arc fault, and ground fault conditions being able to meet standard electrical safety code (NEC/UL/IEE/NEMA) on a reduced scale [14].
- Create a built-in communication system allowing for remote controlled access via a website to allow for real-time monitoring, remote control operation, and predictive maintenance insights through a user-friendly interface.
- Provide predictive fault detection analysis to inform the user of irregularities during power consumption of a home allowing them to respond accordingly.
- Minimize power consumption of each individual breaker branch circuit within the home.

2.2.1.2 Advanced Goals

- Integrate Sensors able to send data through to communication systems with minimal error with quick response time through the app/website.
- Incorporate components capable of withstanding surges to prevent replacements and repairs at later times.
- Implement temperature monitoring to warn users of potential heat surges or fires within the system.

2.2.1.3 Stretch Goals

- Develop a mobile app version of the web-app that includes all of the same functionalities of the web app, but with more convenient access by having it right on the user's home screen.
- Within the app, incorporate live power consumption that will also tell you the total charge of electricity consumption that month/pay period.

- Add machine-learning-based fault prediction and load optimization
- Incorporate integration with smart home/IoT platforms (Alexa, Google Home, etc..).
- Integrate live demonstration of power regulation with a device that clearly shows power consumption over time.

2.2.2. Objectives

2.2.2.1 Basic Objectives

- Develop an antenna system connected to the Microcontroller via an interchangeable PCB to provide real-time communication between the website and the Smart 1 Phase Breaker for Residential Buildings.
- Use a potential step-down transformer to run signals through Analog to digital converters directly into the microcontroller unit to use as a fault detection system.
- Implement signal analysis to predict fault detection within the entire power system of residential homes.
- Integrate power consumption regulation to minimize overall power consumption in a scaled down simulated residential home.

2.2.2.1 Advanced Objectives

- Communication Systems
    - Provide proper frequency range in order to communicate effectively with other systems and without noise distorting data.
    - Isolate PCB and antenna inside insulated material so any fault condition will not damage the system and also allow radio waves to send from the device effectively.
- System can be set to self-test regularly or manually test through the app or website
- Data
    - Incorporate database to allow for multiple months worth of data to be stored and analyzed at any given point.
    - Automatically delete information from the database after a set period of time to remove the need of the user to manually enter the app/website and remove their previous information to store new information while also minimizing software restraints.
    - Keep data password protected inside website and smartphone to ensure data privacy using two factor authentication
- Remove reliance mechanical aspect of conventional breakers and replace it with standard microcontroller board **for testing**
- Implement Depletion mode, N-type MOSFET as a method for the prototype to cut off current from the main power consumption circuit.

2.2.2.1 Stretch Objectives

- Replace microcontroller board with faster MCU or FPGA to implement into residential and commercial areas for faster real-time monitoring and reaction capabilities.

- Install LED light indicators inside the Breaker that illuminate when a specific voltage/current range is reached. For example, within a good reading we will see that a green LED illuminates, when the system predicts that a potential burnout or outlet replacement is required a yellow LED will illuminate and a red LED indicates that the breaker has been tripped and must be reset or replaced.
- 3-D print a usable case to place the prototype inside so that it can actually be tested inside a real home.
- Create a user-friendly, easy to install system where one can easily pick up and place the entire system without having to hire an electrician to install the entire device.
- Make the device as cost-efficient as possible while also reaching the maximum effectiveness that can be reached.

2.3 Description of Features and Functionalities

2.3.1 Hardware

2.3.1.1 Overall Functionality

The idea of the project is to stop an overload from occurring in a home system's main power breaker preventing damage to the circuitry and to the building itself. Instead of using a mechanical design, which is what the mechanical breaker has, the Smart 1 Phase Breaker for Residential Buildings uses an almost entirely electrical and digital design. The prototype will provide real-time monitoring over a residential building's energy usage providing information on any irregularities and predict potential disruptions to the website as long as it is connected to Wi-Fi. The website will also allow the end user to remotely trip their breaker in the event of any abnormalities.

2.3.1.2 MCU

The Microcontroller Unit that we are using is the ESP32 board which carries a dual-core processor of up to 240 MHz and 520 KB of SRAM. The board also allows for WIFI connectivity of up to 2.4 GHz and Bluetooth. Furthermore the board uses Digital to Analog and Analog to Digital Converters. Lastly, the board contains an ultra-low power co-processor to allow for sensor monitoring in sleep modes [5].
The dual-core processor cascaded with the power relay in conjunction with the ultra-low power co-processor will allow the ESP32 board to monitor live power readings in case of any power fluctuations and if triggered, the board will "activate" and react accordingly. Acting in low-power mode would give the most ideal results for power consumptions. The dual-core processing speed and RAM will allow for quick reactions and reaction speeds of up to speeds within the nanoseconds range. The WIFI capabilities of the board assist in the need for live readings of the power system to the app and website that we will require in our final design, when applied with the antenna this allows for full communication capabilities.

2.3.1.3 Antenna

The Adafruit microcontroller Feather V2 w.FL Antenna8 MB Flash + 2 MB PSRAM allows for 2.4 GHz range bandwidth suitable for the application to which we want to install [1]. Furthermore it easily installs to our microcontroller board, this removes the need to use modulation, demodulation, and encoding techniques as the board in conjunction with the antenna will handle this information for us. The latency for the antenna is roughly 2-10 ms on a local network sending 2-5 megabytes per second which can easily support our purposes of real-time monitoring and implementation. An alternative solution to the antenna could be a wired connection depending on how fast the end user would like their data to be accessed.

2.3.1.4 Multimeter Sensor

A desired multimeter must be able to withstand voltages of up to 24 VAC and currents of 5 A at the minimum in order to reliably monitor a power system continuously for years at a time. Furthermore, the data from this sensor must be accurately read and sent to remote devices in real-time to allow the end-user to decide what action should be taken. Furthermore, an additional component will be added to this multimeter sensor that picks up on potential spikes, potentially a power relay which can step down the high voltage that is being used and transfer this data to the microcontroller board and let the board react accordingly to whatever situation is being presented. Minimal power usage within this multimeter sensor is a priority to providing accurate data.

2.3.1.5 Power Relay

The power relay will act as a means to be able to obtain data from the intense power coming from the power supply without having to directly connect the microcontroller board to said power supply, otherwise the limited capabilities of the board will be overloaded and burnt. IT will act as a sort of transistor where we will get our small gate voltage to control the flow of current from one end to the other. Though the prototype is only meant to operate under 24 volts and 5 amperes at the maximum, the power relay will simulate these intense voltages without actually using them. We are looking to experiment with a power relay and a solid-state approach using MOSFETs. However, MOSFETs may not handle the and current demands in the context of mains power, possibly making the relay a more suitable choice

The power relay was brought up as an idea by Dr. Qun Zhou Sun in the sponsor meeting on September 2nd, 2025 after researching previous smart breakers for intense power needs, though for these kinds of power applications it has not been seen before, it was only natural to implement brand new methods of power scaling in order to get the most accurate data into our microcontroller board without completely destroying it.

2.3.1.6 MOSFETs

A configuration of MOSFETs may be used in place of the power relay to be used as the actual breaker portion of our system. Utilizing MOSFETs can provide switching speeds on an order of magnitude faster than that of traditional breakers, or the power relay mentioned previously. However, with use in the context of mains power, a configuration of MOSFETs may not be able to provide the necessary protections against arc faults, ground faults, and or short circuits.

2.3.1.7 Temperature Sensor

The temperature sensor will serve as a means to be as safe in the system as possible and as a second source of power readings. Normally in a conventional breaker, the mechanical aspect of the system will heat up to a certain extent; this will cause the breakage in the current stopping any further damage to the system. The temperature sensor will act in a similar manner but in this instance, it will serve as a backup for the MCU if it fails abruptly. In terms of priority, the MCU will take priority, then temperature will read for intense heat. Furthermore, it will detect any fires in the main system and immediately alert the end user through the app or website.

2.3.1.8 Switching PSU

As opposed to standard linear power supplies that look to step down higher voltages through transformers, switching PSUs makes this conversion through pulse width modulation. Switching PSUs tend to be noisier components as opposed to their linear counterparts, but they can be stuffed in a much smaller form factor while also operating at higher power efficiency. An example of a class small form factor switching PSU is actually the circuit used for the 5W block for Apple chargers. This exact same premise is what we will utilize to step down the 24VAC to 5VDC to provide low power to our MCU and auxiliary sensors.

2.3.2. Software

2.3.2.1 Website/App Interface

The Website and App interface are two key components in ensuring a user-friendly experience with our entire system; it will allow for live readings of the power supply at any given notice and give any irregularities that were found in this proposed system. Furthermore, when said irregularities are found, the website/app will be able to inform the end user and ask how they would like to proceed. Any option chosen will allow the user to remotely control their SABRE as long as they are using the correct software. The microcontroller board in connection with the antenna and the multimeter sensor are the key aspects providing this live data. The app/website will then store this information in its own database for the end user's own personal use. After a selected period of time, the data from this database will then be deleted allowing for new data to be stored inside the database providing a perpetual process of consistent data acquisition never forcing the end user to manually go in and correct any issues, the entire point is so that this prototype can be self-sufficient.

The website is already a requirement, but the team and the sponsors believed it would be better for residential and commercial use if the entire system was able to be accessed anywhere in the world.

2.4 Review of Prior Related Work

2.4.1. Available Devices on the Market

Similar products can be found from brands such as Lutron and Leviton. These will include all of the standard features of a conventional breaker while also implementing smart properties such as monitoring individual breakers, but it comes at the cost of having an entirely new panel installed. Lutron panels specifically leverage integrated breakers with DPMs that can receive commands from a centralized source within the main panel to manage respective functions for each load.

2.4.1.1 Current Market Offering – Leviton

15A 1-Pole AFCI Branch Circuit Breaker with Thermal Magnetic Trip Technology and Plug-On Installation. 120V
•EASY – Leviton's revolutionary design allows the entire Load Center to be wired at rough-in without any circuit breakers present
•SAFE – Leviton GFCI, AFCI and dual-function circuit breakers feature patented reset lockout technology, and will not reset if ground or arc fault protection is compromised
•INTUITIVE – LEDs communicate trip condition and type of fault, and remain illuminated even when tripped
•COMFORTABLE – Rocker-style switches require less activation force than traditional circuit breakers

2.4.1.2 Current Market Offering – Eaton

Eaton BR Thermal Magnetic Circuit Breaker, Type BRRP Industrial Remote Operated Circuit Breaker. 120-240V.
•SWAPPABLE – Individual breakers can be switched in and out of a single panel without having to do any replacements to the load center.
•SAFE – Includes GFCI, AFCI and dual-function circuit breakers feature patented reset lockout technology, and will not reset if ground or arc fault protection is compromised
•RELIABLE – Built with standard thermal-magnetic trip technology to ensure consistent protection against overloads and short circuits.

2.4.2 Previous Projects

In addition to this, Dr. Qun Zhou Sun had provided materials to a previous project that involved a similar idea, but like Lutron before, the design would require the switch of an entire panel box before the individual smart breakers could be utilized.

2.5 Specifications

*Table 1:*Specification of Overall Design

Overall System Specifications		
Specification	**Target Value**	**Tolerance**
Operating Voltage	24 VAC (single phase)	±10%
Rated Current Capacity	5 A	±5%
Trip Response Time (short)	< 5ms	IEEE Standard
Interrupt Rating	500 AIC	Scaled Down Proportional to the UL 489 Standard
Continuous Load Rating	80% of rated value	±5%

Comm. Range	≥ 15 m (indoor)	N/A
Operating Temperature Range	-10 °C to 60 °C	IEC 60068 Standard
Power Consumption (electronics)	< 5 W	±10%
Dimensions (HxWxD)	≤ 120 × 25 × 70 mm	Stand. Size - 0 tolerance

Table 2:Hardware Component Specifications

Component Specifications			
Component	**Specification**	**Target Value**	**Notes**
Microcontroller Unit (ESP32 Board)	Processing Speed	240 MHz	Handles sensing + comms
	SRAM	520 KBits	Memory Type
	Wifi Connectivity	2.4 GHz	Bandwidth of Wifi
	I/O Pins	34	Programmable Analog/Digital Pins for data transfer
	Supply Voltage	3.0 V - 3.6 V	Voltage required for power
	Communication Error handling	UART, I^2C, SPI	Error detection and handling mechanism
	ADC Resolution	≥ 12 bits	For current/voltage sensing
Antenna	Connector Type	w.FL	External antenna attachment
	Impedance	50Ω RF Path	WiFi and Bluetooth Transmissions
	Antenna Style	RP-SMA	adapter to board
Current Sensor	Measurement Range	0 - 10 A	Overcurrent Detection

	Accuracy	±2%	
Voltage Sensor	Measurement Range	0 – 24 VAC	For Monitoring
	Accuracy	±2%	
Temperature Sensor (TMP36)	Operating Range	-40 °C to 125 °C	Overheating Detection
	Voltage Input	2.7 V - 5.5 VDC	Power Supply
	Accuracy	± 2 °C	Accuracy Ranges over Temperature
Wireless Module	Protocol	Wi-Fi (802.11 b/g/n)	Could also support BLE
	Range	≥ 15 m	Indoor Environment
Relay Module (103020132)	Control Voltage	5 V	Logic signal for switching the relay between on and off
	UL Certified Load Capacity	10A 125VAC / 10A 110VDC	Signal being controlled by MCU
	Operating Time	15 ms	Switching Time
	Power Consumption	~0.45w	Energy Usage
	Ambient Operation Air Temperature	-40 °C to 55 °C	Operating Temperatures
N-Channel Power MOSFET (IRLZ44N)	V_{DSS}	55 V	Drain to Source Max Voltage
	$Resistance_{DS(ON),max}$ 25°C	0.022 Ω	Resistance Occurring in transistor
	$I_{D, cont}$ 25°C	47 A	Maximum Drain Current
	$V_{GS, off\text{-}max}$	±16 V	Maximum Gate to Source Voltage
Hall-Effect Sen.	Operating Voltage	3V - 12V	

	Output Operating Current	0A - 35A	Converts high current into low volt. signal for MCU
	Sensitivity	72 mV/A	
Switching PSU	Input Operating Voltage	24VAC	Converts 24VAC into constant 5W output
	Output Operating	5VDC, 1A	

2.6 Hardware Block Diagram

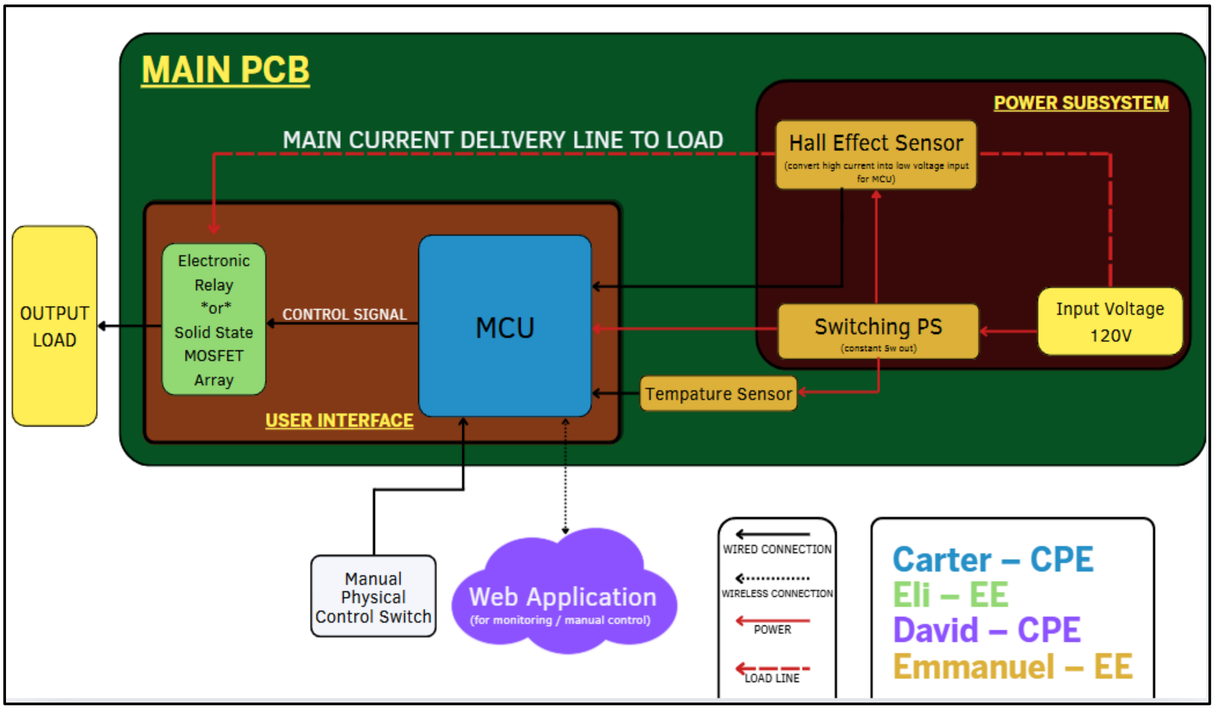

Figure 1: Hardware Diagram by Authors

2.7 Software Block Diagram

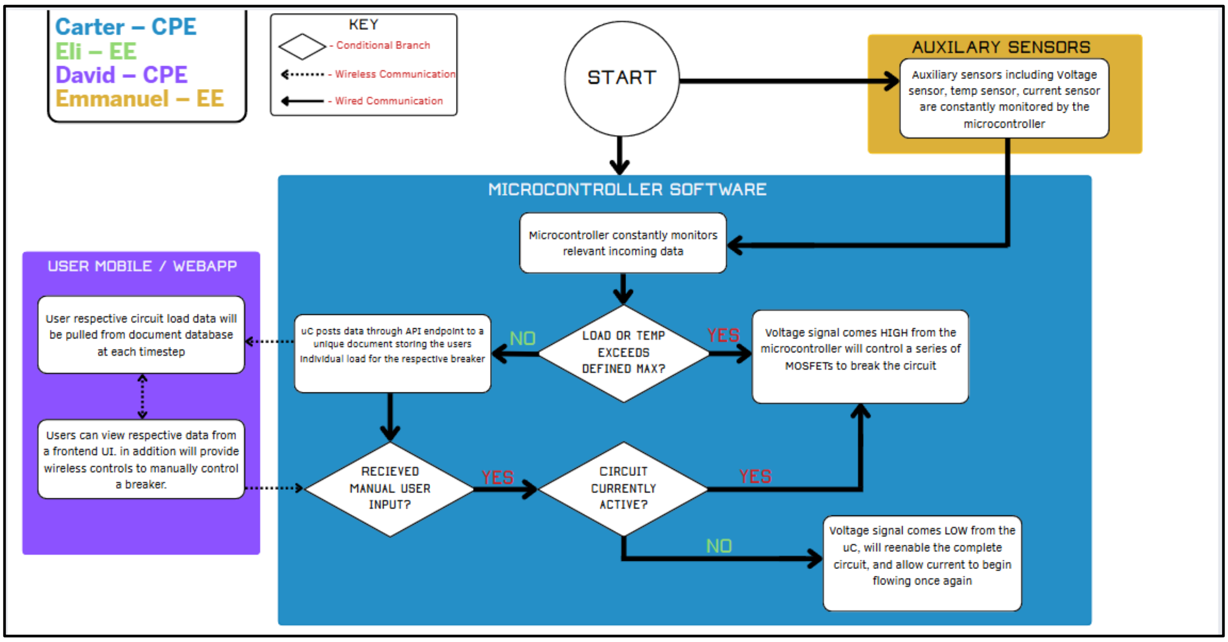

Figure 2: Software Diagram by Authors

2.9 House of Quality

The House of Quality provides us with a good insight into what we should expect when performing cost analysis on our project in areas that include: Safety, Marketability and Efficiency which will be analyzed against themselves.

In our analysis we found that cost was the most impactful factor when compared against the efficiency and safety of the device. Though we want the device to be as effective as possible to the end user, it would be of no use to them if the cost for materials and building was extremely high. In terms of cost analysis the group had decided that safety was the main objective of the project as the design was being funded by Dr. Qun Zhou Sun from the University of Central Florida. Other factors such as sensor accuracy, current capacity, and scalability fit into the theme of safety which was already discussed to have been of greater importance than the former.

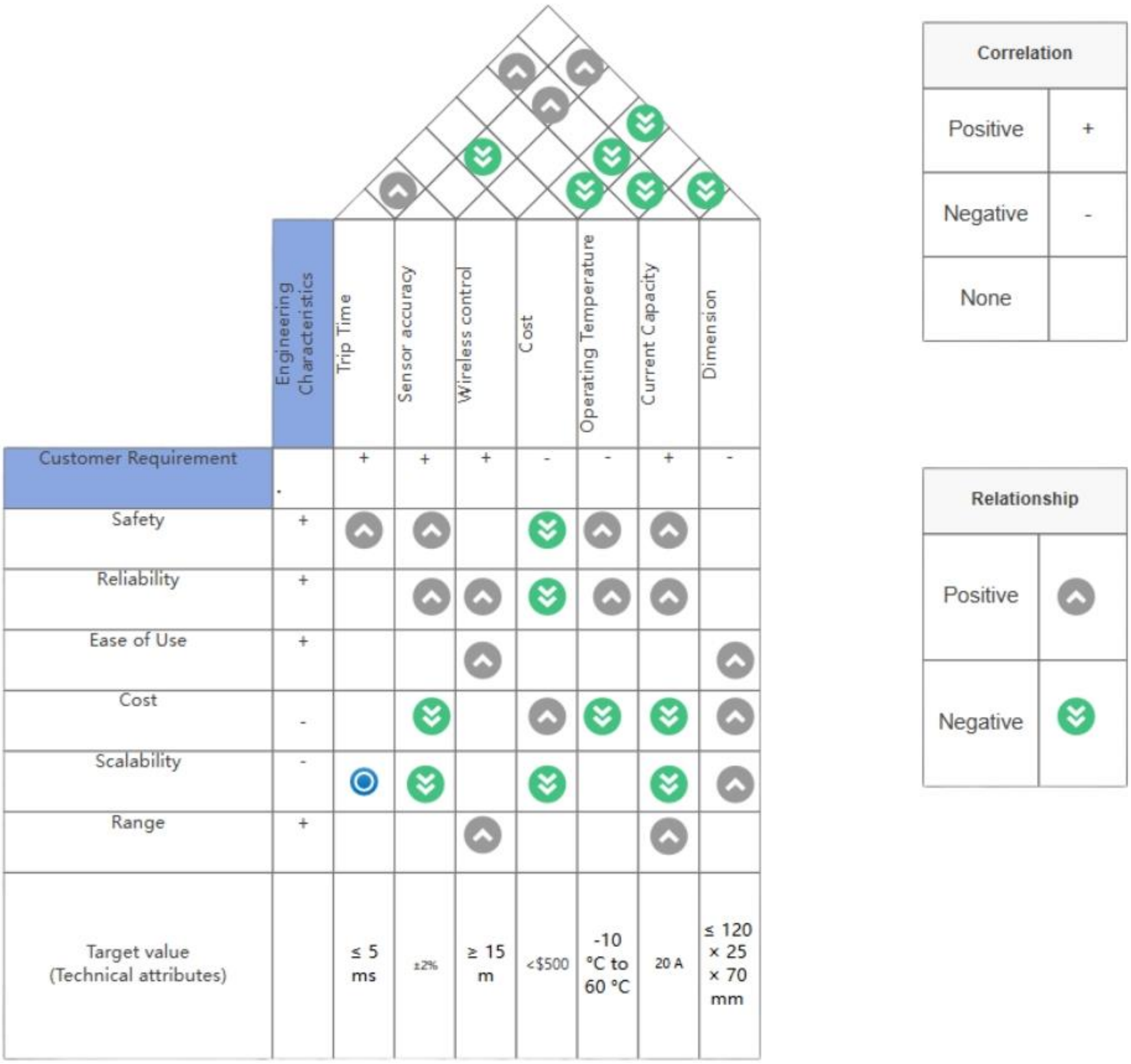

Figure 3: House of Quality by Authors

Chapter 3 – Research and Investigation

3.1 Research of Past Implementations

3.1.1 Overview of Available Smart Breakers

3.1.1.1 Common Features and Functionalities Amongst Smart Breakers

Smart breakers are similar to conventional breakers, yet they include electronic sensing, communication, and control features. Amongst these features, a smart breaker can include remote ON/OFF tripping that allows the user to shut off a circuit remotely via wireless communication. Energy monitoring can also be included to see what each circuit is using. This assists in managing energy usage and detecting issues within the load of the breaker to reduce usage overtime or even detect an issue before it happens in real time. For smart breakers with a microcontroller unit, scheduling is also included in the software to prioritize certain functions of the program and can prioritize energy usage overtime. Compatibility is also a major feature of smart breakers, so they can be installed into their respectable breaker panels with ease while also meeting code requirements and supporting required amperage specifications. Some can support integration such as if a home is automated with certain generative artificial intelligences, or if a home has solar panels included to generate power, some smart breakers are compatible with this type of technology when these same smart breakers are also able to provide battery backups in their systems. Automation can also be included to automatically shut off power to discourage any unnecessary energy usage not during peak hours such as late at night between the hours of 12 AM- 4 AM. Lastly, all smart breakers on the market can satisfy codes such as NEC, NFPA, arc-fault detection, ground-fault detection, and other necessary components within breakers to provide proper protection to homes.

3.1.1.2 Leviton R15-LB220-STR Gen2 20a Smart Branch Circuit Breaker with Remote 2 Pole

The Leviton smart breaker utilizes a Hydraulic-Magnetic tripping mechanism differently compared to the composition of regular breakers that utilize a thermal-magnetic tripping mechanism. A hydraulic-magnetic tripping mechanism uses a magnetic coil similar to how the thermal-magnetic mechanism uses a magnetic strip to trip the breaker; however, the hydraulic-magnetic mechanism uses a hydraulic oil damped piston to control trip timing. Though this tripping mechanism is relatively cheap and is suited for residential use, this is one of its advantages as the timing does not depend on the ambient temperature of the entire panel of the breaker since it does not include the bimetal strip which is one of the major disadvantages of the standard thermal-magnetic breaker. This also causes the breaker to be more precise in its tripping time hence it is more suitable for buildings that uses electronics such as data centers or smart systems. Lastly, because of the use of the Hydraulic-Magnetic tripping mechanism, the breaker is also able to trip whenever it detects fluid damping which could cause a major shortage in the system destroying any technology associated with the breaker as well. One of the only major issues that is associated with the hydraulic-magnetic tripping mechanism is the cost, it is much more costly, a single pole circuit breaker can cost as little as $8.00 in total, however, for this Leviton 2-pole smart breaker, the cost will be around $350, much more costly than the conventional breaker.

The Leviton Smart breaker also has the same capabilities of regular breakers that are on the market today such as being able to remotely breaker the circuit, being able to provide energy monitoring, include a scheduling algorithm/automation to disable nonessential loads during certain hours, include indicator LEDs to tell the user what kind of fault occurred that caused the circuit to break, it includes integration with their Whole-Home Energy Monitor app that allows the user to check their phone for potential breaks or disruptions, smart load shedding so that when a backup power or generator integration is put in place, the system can get rid of nonessential elements during the time that the backup power is on, and includes remote diagnostics and firmware updates to keep the user updated constantly about the energy usage in their home.

The breaker also comes with a few downfalls of its own, for example: The breaker includes a 2-year warranty due to its over-reliance on electronic components such as sensors that can degrade over time leading to a breaker malfunctioning with time. In some areas, remote breakers do not comply with safety standards and constraints, so they are banned in certain areas. Lastly, the Leviton Sensor is prone to overloads and thermal stresses due to it relying on both the hydraulic-magnetic strip and the inclusion of sensing electronics, so the entire system must constantly be performing under top performance conditions which contributes to its 2-year warranty and degradation overtime, anything less than perfect from this breaker can cause the entire system to malfunction.

In conclusion, the LevitonR15-LB220-STR Gen2 20a Smart Branch Circuit Breaker with Remote Control, 2 pole is very strong in its areas in terms of its smart detection capabilities, but this also leads to its downfall. Its overreliance can cause the breaker to degrade rapidly over time, leading to system malfunctions, meaning it can no longer meet the standards of a breaker; hence it can no longer be used.

3.1.1.3 Eaton AbleEdge Smart Breaker

The Eaton smart breaker is a relatively new generation of smart circuit breakers that are designed to merge electrical protection with intelligent energy management. Traditional breakers only serve to interrupt faults currents, meanwhile the AbleEdge smart breaker is able to integrate communication, automation, and monitoring capabilities that make them central components in modern smart homes. Eaton's design allows homeowners to track real time energy consumption, optimize energy usage, and integrate renewable sources like solar energy into their home power system.

The Eaton smart breaker uses the same type of tripping style as the Leviton Smart breaker or the hydraulic-magnetic tripping mechanism where it uses a hydraulic piston to control delay time, meaning that its trip timing precision is high. Furthermore, the smart breaker uses a BR plug-on style which allows the breaker to attach to the panel's bus bars and establish a neutral connection. With this type of connection, the BR type load centers and meter breakers are able to convert traditional breakers into modular smart panels. In other words, these new smart panels support Wi-Fi-connectivity and integration with home energy systems. This allows the user to monitor the home energy consumption and control energy systems directly from anywhere in the world without any issue if there is Wi-Fi connectivity. Furthermore, traditional breakers generally have to be replaced entirely, though with this BR type of loading, the modular breaker can easily be replaced with any type of conventional breaker; the whole system does not have to be replaced. With this BR type of loading, the Eaton AbleEdge Smart Breaker is also able to have priority and non-priority circuits. Given a scenario in which a backup battery supply is in place, the smart breaker will automatically use this supply whenever the need arises. Furthermore, the user can instruct the breaker to focus on the load that is a higher priority when the backup battery is in use to conserve the battery. A solar storage system can also be used with this battery backup in conjunction with the battery itself; the point of the backup system is to extend the backup duration for as long as possible.

Depending on user preferences and experience, the smart breaker can also be coded to have automation incorporated with the design, hence everything can be monitored and controlled without the user having to be involved. This automation will be able to control data-logging and home automation systems. Despite this, the smart breaker is still able to meet safety and code requirements. Due to this, however, the smart breaker is quite costly as it ranges in the price of $200 compared to the price of conventional breakers, which can cost as little as $8.00.

Beyond basic breaker replacement, the Eaton smart breaker includes revenue-grade metering with an accuracy rating of roughly 0.5%, it monitors voltage, current, frequency, power, and energy. Useful for understanding exact energy measurements when monitoring load consumption. Due to its solar powered energy capabilities, the smart breaker is bidirectional-capable, in other words, it can support distributed energy resources such as solar panels or battery storage in both directions, the smart breaker can either import these resources or export them if needed. The specs of the breaker include a 2-pole 60A, 120/240 V, plug-on, Wi-Fi-enabled breaker in the BR style as discussed before with an interrupt rating of 10 kAIC rating. The breaker is also rated for an ambient temperature of down to –30 degrees Celsius or up to 40 degrees Celsius with a humidity rating of up to 90%.

In conclusion, the Eaton AbleEdge Smart Breaker represents a significant step towards the modernization of residential electrical systems by merging traditional protection with intelligent energy management. Its precise hydraulic-magnetic tripping mechanism, modular BR plug-on design, and advanced Wi-Fi connectivity make it both a reliable and flexible solution for smart homes. Beyond safety, it gives homeowners the opportunity to actively monitor, control, and optimize their energy usage, extending the functionality of the electrical panel far beyond its conventional role. Though its long-term benefits in terms of energy efficiency, automation potential, compatibility with renewable systems such as battery storage make it an investment to think over, the smart breaker presents itself with its own issues. The cost is rather large for a smart breaker sitting at roughly $200 for a new model, as well as the fact that due code regulation across certain states in the United States restricting the use of remote breakers, and lastly the fact the breaker is prone to degrade overtime due its large reliance on electrical components. This breaker is a worthwhile investment to think over in terms of an economic standpoint, and some of its features are worth considering within the scope of this research paper.

3.1.1.4 Tuya Wi-Fi Smart Circuit Breaker with Metering

The Tuya Smart Circuit Breaker with Metering is an emerging class of cost-effective, IOT-enabled power control devices aimed at bringing energy management to both residential and light industrial applications. Unlike traditional electromechanical breakers that function solely as fault protection devices, the Tuya smart breaker integrates wireless communication, energy monitoring, and remote-control capabilities into a compact form factor compatible with standard electrical panels. This design allows users to remotely monitor power consumption, control circuit operation, and automate load management directly through the Tuya Smart or Smart Life mobile applications. At its core, the Tuya smart breaker is designed to enhance energy visibility and operational flexibility. Through its built-in Wi-Fi module, the breaker communicates with a cloud-based platform that collects real-time electrical data, including voltage, current, power factor, and total energy consumption (kWh). Users are able to access these measurements remotely from a smartphone or tablet, enabling informed decision-making regarding energy efficiency and consumption patterns. This capability makes the device especially attractive for smart home integration where users may wish to monitor specific loads such as HVAC systems, water heaters, washers, dryers, electric vehicle chargers, or other larger scale two phase power loads. By allowing real-time control and monitoring, the Tuya smart breaker effectively bridges the gap between traditional protection hardware and modern smart home ecosystems.

In terms of functionality, the Tuya smart breaker supports several intelligent control modes, including manual switching via an onboard toggle, remote switching through the mobile app, and automated scheduling based on user-defined routines. For example, users can configure the breaker to power off non-essential circuits during nighttime hours or when occupancy sensors detect that no one is present in the home. The breaker also supports integration with popular voice assistants such as Amazon Alexa and Google Assistant, allowing for voice-activated control. Beyond user convenience, such automation contributes to significant energy savings and load optimization, particularly in applications where multiple high-current devices operate simultaneously. In conjunction with its intelligent modes, another key feature of the Tuya breaker is its metering capability, which distinguishes it from many low-cost smart switches and plugs. The built-in metering function provides accurate real-time measurements of electrical parameters, enabling users to identify energy-intensive circuits and optimize their consumption patterns. In industrial or commercial environments, this function allows facility managers to track power distribution across circuits, detect abnormal consumption, and perform predictive maintenance before faults occur. Furthermore, the breaker can issue alerts or notifications through the app if abnormal voltage or current levels are detected, adding an additional layer of safety monitoring to the system. From a technical perspective, the Tuya Wi-Fi Smart Circuit Breaker is typically rated for 1-pole operation at 32 A, making it suitable for single-phase residential loads. It is built to meet standard IEC and CE electrical safety requirements and is compatible with most distribution panels designed for modular miniature circuit breakers (MCBs). Internally, the breaker employs a conventional thermal-magnetic tripping mechanism to ensure reliable overcurrent and short-circuit protection. This combination of conventional protection hardware with modern IoT technology offers a practical balance between safety, affordability, and digital functionality.

The device's affordability is one of its most distinguishing characteristics compared to higher-end competitors such as Eaton's AbleEdge or Leviton's 2nd generation Smart Breakers. The Tuya Smart Breaker is priced around $30-$40, the breaker provides an accessible entry point for users seeking smart functionality without investing in an entirely new load center and having to pay a larger price similar to that of the Eaton or Leviton Smart Breaker. Though inexpensive compared to the other breakers, this also implies certain drawbacks for the Tuya Smar Breaker. For instance, most Tuya models rely exclusively on Wi-Fi and cloud Communication, which may restrict performance during internet outages or raise cyber security concerns. Additionally, the device lacks advanced protective features such as arc-fault or ground-fault detection, and it may not integrate seamlessly into existing load centers within the United States due to mechanical and certification differences, hence employing this type of breaker into residential buildings may not be up to NEC standards.

Despite these constraints, the Tuya Wi-Fi Smart Circuit Breaker demonstrates the expanding potential of IoT technology in an affordable manner within the electrical protection industry. Its open API and compatibility with the Tuya ecosystem make it an appealing option for experimentation, system integration, and prototyping in academic and industrial research. For engineers and designers, it provides a practical platform for studying the interaction between electrical hardware and cloud-based monitoring systems. For consumers, it represents and accessible step toward greater control over household energy management.

In summary, the Tuya Wi-Fi Smart Circuit Breaker with Metering exemplifies a new generation of intelligent, low-cost circuit protection devices that blend real-time data acquisition with remote operability. While it may not yet meet the full performance and safety standards of premium smart breaker systems, its simplicity, affordability, and adaptability make it a valuable model for understanding the future of decentralized energy control. As IoT–enabled electrical infrastructure continues to evolve, products like the Tuya smart breaker serve as a key steppingstone towards the development of the SABRE smart breaker.

3.1.1.5 Amber Solutions Smart Circuit Breaker

The Amber Solutions Smart Circuit Breaker is a next-generation breaker concept designed to radically upgrade conventional circuit protection by embedding solid-state switching. IoT connectivity, and whole-building energy sensing. Unlike traditional breakers that rely solely on mechanical/thermal-magnetic tripping. This device integrates advanced electronics and intelligence into the circuit breaker footprint. The intention is to transform the breaker from a passive protection device into an active node in the home or building energy system, enabling real-time measurement, control, automation, and enhance safety.

Amber's design approach diverges from standard breakers in several keyways, First, the breaker uses a solid-state or hybrid electro-mechanical/solid-state switching architecture, which delivers arc-free switching, much faster response time to electrical faults, and improved reliability by reducing mechanical wear. Second, the breaker is built for whole-building energy awareness, embedding sensors/meters at the breaker level to monitor voltage, current, energy consumption, power quality, and optionally bidirectional flows in buildings with renewables or storage. Third, it supports wireless communications and IoT integration: settings and status can be accessed remotely, and the breaker may serve as a control point for loads or part of a larger home automation ecosystem.

The functional capabilities of the Amber breaker are significant. The solid-state switching means that tripping speeds are potentially thousands of times faster than legacy breakers, offering less arc exposure and reduced fire risk. For example, Amber claims its switch can disconnect in fractions of an AC cycle versus multiple cycles for a mechanical breaker. Embedded metering allows each circuit to have visibility into energy use and abnormal conditions. The IoT connectivity enables remote on/off control, scheduling, alerting abnormal loads or faults, and integration into home/energy-management platforms. Because Amber's architecture supports retrofitting into existing panels (according to their announcements), the device is positioned as both for new-build and retrofit applications.

From a design and systems perspective, the Amber breaker offers a networked embedded platform where sensors can monitor current/voltage/power. Then the microcontroller will interpret the data collected from the sensor, next a solid-state switching hardware executes protective or load-management actions. Next, a communication interface transmits data or receives commands so that the firmware can implement logic such as load shedding, anomaly detection, and integration with energy storage or solar systems. From this, the breaker as it is known is no longer simply just a protection device, but part of the control/automation plane of the electrical system. Amber's IP portfolio includes claims for extraction of DC power directly from the AC mains to power embedded electronics, MOLSFET-based switching, high-speed digital detection of arc/inductive surges, and solid-state architecture suited for retrofit in standard footprints. The Amber breaker concept also supports important trends in residential or commercial energy systems: increased electronification (EV chargers, heat pumps), distributed energy resources (solar + battery), load management and demand response, and increase fault detection/resilience. Because the breaker can monitor and control loads at the circuit level, one can envision a backup-power scenario where non-essential loads are shed automatically, or solar export is managed at the breaker level, or alerts are triggered when a sub-panel shows anomalous current/voltage signatures. The breaker thereby supports system-level energy optimization, beyond simply protecting wires. This aligns with amber's stated vision of enabling a "5th utility" in homes. That said, there are important considerations when evaluating a product such as this. Amber publicly announced the smart breaker concept and its underlying technologies, full commercial-availability details (specs, ratings, certifications) which appear limited in public disclosures. Therefore, a comprehensive design assessment must consider aspects such as the mechanical fit and form factor, specifically whether the device can retrofit standard breaker panels along with its interrupt rating (kAIC), compliance with safety and electrical code standards such as UL 489, UL 489k for solid-state breakers, and relevant IEC regulations. Additional design factors include thermal performance, firmware reliability, cybersecurity in IoT connectivity, maintenance and firmware-update policies, overall lifecycle cost, and compatibility with existing panel architectures and wiring configurations. Amber has stated that its modules meet or reference UL certification standards, which supports its position as a viable prototype for smart circuit protection systems. Furthermore, the high degree of system integration in a smart breaker introduces several broader design challenges. Network dependence, for example, raises questions about functionality during Wi-Fi outages, while increased connectivity introduces potential vulnerabilities in terms of data privacy, cybersecurity, and susceptibility to unauthorized remote control. Other practical concerns include the differences in failure modes between solid-state and mechanical switching mechanisms, as well as the cost and complexity associated with retrofitting existing electrical panels. Acceptance by certified electricians and inspectors is another critical factor influencing large-scale adoption.

The Amber Solutions Smart Breaker can serve as an effective benchmark for ongoing smart breaker development efforts. Key design requirements that can derived from Amber's architecture include ultra-fast tripping response through solid-state switching, embedded metering for detailed energy monitoring, robust IoT connectivity, retrofit compatibility, modular installation, load-management capability, and system-wide energy visibility. At the same time, certain gaps remain open for future research and development-namely; improvements in cost optimization, standardized communication interfaces, broader panel compatibility, and detailed performance validation for mass deployment.

In conclusion, the Amber Solutions Smart Circuit Breaker represents a forward-looking advancement in circuit protection technology by integrating protection hardware with embedded intelligence, digital control, metering, and IoT capabilities. Although the technology is still in a developmental stage with limited market availability, its architecture highlights the potential for circuit breakers to evolve beyond simple safety devices into intelligent nodes with a connected energy-management ecosystem. The Amber breaker demonstrates both the technical promise and the engineering challenges of merging solid-state switching and IoT systems, providing valuable insight for ongoing research and future innovations in embedded smart power systems.

3.1.1.6 Multi-Functional Smart Wi-Fi Circuit Breaker (63 A)

The GEYA Tuya-based Multi-Functional Smart Wi-Fi Circuit Breaker rated 6 A to 63 A is a new generation of intelligent miniature circuit breakers that merges conventional electrical protection with cloud-based monitoring and remote control. Similar to higher end competitors such as the Eaton AbleEdge and Leviton Smart Breaker series, the GEYA model adopts a design philosophy that integrates IoT connectivity, adjustable protection thresholds, and real-time metering within a compact DIN-rail form factor. While it maintains the mechanical reliability of traditional thermal-magnetic breakers, the addition of Wi-Fi and microcontroller-based logic allows for automation, energy management, and remote supervision.

The GEYA smart breaker's protective mechanism is based on a conventional thermal magnetic tripping system combined with an embedded microcontroller that supervises voltage, current, and temperature measurements. This hybrid approach enables the breaker to maintain the proven dependability of mechanical protection while introducing configurable trip settings through software. The unit's rated current can be adjusted anywhere from 1 to 63 amperes, making it versatile for both residential and light commercial applications. Over-voltage and under-voltage protection can also be set by the user through the Tuya Smart mobile application. When abnormal conditions are detected, the microcontroller initiates an electronic trip command that drives an internal solenoid to disconnect the circuit. Unlike standard circuit breakers, this process does not rely solely on the bimetal strip and magnetic coil to react passively; instead, it provides faster, programmable fault response.

Physically, the GEYA smart Breaker uses a one-pole-plus-neutral modular layout suitable for standard DIN-rail mounting, allowing it to retrofit easily into existing subpanels or smart distribution boxes. The housing is composed of flame-retardant PA66 nylon, providing high mechanical strength and thermal endurance. Electrically, the device is rated for AC 230 V operation and supports a short-circuit breaking capacity of approximately 500 A. Though this value is significantly lower than the 5 kAIC ratings of U.S. residential breakers, it is sufficient for many light-load or branch-circuit applications where available fault current is lower. The breaker also boasts a mechanical lifespan of roughly 100,000 operations and an electrical endurance of 10,000 switching cycles, demonstrating reasonable durability for a unit with integrated electronics.

For a functional perspective, the GEYA Smart Breaker integrates Wi-Fi communication compatible with the Tuya Smart and Smart Life apps, granting users access to circuit control and monitoring through smartphones, tablets, or smart assistants such as Amazon Alexa and Google Assistant. Through this interface, users can remotely open or close the circuit, schedule operations, and configure threshold alarms. Built-in energy metering continuously measures voltage, current, power, and accumulated energy (kWh), which can be visualized in the application's dashboard. This metering capability allows homeowners and facility managers to identify abnormal consumption patterns, enabling early detection of inefficient loads or potential wiring issues. Automation routines can be created to reduce ener4gy waste-for example, by shutting off non-essential circuits during nighttime or when occupancy sensors indicate no presence.

In addition to standard electrical protection, the GEYA Smart Breaker includes several secondary protective functions that enhance operational safety. A high-temperature detection circuit monitors the breaker's internal temperature, automatically opening the circuit if it exceeds 80 degrees Celsius. Adjustable delay settings for voltage faults allow the user to prevent unnecessary trips caused by short-term transients, improving stability, in areas with fluctuating mains power. Furthermore, because the unit's protection parameters are software-configurable, it can be optimized for different regional grid conditions or specialized loads such as HVAC compressors, EV chargers, and solar inverters.

Despite its many benefits, the GEYA Wi-Fi smart breaker presents several limitations that must be considered. First, its relatively low interrupt rating limits its application in main service panels or in locations with high fault current availability. Second, the device's reliance on Wi-Fi connectivity and cloud-based Tuya servers means that its smarts functions are network-dependent; during outages or connectivity failures, remote control and monitoring become unavailable, through the mechanical breaker remains functional locally. Third, because GEYA's smart breaker line is primarily certified under CE and TUV standards rather than UL 489, its installation in North American systems may not meet local code requirements without additional approvals. Long-term reliability of the embedded electronics is another potential drawback, as constant exposure to elevated temperatures and electrical noise within a distribution panel can accelerate sensor and component degradation.

However, the GEYA breaker's advantages in terms of configurability, real-time monitoring, and affordability position it as an accessible alternative to more expensive smart breaker systems. Priced at approximately $60 for the 63 A version, it provides functionality that rivals high-end models costing several hundred dollars. For research and prototyping purposes, the device is particularly valuable since it represents a fully integrated example of how embedded microcontrollers and wireless communication can be incorporated into traditional electromechanical hardware. For embedded systems research, the GEYA breaker offers a compact case study of sensor integration, threshold detection algorithms, and remote control through IoT protocols-all within a power-electronic safety device.

In conclusion, the GEYA multi-Functional Smart Wi-Fi Circuit Breaker (63 A) exemplifies the growing convergence of electrical protection, automation, and digital communication in modern energy systems. While not as robust or as heavily certified as enterprise-grade smart breakers, it demonstrates the technological trend toward networked, software defined electrical components that enable finer energy management at the circuit level. By offering real-time feedback, customizable protection, and remote operation, this breaker serves as a bridge between affordable residential automation and the advanced smart-panel architectures being developed by leading manufacturers, As a mid-range, cost-efficient design, the GEYA Smart Breaker provides an excellent benchmark for analyzing the progression of smart protection technologies and their implications for embedded power systems research.

3.1.1.7 Guetneu Smart Wi-Fi Circuit Breaker (DIN-RAIL, 63 A)

The Guetneu Smart Wi-Fi Circuit Breaker is a DIN-rail mounted miniature circuit breaker that exemplifies the low-cost, IoT-driven class of smart protection devices emerging from OEM suppliers in Asia. Unlike premium, UL-listed load center breakers designed for direct replacement of U.S. panel branch breakers, the Guetneu unit blends a conventional thermal-magnetic switching element with an embedded electronics subsystem (microcontroller, communications module, and sensor front-end) to deliver remote ON/OFF control, real-time metering, and configurable protection thresholds. The product line is commonly marketed under several vendor names and integrates with cloud ecosystems such as Tuya/Smart Life or eWeLink, enabling smartphone control, scheduling, and voice-assistant integration for residential and light-commercial circuits.

The breaker's protective core remains a thermal-magnetic mechanism similar to many miniature circuit breakers (MCBs): a bimetal element handles sustained overloads while an electromagnetic element provides fast response to short-circuit currents. The novelly lies in the addition of an embedded microcontroller that continuously samples current and voltage via front-end sensors (shunt or CT and voltage divider), interprets these signals for energy metering and trip logic, and actuates a solenoid/relay drive to open the contact when a software determined fault is detected. This hybrid architecture preserves baseline mechanical fail-safe behavior (the mechanical contacts still open under severe faults) while permitting software-configured thresholds (for example adjustable overload trip current, over/under voltage limits, and temperature-based alarms). Several vendor datasheets and retail listings indicate rated current ranges up to 63 A and operational voltage windows roughly spanning 76-265 VAC for single-phase applications-specifications that make the device suitable for many branches circuit uses but that also imply careful site assessment before main-panel installation.

Functionally, the Guetneu breaker implements a standard suit of “smart” features: 2.4 GHz Wi-Fi connectivity for cloud pairing (Tuya/Smart Life or eWeLink), remote switching via mobile app, schedule/timer tasks, real-time energy metering (instantaneous current, voltage, power, cumulative kWh), and alarm/notification delivery for threshold events. The unit often advertises additional protective modes such as leakage (earth-fault) detection, over-voltage/under-voltage protection, and internal temperature monitoring that preempts thermal runaway inside a crowded panel. These capabilities transform a branch circuit into an active node for demand-side management and allow homeowners or facility managers to visualize consumption patterns and implement simple automation for example the ability to she nonessential loads during peak tariff windows. Vendor product pages and multiple marketplace listings conform to app interpretability and mattering capability as central selling points.

Mechanically and electrically, the Guetneu device is packaged for DIN-rail mounting with a compact footprint compatible with many distribution and subpanel installations. Typical dimensions and 35 mm rail compatibility make it attractive for retrofitting into industrial control boxes, consumer subpanels, or renewable energy combiner panels. However, the interrupting capacity listed in many OEM datasheets varies and is often modest: while some suppliers claim 6-10 kA short-circuit breaking capability for similar designs. Other listings and user reports caution that the practice al high-fault current capability is limited compared to U.S. residential branch breakers (which commonly specify 5-10 kAIC or higher depending on panel and utility). This variability necessitates a site-specific fault-current analysis before deploying the breaker in applications where high prospective fault current exists.

From the embedded systems perspective, the Guetneu breaker is a compact example of several engineering concepts. The internal electronics typically center on a low-cost MCU (many modern Tuya based d modules use SoCs such as the BK7231N family) coupled with an ADC and metering IC for precise measurement. Community teardown and forum reports for comparable Tuya/OEM breakers reveal common component families (Wi-Fi SoC, overregulation, meeting ICs like BL0942/BL0937 variants, and FET/relay drivers), indicating the firmware must juggle real-time measurement tasks, denounced trip decision logic, network stack handling , and user-interface/reporting tasks while operating within constrained memory and timing budgets. This mix of real-time and networked functions offers a rich testbed for studying interrupt handling, task scheduling, memory addressing of peripheral registers, ADC calibration routines, and resiliency strategies in embedded firmware.

Advantages of the Guetneu class of breakers are clear: affordability, modular DIN-rail form factor for retrofit or panel subassemblies, and integrated metering and remote control that lower the barrier for implementing distributed energy management. Price points for OEM 63 A DIN-rail Wi-Fi breakers are typically a small fraction of premium smart breakers, making them attractive for experimental deployment, research prototypes, or for small commercial installations where advanced analytics are not required. The breaker’s scheduling, remote trip, and metering features readily support studies on load-shedding algorithms, demand response strategies, and the effect of local intelligence on energy consumption profiles.

Nevertheless, several important limitations and safety considerations must be emphasized. Certification and code compliance are primary concerns: many Gueneu/OEm smart breakers are CE/CB/TUB-listed in vendor literature, but explicit UL 489 or UL 1077 listings (commonly required by U.S. inspectors for branch or feeder breaker replacements) are not always present or clearly documented. The result is potential incompatibility with North

American inspection regimes or insurance requirements unless additional approvals are secured. Network dependence is another issue: while the mechanical breaker retains local protective function, cloud or Wi-Fi outrages all disable remote monitoring and scheduling and may complicate automated control schemes, an important consideration for safety critical circuits. Cybersecurity and firmware update policy are nontrivial concerns as well; devices tied to general purpose cloud ecosystems inherit a larger attack surface than isolated mechanical devices, so firmware integrity, secure boot, and OTA update practices must be scrutinized. Finally, the longevity of the embedded electronics in the electrically noisy, thermally stressed environment of a breaker panel is less well characterized than the long history of purely mechanical breakers.

In summary, the Guetneu Smart Wi-Fi Circuit Breaker (DIN-Rail) represents a cost-effective alternative within the smart protection device market, delivering core smart control and monitoring capabilities without the higher premiums associated with industrial or brand-name competitors such as Eaton or Leviton. While it lacks advanced analytical features, deep ecosystem integration, and premium build quality, its accessible price point and essential automation support make it highly competitive for residential and small commercial applications where cost efficiency outweighs advanced system functionality. When compared to higher-end systems, the Guetneu breaker demonstrates that fundamental smart energy management and remote control can be achieved at a fraction of the cost, making it a practical example of how IoT integration continues to democratize electrical infrastructure. This comparison underscores the growing segmentation in the smart breaker market—where affordability and functionality can be balanced to meet diverse consumer and installation needs.

3.1.2 Comparison of Traditional Breaker Vs. Smart Breaker

3.1.2.1 ADC v. Mechanical Breaker

In order to make the breaker smart breaker we needed to make the entire prototype electrical in a sense, whereas conventional circuit breakers tend to go for a mechanical approach by having a coil heated up to which point it will bend and trigger a manual lock to open the circuit. Though this is efficient and entirely capable of providing protection to a home, a digitized approach can be taken instead, and for the prototype to be self-assessing and predictive, we need it to be digitized. The approach is to take our analog signal and apply it through an analog to digital converter so that we can then run this new digital signal through our MCU which will then use the software programmed to compared the digitized signal to a pre-made signal that is comparable to a scaled down version of the analog voltage signal that runs through a standard breaker both single pole 120 V and double pole 240 V according to the National Electrical Code [18]. Of course, our prototype is going to be a scaled version of this by nearly a factor of ten times, but it will still be treated as though it is a high-voltage wire. Once properly scaled down through a potential transformer, the signal will now be able to be properly converted from an analog signal to a digital signal which will then be able to pass through a MCU which then it will be compared and assessed accordingly.

For our prototype, the ESP32 development board contains an ADC with a maximum VAC input of 3.3 volts, hence it works perfectly for our purposes. The only caveat here is that there are only two analog inputs for the ADC and whenever we are running communication through WIFI through the board, it stops any input from entering through the second ADC input. Because our board is going to be communicating with the web application constantly, it is realistic to expect that we are only going to be using one input for this board unless another board with more ADC can be found. For our purposes of a single-pole breaker, one ADC input is all we need.

As for speed, the frequency we will be operating at is the same as in residential buildings which is 60 Hz [17], for the ADC conversion these 100 samples per cycle and luckily the ADC can operate at 6000 samples per cycle which is more than enough for what we need. As for real-time speed, the ADC can convert an analog signal into a digital signal at a speed of 167 microseconds which can be reduced to 50 microseconds if we reduce from 12-bit resolution to 9-bit resolution, which could be likely since we do not need much high-processing information. For a residential conventional breaker, it can take anywhere from 10 milliseconds to 0.5 seconds to open a potential overload, depending on the model for the conventional breaker. As of right now, this prototype is significantly faster than conventional means, though this is strictly speaking about the ADC.

Schneider Electric's QO Series Circuit Breaker is a conventional circuit breaker used in most modern-day homes; its operation time depends on the current running at which the tripping time can vary anytime between .02 seconds to .4 seconds. It uses the conventional Bimetal strip which heats up to trip the breaker which causes its relatively slow tripping time. Though for conventional means, it operates just fine [19].

3.1.2.3 Traditional Breaker Vs. Smart Breaker

Standard breakers must adhere to strict codes found in the NEC [14], they are made up of complex wirings which can be broken down into two main components that trip the breaker whenever there a need is presented. The components consist of the Bimetallic strip and the Magnetic Element. The Bimetallic strip works by equation $E = I^2 Rt$, Kirchoff's voltage law with respect to time. Where the longer the element has energy put through it, the more energy is dispersed. The energy that is lost is dispersed across the bimetallic strip, one metal will expand when heated, and the other will expand less. This causes the strip to bend in a predictive nature towards one specific direction. Attached to this bending end of the strip is a latch/spring-loaded mechanism that holds the breaker's contacts closed, but when heated to a certain extent, the latch will release the spring mechanism causing the contacts to open restricting current to flow any further [20]. In essence, the bimetallic strip operates based on heat due to the equation as described previously, though this does cause the breaker to trip rather slowly in this aspect, yet it still is effective.

The second component of a conventional breaker consists of its magnetic element which primarily relies on its electromagnetic properties. It consists of a solenoid coil, plunger, and a spring-loaded latch. First, the power signal runs through the solenoid coil. Due to Maxwell's equation: $\nabla \times E = -\frac{\partial B}{\partial t}$, which states that as an electric field is flowing there will be a magnetic field rotating around the electric field in a counterclockwise direction, however, due to the solenoid's design which consists of a coil being wrapped cylindrically along an axis around no material, just air. Due to this design, the magnetic field of the electric field can cause any magnetic field to be pulled inward towards the solenoid. This is advantageous for the plunger as the plunger is made up of magnetic material and when placed as part of the solenoid will be moved by the magnetic field if strong enough. Conventionally speaking, the plunger should not move under ideal conditions; however, if a fault were to occur, the magnetic field will push the plunger inwards towards its own solenoid coil causing the plunger to tilt in a specific direction. The plunger is then attached to the spring-loaded latch, and if the magnetic field is strong enough, the latch will open causing the current to be disrupted. The design is simple, yet effective; it is able to open the circuit as fast as a few milliseconds.

These two components are used in unison; the bimetallic strip uses thermodynamics of a strip of metal that consists of two materials to determine when the breaker should trip and the other uses basic electromagnetic field understandings to determine when the breaker should trip. Both are simplistic in nature, cost-effective, and easily reproducible. The Smart Breaker prototype, however, is fast-acting, easy to use, and can track power consumption through a web-based application, or an application on a phone.

The first issue that arises when discussing the repercussions of using a smart breaker over a traditional breaker is the cost. A conventional breaker can be deemed free in terms of cost since it uses basic principles of physics rather than electrical components that require power to keep a constant watch on power consumption. The Smart breaker requires a constant stream of energy to power the microcontroller unit, the sensor, and the switch that is put in place of the latch to control the flow of current. Though the cost is minimal, it is difficult to argue with anything that requires no cost. Though this is the case, the advantage of having a smart breaker outweighs the disadvantages of having a traditional breaker. The main advantage is the web-based monitoring involved in the smart breaker which allows the user to directly see their power consumption data and how their power compares to how an ideal power signal should compare to, any irregularities that are present and the web application will notify the user about it. This also allows fixing one of the main issues involved with the bimetallic strip of the conventional breaker, which is how slow it can act. Traditionally speaking the bimetallic strip portion of the breaker tends to act relatively slowly compared to the magnetic element, in comparison, the magnetic element can act as fast as five milliseconds while the bimetallic strip takes as long as seconds or even a few minutes to act. Furthermore, there is the issue of degradation of the bimetallic strip overtime. Heat does not just cause a material to bend; it can degrade over time, losing its structural integrity over time. Because of this, the conventional breaker could heat to an extreme amount overtime, to which the magnetic element can do nothing about since the electrical component is entirely dependent on the current aspect of the power readings while the bimetallic strip is mainly focused on the voltage and current. Without this bimetallic strip, the building could be put under jeopardy hence why the smart breaker outperforms in this area as firstly the smart breaker is able to trip the breaker in as fast as less than one hundred microseconds, secondly, the smart breaker does not rely on the bimetallic strip anymore, instead it will use an ADC connected to a microcontroller that will compare the original power signal against a predetermined signal that will then determine if the comparison is good enough to be allowed to flow through. No degradation of material with use overtime should occur, instead only degradation overtime of the materials such as the sensor or the microcontroller which should be able to be replaced easily.

The magnetic element is a difficult component to replace as it is extremely reliable and it does not degrade overtime as the bimetallic strip does, instead it uses simple physics through Maxwell’s equation to trip the breaker once the current becomes too high. And because of Maxwell's equation, the magnetic field is able to push the magnetic element in a matter of a few milliseconds. Furthermore, the magnetic element is shielded inside by a ferromagnetic core; this stops any stray magnetic fields from outside of the breaker from accidentally tripping the circuit when it doesn’t mean to. Altogether, the magnetic element is fast-acting, very reliable, and non-degradable. One element is missing from this almost perfect material. It’s not smart, the conventional breaker cannot determine any irregularities within itself which could cause unnecessary power usage in certain areas. The smart breaker is able to combat this issue by using a current transformer with extreme accuracy to correctly determine what current levels it is currently at and what current levels it should be at. Furthermore, with the wireless communication of the smart breaker, the user does not need to access the breaker in-person anymore. As anytime it trips, the breaker can be reset remotely from any location if there is Wi-Fi in the vicinity.

All in all, the smart breaker outcompetes the conventional breaker in major aspects despite its simple yet effective design.

3.2 Embedded Systems

3.2.1.1 The Brains of The System

The embedded systems within this implementation are crucial to both the functionality and performance of the Breaker that is designed. As far as consumer computing electronics go, there are two standard design pathways that can be taken; that is the microcontroller unit or the field-programmable gate array. Both have their own strengths and shortcomings that allow them to shine in their own respective ways depending on how a user implements them into a system.

An FPGA is a device that is "programmed" at the hardware level using a hardware description language that physically draws out how data paths are assembled using interconnecting wires and logic gates. This implementation is especially great for individual specialized tasks that need to have high performance with minimal additional overhead. There is no software that is running on the device that controls the fetching, decoding, and execution of instructions, instead, everything is computed directly through hardware fabricated digital circuits constructed from the HDL mentioned previously, significantly cutting down on the software overhead that is introduced with traditional processors. However, an FPGA application introduces its own drawbacks. For example, FPGAs lack the ease-of-access that microcontrollers can provide through programming with conventional software programming languages, and the associated user written libraries that make implementing protocols such as Bluetooth or WIFI not only more accessible but also allow for rapid testing and execution of a single subsection within a much larger system. While typically offering performance gains, the higher barrier to entry from having to write HDL for multiple software protocols (GPIO, SPI, I2C, ROM, etc.) makes a fully FPGA approach less than appealing.

Microcontrollers at their core carry out a lot of the same aspects of traditional computing architecture packed into a bite sized format. They offer a much lower barrier of entry compared to that of FPGAs and are composed of several integrated circuits fabricated right onto the chip to be able to perform many protocols that are controlled on the software level. The cheapest Microcontrollers are typically designed to include a processing unit, programming interface, flash memory, RAM, and interfaces to utilize communication protocols such as UART, SPI, and I2C. In addition to that, entry level microcontrollers are much more affordable to consumers than FPGAs, and that in turn has led to more widespread adoption and community support of these devices. While the software overhead may be a disadvantage in a pure performance sense, it allows for a much friendlier programming experience, and general-purpose adoption into systems that do not require the pure application specific performance that is gained from using FPGAs. The software written for use are commonly programmed using C, C++, or Python which each have their own widespread adoption and years of documentation online, offering what is an easier to grasp, traditional, sequential based execution of the instructions written in a user's program.

3.2.1.2 MCU v. FPGA for Wireless Communication

As this is a project that will need to make use of wireless communications protocols, it is going to be imperative to choose a solution that is able to be easily implemented, strong error handling, and high redundancy. For this reason, the obvious solution is to utilize a microcontroller to handle any wireless communication that will be implemented. There are numerous entry level microcontrollers that have built in modules on the chip to support WIFI and or Bluetooth depending on which processor is selected. Now, why specify the use of the microcontroller only in the context of its wireless communication capabilities? This ties back to one of the downsides that microcontrollers possess, and that is the fact that there is software overhead that has the potential to cause problems within the system.

Table 3: Microcontroller V. FPGA Comparison

	Microcontroller	FPGA
Avg. Cost	✓	
Avg. Performance		✓
Avg. Power Consumption	✓	
Avg. Barrier of Entry	✓	
Avg. Integration	✓	
Avg. Available Support/Documentation	✓	
Avg. Flexibility		✓
Avg. Parallel Processing Support/Performance		✓

3.1.1.3 ESP32

The ESP32 series from ESPRESIFF is one of the most tried and tested microcontroller platforms available on the market today, with strong community support and a plethora of third-party libraries. Featuring a dual core processor with clock speeds ranging between 80 – 240 MHz, the ESP32 is a robust solution for implementing IoT applications while utilizing a single SoC design. The module has offerings that include a built-in antenna for the wireless communication protocols, in which the ESP32 supports 2.4GHz WIFI and Bluetooth 4.2. The chip comes equipped with 448KB of ROM, 520KB SRAM, and 4MB of Flash memory, giving more than enough overhead in terms of the respective memory capabilities. In addition to that, the system is equipped to work with common wired communication protocols that will be needed for auxiliary sensors, such as SPI, I2C, I2S, and UART [21]. It has a built in 12-bit ADC but is often noted to be one of the most lacking features of the chip, as in certain operating regions the conversion does perform a linear translation which can lead to inaccurate results. If we decide to choose this platform, the subpar ADC will be something to keep in mind and may need the support of an external ADC. Truly, however, the thing that makes the ESP32 such a fan favorite is all the above features are packed into a chip that is sold for at some of the lowest rates on the market. The chip itself can be found for only a couple of dollars, while development boards can be found at $10 [22].

3.1.1.4 CC3235MODx

Texas Instruments' CC3235MODx series of wireless MCU modules are designed for use in IoT implementations [23]. The CC3235MODx series of modules comes equipped with a single core, 80MHz ARM processor with 256KB of SRAM and 1MB of flash memory. While lacking support for Bluetooth, the chip has support for both 2.4GHz and 5GHz WIFI, giving users the option of utilizing a higher bandwidth, better performing protocol at the cost of reduced operating distance. The CC3235MODx series includes support for a number of the standard wired protocols that a user would want to take advantage of, including SPI, I2C, I2S, and UART [24]. The chip includes support for 4 channel 12-bit ADC which is sufficient for accurately measuring the analog signal that is to be tracked by the user on the webapp. Some of the downsides of this chip, however, include the fact that there is little to no third-party documentation or libraries online using this module [23]. Texas Instruments of course provide a sufficient datasheet, but the lack of anecdotes of users working with this device leaves a lot to be desired. In addition to that, the price of the module far exceeds other offerings currently available, with the chip itself costing upwards of $20, and development boards priced at almost $70.

3.2.1.5 Raspberry Pi Pico 2W

Raspberry Pi is primarily known for their single-board, Linux-based, computer offerings, but they also sell a series of traditional microcontrollers as well. For instance, The Raspberry Pi Pico 2W is an example of the standard IoT microcontroller implementation [23]. This module is equipped with an RP2040 dual core processor with clock speeds up to 150MHz, 520KB of SRAM, and 4MB of on-board flash memory. Unlike other Pi Picos, this specific Pico module adds an on-board wireless interface that includes support for both 2.4GHz WIFI and Bluetooth 5.2, giving us a good selection of wireless protocols to choose from for implementing constant metering with the webapp interface [25]. When it comes to wired communication protocols, the module offers support for SPI, I2C, and UART, giving us plenty of options to choose from in regard to communication between the controller and auxiliary peripherals [26]. As opposed to the CC3235MODx series, the Pico 2W has had a lot of adoption from the community, giving way for great support in the form of third-party libraries, documentation, and example programs [23]. A Pico 2W development board retails for under $10 [27], the RP2040 processor for around $1, and the CYW43439 wireless module for roughly $5 [28]. This introduces the biggest issue with this selection; the wireless interface is a separate module entirely from the processor, requiring having to implement both separately with a custom PCB.

3.2.1.6 Nordic nRF52840x

The Nordic nRF52840x is one of the more advanced low-power microcontroller platforms available today, with the benefit of a strong community ecosystem [23]. With a single core 64 MHz processor, this module provides a strong general-purpose platform for a number of applications. The module includes 1MB of flash memory and 256kB of RAM, giving more than enough capacity for our implementation, while also supporting standard protocols for peripherals including a QSPI interface, SPI, I2C, I2S, and UART [29][30]. The nRF52840x also includes onboard support for Bluetooth 5, but like the Raspberry Pi Pico 2W, WIFI capability is not included onboard within the nRF52840x chip itself. Adding support for WIFI requires wired communication over its SPI port with an external WIFI module to provide the desired interface. Specifically, the chip is designed to be used in tandem with Nordic's nRF700x series of chips to provide WIFI support. The nRF700x allows support for both 2.4GHz and 5GHz WIFI protocols, and when used together with the host module, it can offer a capable solution for modern wireless implementations [31].

3.2.1.7 STM32WB55

The STM32 series of microcontroller chips is one of the most widely adopted platforms available for use today. Equipped with ARM Cortex-Mx chip architecture, the STM32 series allows for high performance computing with an extensively used framework that makes implementations both accessible and widely supported by many third-party toolchains [32]. The STM32WB55 in particular is equipped with a 32-bit ARM Cortex-M4 for general purpose computing, and then a Cortex M0 for handling the wireless network related tasks. The chip comes equipped with 1MB of flash memory and 256KB of SRAM, offering a solid amount of memory and certainly enough for the intended application. In addition to that, the chip is outfitted with all the common wired communication protocols and interfaces you would expect, USART, SPI, I2C, and QSPI for use with auxiliary peripherals. The STM32WB55 also offers an onboard 12 – Bit ADC, perfect for the intended implementation. One thing that sets this processor apart from some of the others mentioned above is the absurdly high GPIO pin count that is supported. The amounts can vary depending on which variant of the STM32WB55 is selected, but the datasheet specifies that the max number of offered GPIO pins that can be used is 72, far and away the highest GPIO pin count out of any of the offerings listed here, and way more than would ever need to be utilized in this implementation [33][34]. However, the above merits listed for STM32WB55 come with some downsides. For example, the chip fails to provide any onboard support for WIFI, requiring a separate module such as the 'STM32WBxM' to provide the necessary support needed. In addition to that, while the individual processor might cost less than $10, a dev board for prototyping can range anywhere from $20 - $50 depending on how many of the processor's features are available for use with the dev board.

Table 4: MCU Comparison by Authors

Metrics	ESP32	CC3235MODx	Pico 2W	nRF52840x	STM32WB55
Cost – Dev Board	$8.00	$71.00	$7.00	$49.00	$45.00
Cost – Individual Module	$7.00	$26.00	$7.00	$9.00	$11.00
Processor	Dual Core 240MHz	Single Core 80 MHz	Dual Core 133MHz	Single Core 64MHz	Dual Core 64MHz + 32MHz
RAM	520KB SRAM	256KB SRAM	520KB SRAM	256KB DRAM	256KB SRAM
Flash	4MB Flash	1MB Flash	4MB Flash	1MB Flash	1MB Flash

WIFI	Yes – Integrated	Yes – Integrated	No – Req. Separate Module	No – Req. Separate Module	No – Req. Separate Module
Bluetooth	Yes – Integrated	Yes – Integrated	No – Req. Separate Module	Yes - Integrated	Yes - Integrated
UART	Yes	Yes	Yes	Yes	Yes – USART
I2C	Yes	Yes	Yes	Yes	Yes
I2S	Yes	Yes	No	Yes	Yes
SPI	Yes	Yes	Yes	Yes	Yes
ADC	Yes – 12 bit	Yes – 12 bit	Yes – 12 bit	Yes – 12 bit	Yes – 12 bit
Operating Voltage (V)	3.3V	3.3V	5V	5V	1.6V - 3.6V
Power Consumption (Active Mode)	0.528 Wh	0.736 Wh	0.297 Wh	0.0158 Wh	0.029 Wh

3.2.2 Switching and Interruption Technology

3.2.2.1 Comparison of Switching and Interruption Technologies

The SABRE Smart Circuit Breaker design requires a robust method of interrupting current flow when it exceeds the specified threshold and manually at the user's request. The selection of interrupt mechanisms will determine the speed, efficiency, durability, and ease-of-implementation of incorporating the actual switching of the actual current branch to the load. Three options were evaluated: mechanical relays, solid-state relays (SSR), and back-to-back MOSFETs.

3.2.2.2 Mechanical Relay

Mechanical relays are electromechanical devices that utilize an electromagnetic coil and movable armature to physically switch open a set of contacts to conduct current. The electromagnetic principle at play is similar to what can be seen in traditional residential circuit breakers; where the electromagnetic field from the current passing through directly opens the circuit if it surpasses the set threshold. Compared to other options, mechanical relays are inexpensive and straightforward to integrate, making them enticing for cost-sensitive designs.

However, the performance is limited by the inherent mechanical movement of contacts. Switching speeds are relatively slow, typically in the order of 10–15ms, which may be insufficient for fast fault clearing in sensitive loads. Additionally, in certain high voltage environments, arcing can occur between the contacts which introduce unintended wear and tear on the pads, reducing overall lifespan. Noise and vibration that occurs during switching operation are further disadvantages. Mechanical relays, though reliable for a range of applications, are not suitable for the goals of this project, which seeks to eliminate mechanical components to improve both durability and accuracy.

3.2.2.3 Solid State Relay

Solid-state relays use semiconductor components like thyristors, triacs, or transistors to replace the physical movement action found in mechanical relays. This design minimizes mechanical wear, resulting in significantly improved reliability and provides silent operation. Switching speed is faster than mechanical relays, ranging from order of microseconds to milliseconds depending on the relay chosen. Furthermore, many SSRs provide strong electrical isolation through optical coupling between the input and output stages, ideally separating the microcontroller block from the subsequent load block.

Some inherent drawbacks are introduced when using SSRs. For one, the use of semiconductor components can lead to voltage drops being introduced across the semiconductor junctions. This aspect can result in additional power dissipation and therefore increased heat generation throughout the device. Depending on the current draw, this necessitates the use of heat sinks or thermal management solutions. SSRs are also more expensive than mechanical relays, and unlike mechanical contacts, they cannot achieve true zero-leakage isolation, as a small leakage current typically flows through the semiconductor device even when its not conducting. Despite these limitations, SSRs present a robust solution in providing controlled switching while minimizing the number of moving components.

3.2.2.4 MOSFET Configuration

A back-to-back MOSFET configuration consists of two power MOSFETs connected in series, oriented in opposite directions to block current flow in both polarities. This approach leverages the extremely fast switching speeds of MOSFETs, typically in the nanosecond to microsecond range, allowing near-instantaneous interruption of fault conditions. Additionally, MOSFETs provide precise control over switching events, making them well-suited for integration with microcontrollers such as Arduino or ESP32, which can directly monitor and actuate them.

Compared to SSRs, back-to-back MOSFETs typically exhibit lower conduction losses due to their low on-resistance (Rds(on)), improving efficiency and reducing heat generation. The absence of moving parts ensures long operational life and silent operation. However, this approach requires careful gate driver design to ensure proper switching, as well as adequate thermal management under higher current loads. Unlike mechanical relays and SSRs, back-to-back MOSFETs do not inherently provide galvanic isolation, so additional design considerations may be required to achieve full system safety.

N-type Depletion Mode MOSFETs are the ideal transistor to use in this configuration as their gate already allows for current flow from drain to source without the need for outside input. This type of MOSFET allows for ideal energy consumption as no power is needed under ideal conditions, until the breaker is required to be tripped will a current need to be supplied to the drain to close the drain to source nodes stopping the current from flowing any more. The only issues that can is present is leakage current from the drain to the source, yet this can be mitigated with the path of least resistance principle where we apply another MOSFET that will flow to ground but only be opened if the original MOSFET is closed off. This new MOSFET will require the use of a N-type Enhancement MOSFET opening the gate to allow the current from Drain to source to flow directly to ground, yet the power consumption will be minimal. Both MOSFETs will be required to work in unison to prevent leakage current from flowing at all though it is unlikely if any leakage current does flow through that it will disturb any load due to how low it can be.

Table 5: *Comparison of Switching Methodologies*

	Mechanical Relay	Solid-State Relay	MOSFET Configuration
Avg. Cost	**$5.00**	**$25.00**	**$2.00**
Avg. Switching Speed	15 ms	10 ms	1 µs
Switching Element	Metal Contacts actuated by electromagnetic coil	Triacs, Thyristors, or MOSFETs	MOSFET Channel
Isolation	High – Physical gap between coil and contacts	Medium – Optical Isolation	Low – No inherent isolation
Avg. Durability	10^5 operation	10^9+ operations	10^9+ operations
Leakage Current	Extremely low: pA range	10 mA	Low: µA range
Form Factor	Bulky: Coil, Contacts, Housing	Medium: flat modules or DIN-rail units	Very Compact: SMD

3.2.3 Comparison of Solid-State Relays

3.2.3.1 Carlo Gavazzi RP1A48D5

Carlo Gavazzi's RP1A48D5 is a PCB mounted solid state relay designed for facilitating the delivery of high-power signals through the control of a relatively low power digital signal. This relay is rated for a maximum 480 VAC load signal operating at 5A, giving more than enough head room in terms of voltage and will be sufficient for delivering the maximum current that will be seen by the load. The acceptable input control signal for the RP1A48D5 is between 3 VDC and 32 VDC, which may introduce problems for a microcontroller such as the ESP32, which has GPIO output voltages rated for 3.3V, just within the rated threshold [35].

3.2.3.2 Crydom CX240D5

The Crydom CX240D5 is a PCB mounted solid state relay that has a similar footprint to that of the RP1A48D5. Just like the RP1A48D5, it is designed in a manner that allows for the control of a high-power signal through the use of a relatively low power digital signal from something like a microcontroller. This relay is rated for aa maximum 280 VAC load signal operating a 5A, once again giving a fair amount of overhead in terms of voltage, and an acceptable current rating to supply the maximum amperage the load may draw. The input control range for the CX240D5 is between 3 VDC and 15 VDC, which is within the range for a microcontroller such as the ESP32 to be able to properly control it at 3.3 V, but this is just within the threshold so could potentially lead to inconsistent behavior [36].

3.2.3.3 Omron Electronics G3VM-WR P-SON Series MOSFET Relays

The Omron G3VM-WR P-SON is a series of ultra-compact, SMT mounted solid-state relays designed for controlling the supply of a high-power signal while minimizing the space it occupies. The specific component from this series that works best in this design would have to be the G3VM-31WR model, and even given its extremely small size, is assembled to supply a maximum load voltage of 30 VAC while supplying 4.5 A. The relay is controlled with a forward current of 30 mA, making it sufficiently within an acceptable range for a microcontroller to properly control it. The small form factor certainly makes this module an enticing option. However, with a maximum current load rated for 4.5 A, the G3VM-31 WR might just be short of safely controlling the supply of a maximum 5 A signal [37].

3.2.3.4 Vishay VOR1003M4T

The VOR1003M4T from Vishay is a solid-state relay assembled with a footprint that matches comparatively to the G3VM-31WR. It is a SMT mounted solid state relay capable of controlling a 30 VAC load at 5 A, perfectly within the parameters chosen with the SABRE smart breaker. The relay is controlled through a 1.2 VDC signal, a bit of a lower voltage than what is typically seen from most GPIO output pins, however this can be easily remedied by utilizing a voltage divider to effectively step the control signal down to an appropriate level [38][39].

3.2.3.5 Toshiba TLP3547

Toshiba's TLP3547 is a through hole mounted solid state relay made with a footprint that slightly eclipses the size of some of the more compact SMT models like the VOR1003M4T and the G3VM-31WR. This model is designed to carry a maximum of 60 VAC signal operating at 5 A, another component that properly fits the supplied load parameters set for this iteration of the smart breaker. The relay is controlled by a current rated 5 mA maximum, which should be acceptable for a microcontroller GPIO and resistor in series [40].

Table 6: *Comparison of Solid-State Relays*

	RP1A48D5	CX240D5	G3VM-31WR	VOR1003M4T	TLP3547
Cost	**$27.55**	**$20.40**	**$9.99**	**$3.20**	**$7.66**
Size LxWxH (mm)	43.4 x 10.5 x 25.55	43.1 x 7.6 x 25.4	3.4 X 2.1 X 1.3	5.2 x 4.3 x 2.18	9.66 x 6.4 x 3.85
Load Voltage Threshold	480 VAC	12 – 280 Vrms	30 V_Peak	30 V_peak	30 V_Peak
Load Current Threshold	3 A – 5.5A	0.06 A – 5 A	4.5 A	5 A	5 A
Control Signal	3 VDC – 32 VDC	3 VDC – 15 VDC	30 mA (verify)	100 mA (verify)	5 mA (verify)

Mounting Method	Through-Hole	Through-Hole	SMT	SMT	SMT
Switching Speed	< 10 ms	< 10 ms	Turn-On: 3ms – 5ms Turn-Off: 0.04ms - 1ms	Turn-On: 1.5ms Turn-Off: 0.15ms	Turn-On: 2.5ms - 5ms Turn-Off: 0.1ms - 1ms

3.2.3 Low-Voltage Protection

3.2.3.1 Comparison of Low-Voltage Circuit Protection Methods

In the design of the smart breaker, protection elements play a crucial role in ensuring both user safety and the reliability of electronic components. Several technologies were considered, each with distinct advantages and limitations.

3.2.3.2 Varistor

To ensure both user safety and system reliability, protection elements must be integrated into the smart breaker. The one we devices we used for this purpose is the Metal Oxide Varistor (MOV).

A varistor is a voltage-dependent resistor that changes its resistance drastically when the applied voltage exceeds a certain threshold. Under normal operation, the varistor exhibits very high resistance, effectively acting as an open circuit. However, in the event of a voltage surge or transient spike, the resistance drops sharply, allowing the excess current to be diverted safely to ground . For our scaled prototype, the MOV provides an excellent balance between cost, speed, and protection capability.

Advantages:

- Fast response to voltage spikes.
- Simple and cost-effective.
- Can absorb multiple small surges.

Limitations:

- Limited energy absorption (can degrade after repeated large surges).

3.2.3.3 **Fuse**

a fuse is a thin conductor (usually an alloy wire or strip) inside a sealed cartridge or SMD package. When current exceeds the rated value for long enough, the element heats up and melts, opening the circuit permanently. last line of defense. They protect wiring and components from overheating or fire if an upstream fault allows excessive current.

A fuse is a sacrificial element that melts and opens the circuit when sustained current exceeds its rating. A polyfuse (PTC) is a resettable device that increases resistance when heated by overcurrent and then resets after cooling.

Advantages

- Highly reliable for sustained overcurrent protection.
- Simple and inexpensive (single-use fuse) or convenient (resettable polyfuse).
- Provides physical disconnect when tripped.

Disadvantages

- Fuses are single-use and require replacement after operation.
- Polyfuses have slower response and higher on-resistance under fault than a blown fuse.
- Do not protect against high-speed voltage transients.

3.2.3.4 Transient Voltage Suppression Diode

A TVS diode is a semiconductor clamp that reacts within nanoseconds to limit voltage spikes to a tightly defined level. It is typically used across supply rails or signal lines to protect sensitive electronics. ideal for protecting low-energy signal or sensor lines and for providing a precise clamp on sensitive nodes (e.g., ADC inputs). Often used in parallel with MOVs: MOVs handle bulk energy, TVS handles fast, lower-energy spikes.

Advantages

- Extremely fast response and precise clamping voltage.
- Excellent for protecting low-voltage electronics and signal lines.
- Small form factor suitable for PCB mounting.

Disadvantages

- Lower total energy absorption compared to MOVs (not ideal as the only protection for high-energy surges).
- Can be more expensive per unit than MOVs for power-line use.

3.2.3.5 GFCI / RCD (Ground Fault Protection):

These devices protect users by disconnecting the circuit when leakage current to ground is detected. They are especially valuable in residential applications to prevent shock hazards. While highly effective for human protection, they do not address transient spikes or equipment safety, making them more of a complementary solution than a replacement for MOVs.

Advantages:

- Provides user safety by preventing shock hazards.
- Widely used in residential and commercial installations.

Disadvantages:

- Does not protect electronics from surges or transients.
- Adds complexity and cost to the system.

3.2.3.6 Selection

From this investigation, we determined that the varistor is the most practical starting point for our smart breaker design, especially at the prototype stage. Its ability to clamp high voltages quickly ensures that sensitive electronics remain safe, while its low cost makes it ideal for integration into consumer devices.

3.2.4 Branch Circuit Wiring and Connections

A reliable branch circuit requires careful selection of wiring and connections to ensure safety, performance, and compliance with electrical standards. For this project, which operates at a scaled-down level of 24 V AC and 5 A, conductor choice, insulation, and connection methods are particularly important for both testing and demonstration purposes.

Conductor Selection

The two most common conductor materials are copper and aluminum.

Copper offers high electrical conductivity, low resistance, and excellent durability. It is widely used in low-voltage applications because of its ability to handle current with minimal losses and heat generation. However, copper is more expensive and heavier compared to aluminum.

Aluminum, while lighter and less costly, has higher resistance, is prone to oxidation at contact points, and requires larger gauge sizes to carry the same current as copper. These drawbacks make it less suitable for small-scale prototyping.

For this project, stranded copper wire in the range of 16–18 AWG will be used. Stranded conductors provide better flexibility and are easier to route on a test bench, making them well suited for prototyping.

Connections and Terminations

Secure and durable connections are essential to avoid resistive heating, accidental disconnection, or unsafe operation. Options include:

Screw terminals: Robust and widely used, but less convenient for quick changes.

Barrier strips: Provide organization and safety with clear separation between conductors.

Quick-connect spade terminals: Allow modularity and fast assembly/disassembly.

Branch Circuit Layout

The branch circuit will follow a structured sequence:

1. Input supply
2. Protection devices (varistor and fuse)
3. Switching element (relay or MOSFET)
4. Sensing stage (voltage/current monitoring)
5. Output terminals connected to the load

A continuous ground connection will be implemented throughout the circuit to ensure both equipment safety and user protection.

Advantages and Disadvantages of Cable Options

Copper Wiring:

Advantages:

High conductivity, reliability, long service life, less prone to failure.

Disadvantages:

Higher cost, heavier, less economical for large-scale installations.

Aluminum Wiring:

Advantages:

Lightweight, lower cost, widely available.

Disadvantages: Higher resistance, larger wire gauge needed, prone to oxidation, less durable in small-scale circuits

In summary, copper conductors with PVC insulation and modular terminal blocks are the most appropriate choice for this smart breaker project. This selection ensures safety, efficiency, and ease of prototyping while maintaining compliance with common wiring practices.

3.2.5 Load Line Current Measuring

3.2.5.1 Comparison of Methods to Perform Current Measurements

One of the key aspects of the SABRE smart breaker is its ability to provide wireless, real-time data to the webapp interface. For this to happen, the microcontroller is going to need to be able to take a DC voltage signal proportional to the AC current provided on the load line, use an ADC to properly read this data in a format compatible with the processor, and then transmit this data wirelessly for the user to read on their respective instance of the webapp. There are several methods of going about this that are to be covered, each with their own respective strengths and weaknesses.

3.2.5.2 Standalone Shunt Resistor

The most simple and common approach to calculating a current value using a microcontroller is to use a shunt resistor. A shunt is a low value resistor to be placed in series with other load elements that need to be calculated. The current across this resistor produces a small voltage drop that can be fed into the microcontroller, and when used in conjunction with Ohm's Law through software implementation, the current being supplied on the load line can be properly calculated. While this is a simple application for calculating the current on the load line, this method comes with some noticeable drawbacks. The biggest disadvantage in this approach is that to get a proper measurement across the shunt resistor requires the shunt itself to be in series with the delivery line. This is an issue for several reasons, for one, the shunt being in series along the load line would thus imply that the microcontroller itself would also have to be in series along the delivery path. This is obviously a problem, as the microcontroller selected would stand no chance withstanding the power delivered to it, and would almost certainly break the processor itself. In addition to that, even if the chip itself could withstand the high power being delivered through itself, the microcontroller would have to be capable of either one, directly allowing the signal to pass through by having a direct trace between whichever input pin would be selected, or two, have an onboard method of sampling this AC signal through its ADC, and generating a proportional PWM signal out to the load itself all in real time with no signal degradation or loss of power. In addition to that, say that the shunt resistor was arranged in parallel with the delivery line so that the microcontroller would not have the guarantee of bearing the brunt of the full signal, this would still not be a full proof solution of protecting the processor or providing an accurate measurement. Shunts are designed to have their resistance minimized as to reduce the power that is dissipated as heat, and since the shunt is almost certainly going to be of much lower resistance than that of the attached load, most of the current will be bypassing the load. This will in turn fail to power the devices on the circuit, provide a correct measurement of what is flowing through the load, and still fail to protect the microcontroller from a high voltage signal.

3.2.5.4 Current Transformer w/ Shunt Resistor

The utilization of a current transformer in conjunction with the shunt resistor mentioned previously presents the needed improvement over the standalone shunt approach. A current transformer works in a similar manner to that of a voltage transformer. Using electromagnetic principles, a step-down current transformer single core conductor can be seen as having a primary winding of 1. The secondary windings will have a number corresponding to whatever the step-down ratio is mentioned within the datasheets. This allows the current transformer to be placed in series with whatever load current is needed to be measured and supply a separate isolated output proportional to that being supplied to the load. This improves the standalone shunt for a number of reasons. For one, this allows for constant proportional output current to that being supplied to the load on a separate isolated signal line, something that a single shunt resistor would fail to accomplish. However, the shunt resistor will still be necessary for use in conjunction with the current transformer, as the microcontroller will still need to have a known resistance along the signal path to be able to calculate the current from the voltage seen by the input pin.

3.2.5.3 Hall Effect Sensor

A great standalone approach that does not require the need for separate shunt resistor to be used in concurrence; a Hall-Effect sensor is a ring that allows a wire to pass through it. The current's magnetic field is measured and converted into a proportional voltage signal that is supplied from one of the sensor's pins [41]. This pin can be connected directly to one of the GPIO pins located on the microcontroller, and by reversing the conversion of current to voltage that is listed in the data sheet, we arrive at a method for a proper current measurement of the load line. A hall effect sensor provides several benefits from the above methods of current calculation. For one, the hall effect sensor provides galvanic isolation, meaning that there is no conductive connection between the load line and the signal that is reporting measurement to the microcontroller [42]. This is great as it provides a much higher standard of safety to the microcontroller as opposed to a method such as a shunt resistor, which facilitates the need for a direct trace between the load line and the service line providing calculations to the processor. In addition to that, by not having any direct connection between our two signals, there is no need to construct a current source to provide a load proportional constant signal to the shunt resistor and subsequent microcontroller.

3.2.6 Comparison of Hall-Effect Sensors

3.2.6.1 WCS1800

The WCS1800 is a hall-effect sensor operating at 5V with a current measuring range between 0A – 35A for a DC signal, and 0A-25A for an AC signal. It has a sensitive conversion ratio of 72mV/A allowing for precise conversion of the supplied load current to a DC signal that can be picked up by the microcontroller. The sensor allows for wires as large as 9mm to be passed through the conductor through holes, far exceeding the size of the load line needed within the design [43]. In addition, many existing development PCB boards exist that include the sensor itself, along with an MCP6021 microchip stage before the final output, allowing for proper amplification in scenarios where the input amperage is on the lower end. This helps to provide a more linear signal back to the microcontroller for processing.

3.2.6.2 Honeywell 91SS12-2 CSLA2CD

The Honeywell CSLA 91SS12-2 CSLA2CD is a Hall–Effect sensor operating between 6V - 12V with a current measuring range of 0A – 72A. It has the highest maximum sensed current peak out of the bunch. The sensor includes a conducting ring structure, allowing for wires as large as 11mm to pass through, once again providing more than enough overhead for a load line carrying the main signal to pass through with no issues [44].

3.2.6.3 ACS712-30A

The ACS712 is a hall-effect sensor from Allegro Microsystems operating at 5V with a current measuring range of 0A – 30A. It has a comparable conversion ratio of 66mV / A allowing for an accurate conversion of the supplied load to a sufficient DC signal for use with the microcontroller. This surface mounted IC benefits from a very compact design and removes the need for a jumper wire coming off a PCB trace to pass through a conducting ring, such as is the case with the WCS1800. This implementation allows for direct soldering in series to the PCB trace carrying the load line [45].

3.2.6.4 ACS772LCB-050

The ACS772LCB-050 is another hall-effect sensor from Allegro Microsystems that operates at 5V with a current measuring range between 0A – 50A. It has a slightly lower conversion ratio as compared to the ACS712, coming in at 40mV / A, a slightly worse performing conversion ratio compared to its sister IC. Like the ACS712 before, the ACS772LCB-050 is another surface mounted IC featuring a compact design that removes the need for the large conducting ring featuring other hall-effect sensors. As opposed to the ACS712, the terminal for the load line is much larger than that of the supply and output voltage terminals, which is something to possibly keep in mind when utilizing this component [46].

3.2.6.5: *Comparison of Hall Effect Sensors for Load Branch Monitoring*

Metrics	WCS1800	91SS12-2 CSLA2CD	ACS712-30A	ACS772LCB-050
Cost	$12.00	$700.00	$12.00	$8.00
Dev-Board	Yes	***No***	***No***	***No***
Input Supply Voltage	5 VDC	6 VDC – 12 VDC	5 VDC	5 VDC
Current Range	0 A – 25A	0 A – 72 A	0 A – 30 A	0 A – 50 A
Form Factor	Exposed Flux Collector	Exposed Flux Collector	Integrated Circuit	Integrated Circuit

Mounting Method	Through Hole	Through Hole	SMT	SMT
Output Resolution	72 mV / A	32.7 mV / A	66 mV / A	40 mV / A

3.2.7 AC Transformer for Proper Simulated Assessment of Build

3.2.7.1 Scaled Down, Simulated Mains Supply AC Transformers

In order to properly connect and assess our initial signal to the ADC, we need to scale it down to a current and voltage that do not exceed 12 mA and 3.3 V. Our signal is expected to be 24 V and 5 A, and for safety reasons it cannot exceed these levels. The main challenge lies in selecting a potential transformer capable of scaling the signal with high precision. any inaccuracies would prevent us from reliably detecting overload conditions and correctly tripping the breaker. For our purposes, we require a 5:1 potential transformer that can step down from a 120 V mains input to 24 VAC while being able to supply 5 A, resulting in a total power delivery of 100 VA. High-quality isolated potential transformers can achieve precision ratings as tight as 0.1%, which is necessary for our metering application.

3.2.7.2 TR100VA001 Transformer

The TR100VA001 transformer meets a few of the criteria required to properly evaluate the functionality of our breaker technology. This transformer features a single primary winding rated for 120 V AC at 50/60 Hz, making it directly compatible with standard mains voltage. On the secondary side, it provides a single 24 V AC output capable of supplying approximately 4.2 A, resulting in a total power delivery of 100 VA [47]. This capacity is slightly less than the desired rating for simulating the maximum operating conditions expected in our system and might require an additional 24VAC output transformer to be used in parallel with this unit to supply our desired 5A maximum load. A benefit of this choice is that since it only includes a single input and output terminals, using this transformer alone makes constructing the circuit much simpler than that of other options that include multiple input and output terminals. The transformer is rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input are accurately represented at the output. This level of accuracy is critical for reliable overload detection and measurement during testing. In addition, the price of the unit at $54.99 makes it relatively competitive compared to other options on the market [48].

3.2.7.3 RS PRO Toroidal Transformer

The 120VA Toroidal Transformer from RS PRO meets several of the specified criteria that have been specified to properly assert the functionality of our breaker technology. The transformer features 2 primary voltage windings rated for 115VAC, allowing for them to b e configured in parallel for a single 115VAC input or in a series configuration of 230VAC. The transformer comes equipped with two output terminals, each supplying 24VAC with each capable of driving a total 60VA load. This leads to the fact that to properly assess the maximum power capability of the breaker technology, the transformer secondary windings will also need to be wired in parallel to so that each is able to supply about 2.5A under max load conditions, and successfully supplying 100% of the load current [49]. The transformer is rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input are accurately represented in the output. This level of accuracy is critical for reliable overload detection and measurement during testing. One of the most compelling aspects of this unit is the low price of $26.99, making it far and away the cheapest of the bunch [50].

3.2.7.4 Edwards Signaling 88-100

Edwards Signaling's 88-100 is an adequate solution for meeting the demands needed to properly assess the functionality of the breaker. The transformer features primary input terminals rated for 120VAC with two secondary output terminals rated for 24VAC at 100VA and a 12VAC at 50VA respectively. The transformer is rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input are accurately represented in the output. The single 24VAC output terminals are a reliable option for driving a signal. At 100VA it can drive approximately 83% of the maximum load specified by our breaker. The additional 12VAC output terminals at 50VA might initially seem like a good inclusion, but further investigation shows that this will not be case. Attempting to use the 12VAC output in parallel with the 24VAC output to drive a higher load will not work as it might initially seem. Combining voltage supplies that do not share the same value will cause the less powerful of two to act as more of an additional load as compared to a supply as intended. Because of the low impedance that transformers are intended to act with, this will essentially create a short circuit between both transformers, leading to overheating and or damage to both transformers. In addition, the price tag of almost $200 puts makes this one of the least compelling options out of the bunch, as it has far and away the highest pricings out of the array of selections to pick from [51].

3.2.7.5 Chemscan 96VA Transformer

The Chemscan 96VA Transformer is again another satisfactory solution for providing the main power for assessing the breaker technology. As suggested by the name, this transformer has a single 120VAC, 50/60 Hz primary input and a single 24VAC secondary output capable of supplying 96VA to a load. With a max power output of 96VA, this means that the max current that can be supplied is 4A, or 80% of the specified threshold of the breaker. This capacity is slightly less than the desired rating for simulating the maximum operating conditions expected in the system and might require the use of an additional 24VAC transformer in parallel with this one to supply 100% - 120% of the maximum operating current. Like the TR100VA001, it benefits from a single set of input and output terminals that allow it on its own to be much simpler to connect to mains power on the input and supply the circuit on the output. The transformer is rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input are accurately represented in the output. This level of accuracy is critical for reliable overload detection and measurement during testing. In addition, the price tag of only $65 puts it in a competitive price range with the other selections mentioned previously [52].

Table 7*: Comparison of AC Transformers for Simulation Purposes*

	TR100VA001	RS PRO Toroidal	Edwards Signaling 88-100	Chemscan 96VA Transformer

Cost	$54.99	$26.99	$200	$64.99
Input Winding(s) Count	Single Input	Dual Input	Single Input	Single Input
Output Winding(s) Count	Single Output	Dual Output	Dual Output	Single Output
Primary Input Rating	120 VAC	115 VAC	120 VAC	120 VAC
Primary Output Rating(s)	24 VAC	24 VAC	24 VAC 12 VAC	24 VAC
VA Rating	100 VA	60 VA (Per Output)	100 VA 50 VA	96 VA
Max Supply Current	4.2 A	2.5 A (Per Output)	4.167 A (Per Output)	4A

3.2.8 Power Regulation and Converter

3.2.8.1 Power Regulation and Polarity Conversion Comparisons

To incorporate the "smart" functionality into the SABRE circuit breaker, it is imperative to integrate a microprocessor capable of both constant current monitoring, as well as the transmission of this data to a web interface through a wireless connection. However, the primary power supply for this prototype design is 25VAC, and for a future implementation will operate at mains 120VAC. This is incompatible with the majority of commercially available microcontrollers that typically function within a voltage range of 2VDC – 5VDC. This discrepancy not only highlights the significant difference between the supply voltage value and the operating voltage value of the microcontroller but also emphasizes the need for a direct current signal as opposed to an alternating one. Due to this fact, it is essential that a portion of the circuit facilitates both stepping down the voltage to an acceptable level and rectifying the alternating current to produce an appropriate DC signal.

3.2.8.2 Voltage Regulation

3.2.8.2.1 Voltage Divider

A voltage divider is a fundamental passive circuit design that utilizes Ohm's law to lower the voltage at a specific node. By connecting two or more resistive loads in series, the current remains constant through both loads, resulting in an individual voltage drop at the respective nodes between the resistive loads. Using Ohm's law, one can precisely determine the needed resistive values to achieve the desired voltage reduction. Within an AC circuit, such as the one in this build, impedance becomes the relevant measure to base the voltage drop of, allowing for the inclusion of capacitive and induction components to be included in the load arrangement. While this method satisfies reducing the applied voltage, there are a number of caveats introduced with this approach when carrying out such a significant voltage drop. For one, this method fails to provide galvanic isolation for the microcontroller portion of the circuit. Galvanic isolation refers to isolating different sections of an electrical circuit through the prevention of current flow to differentiate ground potentials and avoid ground loops while still having the ability to "share" information or signal [53]. In this case, having a supply with a much higher voltage than the operating voltage of the microcontroller shares a single ground reference can lead to not only unexpected behavior on the microcontroller end of things, but can also cause potential damage to the processor. In addition to this, using a voltage divider to implement such a significant voltage drop is extremely inefficient. Voltage dividers work by distributing the input voltage across multiple voltage drops caused by the resistive components, each of which will have the same current flowing through them. Each subsequent resistor will effectively waste a portion of the current flowing through the circuit. Not only that, but this wasted power is dissipated as heat within the resistive components which can easily lead to overheating in a design that is already made to be very compact.

3.2.8.2.2 Capacitive Dropper

A capacitive dropper is a circuit consisting of a capacitor and resistor connected in series to achieve a voltage drop. The impedance of the capacitor is determined by the formula Z_c = 1/jwc, where 'j' represents the imaginary unit, 'w' is the angular frequency (frequency * 2pi), and 'c' represents the capacitance value of the component. Capacitors of low capacitance are able to generate high impedance, limiting the current that can flow through it. This configuration offers advantages over traditional voltage dividers by improving power efficiency, which not only conserves energy that can be used for supplying the actual load, but also minimizes heat dissipation that would otherwise occur when reducing 25VDC to 3.3VDC-5VDC using purely resistive components [54]. However, similar to a simply resistive voltage divider, this setup does not provide galvanic isolation between the two circuits. This can lead to potentially undesirable effects for the microcontroller and can create hazardous conditions when physically operating on this side of the circuit.

3.2.8.2.3 AC Transformer

An AC transformer is a passive component that through electromagnetic induction can transfer energy from one AC circuit to another. Composed of two wound coils bound around a magnetic core, the alternating current flowing through produces an inductive magnetic force that can transfer energy between the two coils without the need for a conductive connection between the two separate circuits. The voltage ratios between the primary and secondary windings are directly proportional to the ratio of turns between the primary and secondary coils. Through manually assigning the ratio of windings between the two coils, the transformer allows for the change of voltage between the two terminals [55]. In this case, by having a primary coil with seven times more turns than that of the secondary, transformers will allow for dropping the voltage from 25VAC to about 3.5VAC. AC transformers improve upon the previously mentioned methods in a couple ways, as mentioned before, the transformer is able to transfer energy without the need for conductive conduct between the two circuits. This effectively solves the issues of providing galvanic isolation between the two circuits, while also achieving significant voltage drops. In addition to that, transformers are especially efficient in doing this conversion, minimizing the amount of power dissipated as heat. The main drawback that arises when utilizing an AC transformer is that compared to other methods that use standard resistive and reactive components, it can take up a much larger area which is something to consider when operating in a finite space.

3.2.8.2.3 Linear Regulator

Linear regulators are an integrated circuit that can step down and regulate a constant voltage output using OPAMPs and transistors. The OPAMP is used to compare a reference voltage to the output voltage and based off that drives the transistor to control and maintain the flow of current in a way that produces a constant output voltage. Linear regulators are inexpensive and easy to implement within most circuit configurations due to them being easily packaged in a single IC form factor. While these regulators sound great on paper, they do suffer a number of drawbacks. For one, on their own, linear regulators fail to provide any sort of galvanic isolation between the primary and secondary sides of the circuit which can introduce safety hazards for anybody working on the low voltage side of the circuit and can cause undesirable effects for the microcontroller itself. In addition to that, like a standalone resistor divider, the voltage drop provided by the regulator is inefficient and can dissipate considerable heat. Using a linear regulator to step down a 25 V signal to 5 V with an intended output current of roughly 500 mA can dissipate almost 10 W of power, leading to temperatures far outside of the safe operating ranges and would almost certainly require the use of a heatsink to mitigate this.

3.2.8.2.4 Switching Buck Regulator

Buck converters are a variant of switch mode power supplies (SMPS) that step down an input voltage to a lower, regulated output voltage through a combination of capacitors, inductors, and high frequency switching transistors. They operate by having a MOSFET switch on and off quickly. When switched on, current flows through to the inductor which stores the energy within its magnetic field and charges the capacitors. When the FET is switched off, the capacitors discharge and the inductor continues to supply current to the load. The circuit utilizes a feedback system with an IC controller, so that depending on the output voltage, the frequency of the switching of the FET adjusts to maintain this desired output voltage. In addition, a topology can be designed to include a flyback transformer, a variant of transformer specifically used in these SMPS to provide galvanic isolation in a much smaller form factor compared to that of a standard AC transformer. As well, they run much more efficiently compared to standard linear regulators, minimizing the heat dissipation that would be found in these regulators.

Table 8: *Comparison of Voltage Step-Down Methodologies*

	Voltage Divider	Capacitive Dropper	AC Transformer	Linear Regulator	Buck Regulator
Avg. Cost	**Best**	**Best**	**Good**	**Good**	**Good**
Avg. Size	**Best**	**Best**	**Poor**	**Best**	**Good**
Efficiency	**Poor**	**Good**	**Best**	**Poor**	**Good**
Heat Dissipation	**Poor**	**Good**	**Best**	**Poor**	**Good**
Isolation	**Poor**	**Poor**	**Best**	**Poor**	**Good**

3.2.8.3 Buck Regulator IC Comparison

3.2.8.3.1 LM5180NGU

The LM5180NGU is a primary side regulating (PSR) flyback controller for use in DC/DC buck regulators. The controller supports an input range between 4.5 V - 65 V, with its own integrated 100 V-rated, 1.5 A power MOSFET. The primary side regulating label means that the regulation comes from feedback read from the primary side input, removing the need for a separate isolated opto-coupler to carry out this task. The complete regulating circuit offers an overall efficiency rating of ~81% with an overall footprint of less than 250 mm².

3.2.8.3.2 LM25180NGU

The LM25180NGU is also a PSR flyback controller designed for DC/DC conversion applications, optimized for systems operating from mid-range input voltages. It supports an input range between 4.5 V and 42 V and integrates a 65 V-rated, 1.5 A power MOSFET. Like the LM5180, it eliminates the need for an opto-coupler by using primary-side voltage sensing for feedback regulation, simplifying design. The complete regulation circuit typically delivers an efficiency of around 75%, with a similar compact footprint that remains under 250 mm².

3.2.8.3.3 LM5160DNT

The LM5160DNT synchronous step-down converter for DC/DC conversion applications. It operates from an input voltage range of 4.5 V to 65 V and integrates both high-side and low-side MOSFETs for high efficiency and reduced component count. Using an adaptive constant on-time (COT) control architecture, the LM5160 provides fast transient response and excellent regulation without the need for external loop compensation. Like the previous offerings, the device regulates alone from the primary-side input, providing an isolated output without requiring opto-couplers or additional coupled inductor windings. The complete regulation circuit typically delivers an efficiency of around 72%, with a slightly larger but still compact footprint closer to 255 mm².

3.2.8.3.3 LMR71915F-DDA

The LMR71915F-DDA synchronous step-down converter for DC/DC conversion applications. It operates from an input voltage range of 4.5 V to 65 V and, like the LMR71915F-DDA, integrates both high-side and low-side MOSFETs for high efficiency and reduced component count. In addition, the LMR71915F-DDA uses an adaptive COT control architecture for fast transient response and regulation without the need for external loop compensation. Like the previous offerings, the device regulates alone from the primary-side input, providing an isolated output without requiring opto-couplers or additional coupled inductor windings. The complete regulation circuit typically delivers an efficiency of around 73%, with a similar footprint to that of the LM5160DNT at around 255 mm².

	LM5180NGU	**LM25180NGU**	**LM5160DNT**	**LMR71915F-DDA**
Avg. Cost	$4.50	$1.50	$5.00	$2.82
Efficiency	88%	88%	85%	90%
Size	4mm x 4mm	4mm x 4mm	4mm x 4mm	SMD only
Max Power Capability	7 W	7 W	130 W	172.5 W
Max Input Voltage	65 V	42 V	65 V	115 V

Max Input Current	1.5 A	10 mA	2 A	1.5 A

3.2.8.4 Power Regulation and Polarity Conversion Comparisons

It is standard for not just microcontrollers, but for the majority of auxiliary IC components as well as requiring the need for a DC signal to operate. Utilizing an AC signal for these components can lead to inducing permanent damage, facilitating the need for a method to convert the AC signal to a DC one.

3.2.8.5 Half Wave Rectifier

A Half Wave rectifier is a type of circuit that leverages the properties of diodes to convert an AC signal to a DC signal. Standard diodes are designed to only allow current to pass through in one direction, effectively blocking the negative half on an AC voltage waveform. This alone will produce a waveform that cycles between the peak magnitude of the positive waveform, effectively achieving DC signal, but one that has substantial ripple between the peak and valley of the waveform. To reduce this ripple, a capacitor can be placed in parallel with the output of the rectifier to significantly smooth out the signal enough to create a constant enough signal to power a microcontroller and additional ICs [60]. When using a Half Wave rectifier, it is important to note that the negative portion of the AC signal is entirely eliminated, resulting in periods where the output is effectively zero. This discontinuity significantly reduces the efficiency on the microcontroller load side by nearly 60%.

3.2.8.6 Full Wave Rectifier

A Full Wave Rectifier is a circuit that improves upon the drawbacks introduced by the Half Wave Rectifier. Instead of having periods of zero output, a Full Wave Rectifier can remedy this by effectively converting the negative half of a waveform to a positive one. This change alone essentially doubles the efficiency of the output supplied to the load compared to a Half Wave Rectifier. The Full Wave Rectifier is configured using a center-tapped transformer, two diodes in parallel, and a resistive element sandwiched between in parallel and connected to the center tap. During the positive half of the input waveform, the first of two diodes will conduct, allowing current to flow to the supply. During the negative half, the first diode shuts off, and the second will begin to conduct, allowing for a constant positive signal to be supplied to the load [61]. While this certainly had noticeable improvement, there is a slight caveat that is important to be noted. The Full Wave Rectifier facilitates the need for a center-tapped transformer specifically to operate properly. A CT transformer varies slightly from traditional transformers in that instead of a single pair of output terminals, a CT transformer contains two pairs of output terminals with the reference point between them. In addition, these output terminals are 180° out of phase from each other, leading to each output terminal conducting in the positive cycle while the other is in its negative cycle.

3.2.8.7 Full Bridge Rectifier

A Full Bridge Rectifier is a variant of the Full Wave Rectifier that provides the same full wave rectification without the need for a center-tapped transformer. As opposed to using two diodes in conjunction with the CT transformer, the Full Bridge Rectifier employs the use of four diodes arranged in a bridge configuration that allows for both halves of the AC waveform to be utilized in a single polarity. This bridge arrangement allows for two of the diodes to conduct single cycle halves in opposite polarity, ensuring that a constant flow of positive current can be supplied to the load. The elimination of the need for a center-tapped transformer leads to a more flexible and cost-effective approach to achieving full wave rectification. Just like the two previous approaches, a Full Bridge Rectifier outputs a signal with significant difference between the peak and floor magnitude, and likely requires a capacitor placed in parallel to the output to significantly smooth out the signal.

Table3.2.8.8: *Comparison of AC/DC Conversion Methodologies*

	Half Wave Rectifier	Full Wave Rectifier	Full Bridge Rectifier
Avg. Cost	**$0.50**	**$0.80**	**$2.00**
Efficiency	**50%**	**75%**	**75%**
Size	**1 Diode**	**2 Diodes + Transformer**	**4 Diodes**
Max Input Voltage	**50 V**	**Limited by Diodes**	**Limited by Diodes**
Ripple	**High ripple: Requires filter capacitor**	**Lower ripple**	**Lowper ripple**

3.3 Communication Protocols

3.3.1 Wireless Communication Protocols

3.3.1.2 Comparison of Wireless Communication Protocols

A key feature of the smart breaker is its ability to exchange data with external devices for monitoring, control, and integration into larger energy management systems. The communication interface must provide sufficient bandwidth for real-time reporting, low latency for fast response, and reliability in residential and commercial environments. Four technologies were evaluated: **Wi-Fi, Bluetooth, Zigbee, and Ethernet.**

3.3.1.3 Wi-Fi

Wi-Fi is the most common wireless protocol for residential and commercial environments. It offers high bandwidth, typically up to hundreds of Mbps, which is more than sufficient for transmitting breaker data such as voltage, current, and power status. One of Wi-Fi's major advantages is its ubiquity: nearly every building already has a Wi-Fi network, making integration straightforward. Additionally, Wi-Fi allows remote access through cloud platforms, enabling users to control and monitor the breaker from anywhere with internet access.

However, Wi-Fi requires relatively high-power consumption compared to other protocols, which may be a drawback to low-power embedded systems. Network congestion and security vulnerabilities are additional concerns in environments with many connected devices. Despite these limitations, Wi-Fi provides the most seamless user experience for end-customers due to its availability and range (tens of meters indoors, longer with external antennas).

3.3.1.4 Bluetooth

Bluetooth is a short-range communication protocol (typically less than 10 meters for standard devices, up to 100 meters with Bluetooth Low Energy or Class 1 modules). It is optimized for **low power consumption**, which makes it suitable for battery-powered or energy-constrained applications. Bluetooth modules are inexpensive, easy to implement, and supported by virtually all smartphones, providing a convenient local interface for setup or direct control.

The limitations of Bluetooth are its restricted range and lack of inherent internet connectivity. While it works well for commissioning, local monitoring, or one-to-one communication, it cannot provide the same remote access capabilities as Wi-Fi without additional hardware acting as a bridge. For a smart breaker intended to serve as part of a broader home or building energy management system, Bluetooth alone may be insufficient.

3.3.1.5 Zigbee

Zigbee is a wireless protocol specifically designed for low-power, low-data-rate applications in building automation and the Internet of Things (IoT)**.** It operates in mesh networks, allowing multiple devices to relay data and extend overall range. This makes Zigbee particularly effective for environments with many distributed sensors or devices, such as smart homes and smart grids. Its power consumption is lower than Wi-Fi, and it is more scalable than Bluetooth.

The main disadvantages of Zigbee are limited bandwidth (sufficient only for sensor data) and the need for a dedicated hub or gateway, which may increase deployment costs for end-users. However, its robustness, reliability, and ability to support a large network of devices make it an attractive option for utility or industrial partners who envision scaling to multiple breakers and smart devices.

3.3.1.6 Ethernet (Wired Communication)

Ethernet represents the most robust and reliable communication option among the technologies considered. It offers very high bandwidth (up to 1 Gbps or more), extremely low latency, and a stable connection that is not affected by wireless interference or congestion. These characteristics make Ethernet highly attractive in **industrial or commercial applications** where uninterrupted communication is critical. Furthermore, Ethernet provides better security since it is a closed, wired medium and not as exposed to cyber threats as Wi-Fi.

The primary drawback of Ethernet is the lack of flexibility: it requires physical cabling, which increases installation cost and complexity, especially in retrofitting existing residential systems. It also limits mobility, as the device must be located near a router or switch. For large-scale consumer deployment, this can be a significant barrier. Nevertheless, in controlled environments such as data centers, factories, or smart building infrastructures, Ethernet remains the most dependable choice.

3.3.1.7 Final Selection

For this project, **Wi-Fi** was selected as the primary communication technology. Its wide adoption, high bandwidth, and ability to enable remote access through standard networks align with the project's goal of giving users full visibility and control over their power systems. While Wi-Fi consumes more power, this drawback is manageable in a breaker that is continuously powered from the grid.

Ethernet is recognized as the most reliable option and could be considered in future iterations targeting industrial or commercial customers who require guaranteed uptime.

3.4 Embedded Software

3.4.1 Software Scheduling Algorithms and Power Modes

3.4.1.1 Comparison of Scheduling Algorithms

The ESP32 microcontroller unit will handle the computational control, requiring it to monitor voltage/current detection, Analog to Digital Conversion, communication to the switches, data logging, and communication to the website for display across anywhere in the world where there might be Wi-Fi, all on a dual-core processor, each of which is only capable of handling one task at a time, and because we are using wireless communication, core 0 of core 0 and core 1 is primarily used for said wireless communication, hence we are mainly reliant on core 1 for almost all of our processes which require us to use a precise scheduling algorithm in our code to effectively prioritize which operations will be running. Primary scheduling algorithms will be Priority-Based Preemptive Scheduling, Round Robin Scheduling, Rate Monotonic Scheduling, Cooperative Scheduling, Event-Driven (Hybrid) Scheduling, and Dynamic Power-Aware Scheduling.

3.4.1.2 Priority-Based Preemptive Scheduling

Priority-Based Preemptive Scheduling is what most embedded software, especially ones like the ESP32 board use due to being able to assign each task as a priority, and the scheduler will run the highest-priority ready task set by the user to run first. This allows the voltage/current detection to always be prioritized over other low-priority tasks and if given an interruption, will trip the breaker to stop the flow of current within a few microseconds. Though this could cause starvation within the lower-priority tasks due to the higher priority tasks always taking precedence first. The algorithm is simple yet effective and can be changed to prioritize whichever task we designate of most importance first.

3.4.1.3 Round Robin Scheduling

The algorithm allows for each task to get a slice in rotation whenever the code is running, ensuring fair CPU use throughout its runtime. Higher priority tasks will still maintain their priority compared to their lower priority tasks which will always follow the priority tasks but there is still a chance for starvation depending on delays and interrupts used so extremely low priority tasks like data logging may be missed in the event of the tripping of the breaker.

3.4.1.4 Rate Monotonic Scheduling

Each task will run depending on its period, or how often the task must run, the shorter a task the higher priority it will take. In terms of our smart breaker, the fault detection aspect will be the highest priority always, then the other tasks will follow. This doesn't mean that the task will run every execution time as the execution time will vary depending on the task. For example, the period of the fault detection task may be every 10 ms but the period may be every millisecond, this means after that millisecond has concluded the next priority task will run until it is required again. This type of scheduling is effective, yet this could mean that lower priority tasks are once again starved depending on the duration of each execution time and period. Furthermore, certain tasks periods may take a while such as communication, yet it may be the second highest priority due to the website being able to shut down the breaker remotely. This scheduling algorithm is most likely one of the least useful algorithms that will be considered.

3.4.1.5 Cooperative Scheduling

Cooperative Scheduling involves a task voluntarily yielding control of the CPU to let other tasks run. Basically, the scheduler does not forcibly interrupt a task; instead, the current running task must give up the processor by using a yield or sleep command. There is no timer interrupt like in preemptive scheduling. Cooperative Scheduling is simple to implement and has no race conditions, however, a misbehaving task can block the whole system and there is no real guaranteed real-time response, any task can be blocked given the conditions. Though the CPU is able to share all processes, priority tasks are not prioritized. This algorithm is not one that will be used in the smart breaker as it is not energy efficient and does not align with our goals in safety and protection.

3.4.1.6 Event-Driven Hybrid Scheduling

This scheduling algorithm is a combination of cooperative and preemptive scheduling techniques. First, there is an event-driven (interrupt-based) layer that handles urgent time-critical events extremely quickly, such as sensing a sudden spike in energy to which the task can immediately react but tripping the breaker. Though as stated, this is triggered by interruptions which can cause issues if too many are implemented. If the interrupt is not triggered, the rest is simply handled by the cooperative scheduling algorithms that handle less important tasks such as data logging. This scheduling algorithm is extremely efficient at handling power as the CPU is only active when something happens and is simpler to implement than a preemptive Real-Time Operating System. The only issue is that if there are too many event types and if the event that is triggered by the interrupt takes too long, priorities may get misconstrued.

In terms of the smart breaker, this algorithm would be one of the stronger ones to use as it is extremely effective at handling power, only waking up the CPU whenever an event is triggered causing an interrupt to occur. We can control this with our smart breaker by having the sensor constantly checking the power signals as the CPU is asleep and whenever there is a sudden strike in current or voltage, then the CPU will wake up immediately and trip the breaker to ensure everything is completely safe. All in all, this is a more effective choice in deterring algorithms.

3.4.1.7 Dynamic Power-Aware Scheduling

This scheduling technique optimizes CPU performance and energy consumption by adjusting how and when tasks run based on power and workload conditions. The scheduler will not just consider deadlines such as in the earliest deadline first algorithm, rather it considers other key aspects such as energy usage, system state (voltage, frequency, battery level, and temperature). The main concept of this algorithm is that the CPU will adjust its own clock frequency and voltage depending on how much computational power is needed, for example a higher workload will require a higher frequency and voltage hence resulting in a faster execution, meanwhile, a low workload will result in a lower frequency and voltage which will allow the smart breaker to conserve energy during its "sleeping" hours. Furthermore, the scheduler will decide when and on which core to run tasks to minimize total energy while still meeting deadlines. The scheduler is able to estimate the minimum frequency needed so all tasks are able to finish on time, so during the runtime the scheduler may lower the clock frequency, raise the clock frequency, or even put unused cores/peripherals to sleep to save power.

Dynamic Power-Aware Scheduling is able to reduce overall energy consumption, which in turn extends the overall battery life. This low battery usage is also able to reduce heat and electromagnetic interference which is not as essential as before the smart breaker was involved when using a magnetic element to know when to trip the breaker. Lastly, the algorithm is still able to hit its deadlines.

Though extremely advantageous for us to use, it does require more complex scheduling algorithms to encode into this embedded system. The real-time events are harder to analyze because of the constant frequency changes that affect timing. Lastly, it requires more hardware support. As stated before the ESP32 board is a dual-core processor and due to the Wi-Fi constraints that were set earlier, there would only be one core available at all times, hence more hardware would be required to be added in conjunction with this one or even a new development board entirely. Multiple ESP32 Boards will be required to work in tangent to achieve maximum results. However, due to the cost one board, this factor does not result in much of an issue.

3.4.1.8 Final Scheduling Algorithm Selection (THIS WILL PROBABLY CHANGE DEPENDING ON COST)

The final algorithm that will be used is Dynamic-Power Aware scheduling since the smart breaker is supposed to be as energy efficient as possible, all other algorithms aside from the event-driven algorithm require both cores to operate at all times. However, with the Dynamic-Power Aware scheduling algorithm it is able to put either core to sleep whenever that core is not required for major processing data. During operating hours, the smart breaker should be monitoring power consumption throughout the residential building

3.4.1.9 Predictive Algorithms and Load Management

Modern power systems increasingly rely on intelligent control methods to anticipate faults and optimize energy distribution. To enhance safety and efficiency, the proposed Smart Circuit Breaker SABRE integrates predictive algorithms that analyze real-time and historical electrical data to forecast potential overloads, identify high-demand periods, and perform selective load control. This transforms the system from a traditional reactive protection device into a proactive, adaptive control unit capable of managing power flow intelligently.

3.4.1.10 Data Acquisition and Monitoring

The Smart Circuit Breaker SABRE continuously monitors several key electrical parameters:

- Voltage (V): to ensure that supply levels remain within safe operating limits.
- Current (I): to detect overload conditions or short circuits.
- Instantaneous Power ($P = V \times I$): to calculate the real-time energy usage of the connected load.
- Energy Consumption: to determine cumulative demand trends over time.

This data is sampled at high frequency using precision sensors and processed by the onboard microcontroller. Continuous monitoring allows the system to identify deviations in expected patterns and apply corrective actions when necessary.

3.4.1.11 Predictive Load Behavior

The Smart Circuit Breaker SABRE uses a time-based predictive algorithm to analyze patterns in power consumption. By applying statistical models such as moving averages and exponential smoothing, the controller can predict periods of increased load based on daily or weekly behavior.
For instance, if the system recognizes that a particular load consistently draws higher current during certain hours, it can prepare by gradually reducing non-essential loads or alerting the user before the demand exceeds safe operating limits. This predictive approach minimizes unnecessary breaker trips and enhances operational stability.

This conditional algorithm enables smooth transitions between monitoring, prediction, and controlled protection without abrupt interruptions.

3.4.1.12 Demand Forecasting and Scheduling

Beyond simple overload prevention, the system incorporates demand forecasting, allowing it to predict high-demand intervals and adjust operation accordingly. Using time-of-day data, The Smart Circuit Breaker SABRE can schedule or delay the operation of non-critical loads during peak periods, improving overall energy efficiency.
This function can be extended to interface with smart grid communication protocols, allowing the breaker to respond dynamically to external grid signals — for example, reducing consumption when the grid is under stress or electricity prices are high.

3.4.1.13 System Benefits

Implementing predictive and adaptive algorithms provides the following key advantages:

- **Enhanced safety**: Early detection of overload conditions before faults occur.
- **Increased efficiency**: Optimized power distribution based on real-time usage.
- **Reduced downtime**: Fewer unnecessary trips and smoother recovery from overloads.
- **Extended lifespan**: Reduced thermal and electrical stress on connected equipment.
- **User awareness**: Predictive alerts and notifications before critical events.

By combining sensing, analytics, and decision-making, the Smart Breaker effectively becomes a self-learning power management device, capable of adapting to usage behavior and ensuring optimal electrical performance under varying conditions.

3.4.1.14 Algorithm Selection and Comparison

To ensure efficient and reliable predictive operation, several algorithmic approaches were evaluated for implementation in the Smart Breaker's control logic. Each method offers distinct advantages depending on computational complexity, accuracy, and adaptability. Table 41 summarizes the comparison between three primary algorithm categories — threshold-based, time-series predictive, and machine learning-based algorithms — followed by an explanation of the selected approach.

Table 9: *Comparison of Algorithm Implementations*

Algorithm Type	Description	Advantages	Disadvantages	Suitability
Threshold-Based Algorithm	Uses fixed voltage and current limits to trigger protection or alert conditions.	Simple, fast, and requires minimal processing power. Ideal for real-time protection.	Cannot predict overloads; only reacts to events after they occur.	High for baseline protection control.
Time-Series Predictive Algorithm	Uses moving averages, exponential smoothing, or regression on historical data to forecast high-demand periods.	Predicts future loads, allowing preemptive response; moderate computational cost.	Requires sufficient data history; less effective with random or irregular loads.	Very High — chosen for this project.
Machine Learning Algorithm	Employs neural networks or decision trees to learn complex usage patterns over time.	Self-adaptive and highly accurate in long-term load forecasting.	High computational cost requires large datasets and cloud or edge computing resources.	Medium (for future implementation).

3.4.16 Selected Algorithm

For this phase of the project, the Time-Series Predictive Algorithm was selected as the most appropriate choice. It provides a balanced combination of accuracy, real-time responsiveness, and computational efficiency suitable for an embedded system such as The Smart Circuit Breaker SABRE .

This algorithm analyzes recent current and power readings, identifies load trends, and estimates short-term demand spikes. By doing so, it allows the system to perform proactive

protection — reducing load or issuing alerts before an overload occurs — rather than waiting for threshold violation events.
Additionally, this approach can be easily upgraded in the future to incorporate machine learning for improved adaptability once sufficient operational data has been collected. This scalability ensures that the Smart Breaker remains a forward-compatible platform for intelligent energy management.

3.5 Software Comparison and Selection

3.5.1 Web Development Software Stacks

3.5.1.1 LAMP Stack

The LAMP stack is a tried-and-true full software stack for development on the web. Known for its open-source nature and years of robust development, the LAMP stack is commonly composed of Linux, Apache, MySQL, and PHP.

3.5.1.1.1 Foundational Layers

The foundational layers that everything else in the stack relies on is encompassed in both Linux and Apache. Linux is at the lowest level on this footing, and it is the standard for open-source operating systems; it is at the heart of most server architectures still managed today. Linux acts the same in a server operating system as it does for single users utilizing it for local personal computing. It provides a middleman of sorts between the hardware and software running on the machine, and oversees managing system resources including memory, processes, and the file system. While there exist alternatives available that can fill the role that Linux provides, none of these replacements have as rich an ecosystem and ease of use that Linux provides for this software stack.

Apache is the actual web server that sits on top of and is being hosted by the Linux operating system. It manages the client-side connections and the parsing of HTTP requests to deliver appropriate files or data back to respective clients based on their needs. Just like Linux in the operating system sphere, Apache has remained a long-standing, widely used, supple server platform for carrying out a variety of network related tasks. In conjunction with Linux, the two serve as the foundational layers for which the remainder of the stack relies on [62].

3.5.1.1.2 Database

MySQL serves as the database platform within a LAMP stack. As the name implies, MySQL utilizes SQL for executing queries related to posting, editing, and retrieving persistent data during server runtime [63]. As a prime example of a relational database, MySQL organizes data into tables that are then composed of rows and columns. The relational nature of this platform stems from how data entries are defined and spread across multiple different tables *(this line might be able to be written better)* [62]. For instance, one table is likely to be arranged to store individual user information, with one of these entries containing information detailing a user's position in a particular hierarchy. Another table would then provide the specific details of this hierarchy, allowing SQL queries to extract relevant information pertaining to these tiers. This sort of scheme enables both flexibility and scalability for database management, solidifying MySQL as the standard for relational database implementations.

3.5.1.1.3 Backend

The typical backend scripting language used in a LAMP stack is PHP, an open-source programming language purposed to execute dynamic operations initiated by the client and served through the Apache web server. PHP acts as an intermediary between client requests and the database. It processes user interactions from the client side, executes the appropriate SQL queries on the server, and returns the resulting data to the user. There are alternatives for handling backend operations in this stack such as Perl and Python, however PHP emerged as the de facto standard for backend development in the LAMP stack [62].

3.5.1.1.3 Frontend

In the conventional LAMP stack architecture, there is no specific framework dedicated to front-end development. Web applications built on this stack typically utilize basic HTML, CSS, and JavaScript for user side styling. This approach offers the advantage of minimal abstraction between the code and the visual output, which can enhance performance and optimize resource utilization. However, it also means that many of the dynamic client-side UI rendering features found in modern web applications are either absent or must be manually rewritten in JavaScript.

3.5.1.2.1 End-to-End JavaScript

With how ubiquitous JavaScript became for client-side scripting within web browsers, it weas only a matter of time before options would arise for using JavaScript for every portion of the stack [64]. This is where Node.JS emerged, and in conjunction with the Express.JS framework, allowed for modular server-side scripting written in JavaScript. Node.JS still ranks as the most used web framework in 2025 according to a Stack Overflow survey of developers and is the catalyst behind today’s contemporary tech stacks like MERN and MEAN [65].

3.5.1.2.2 MEAN Stack

The MEAN stack was one of the first end-to-end JavaScript tech stacks that gained widespread adoption. The stack is built on MongoDB, Express.JS, Angular, and Node.JS, allowing for programming in JavaScript on both the backend and frontend sides of the web application [64].

3.5.1.2.3 Foundation

Node.JS is the foundation for which the rest of stack is built upon. Node is primarily responsible for providing a cross-platform runtime environment for executing JavaScript outside of the web browser, allowing developers to create server-side scripting with JS. In addition to that, Node's popularity has brought with it the Node Package Manager (npm), which provides a rich ecosystem of open-source packages to be integrated within a project.

While Node on its own is a great tool for providing backend scripting support, used in conjunction with Express.JS is where this framework truly shines. Express.JS is a strong framework built on top of Node that welcomes several rudimentary web application features that allow for an even more streamlined developer experience writing server-side JavaScript. It introduces several APIs that make handling HTTP requests, developing custom API, and routing that makes the buildout of the backend much simpler *(maybe rework this sent.)* [64].

3.5.1.2.4 Database

MongoDB established itself as the go-to database platform within unified JavaScript software stacks. It is the most popular NoSQL style database, subsisting for the relational table format found in SQL for an unstructured document styled storage solution resembling JSON object formatting. This makes it a wonderful tool for use with other JavaScript tools that natively support data formatted in JSON objects and allow for flexibility in not having data stored in a structured format that is seen in SQL style databases [66]. *(add more).*

3.5.1.2.5 Frontend

A key advantage of modern web development stacks is their usage of front-end frameworks that can significantly speed up development processes for adding dynamic client-side rendering. The MEAN stack in particular takes advantage of the Angular framework for front-end development. Angular offers a fully-fledged framework for creating dynamic Single Page Applications (SPAs), a front-end design model allowing for multiple views to be rendered within a single HTML file, enhancing load times for users. This paradigm is supported by Angular's built-in front-end routing capabilities, which are then made up of reusable components to streamline the development process and facilitate adherence to the DRY (Don't Repeat Yourself) principle [67].

3.5.1.2.6 MERN Stack

An alternative to the MEAN stack previously discussed is that of the MERN stack, which as the acronym implies, keeps most of the stack the same except for substituting Angular for the React framework for front-end development. React is a front-end library facilitating a component-based architecture for creating modular UI / UX frontend elements. Similar to Angular, React is designed for building single-page applications (SPAs) with a strong emphasis on optimizing user performance, and avoiding full page re-renders. It does this by employing its own virtual Document Object Model (DOM) which is composed of the current UI state and a previous copy. React then compares changes between these two and only updates what has been changed between the two states, allowing for an even more efficient DOM updates within SPAs. Additionally, React utilizes JSX, a syntax extension for JavaScript that enables developers to write HTML directly within JavaScript programs, enhancing readability [68]. Compare that to Angular where the logic of a particular component is split separately from the HTML markdown that is rendered to the user. As React was originally created as a library focusing on strictly creating dynamic UI / UX elements, in its original build, it does lack a lot of the full-fledged features that come baked right in with Angular. However, extensive community support for React has allowed additional libraries that can be integrated with React to address these shortcomings [69].

3.5.1.3.1 Django

Django is a comprehensive framework for web development built on top of Python. It is useful for it's all-in-one ability approach, employing many different layers of a full stack application in just a single framework. Django provides options for routing, frontend templating, and database management in a single unified package. The framework alone allows for similar implementation of the functionalities of Node.JS and Express.JS all in a single framework. Django employs a Model View Template (MVT) architectural pattern. In this framework, the "Model" is responsible for managing data retrieval and formatting from a database. The "View" acts as the front-end request handler, delivering the appropriate HTML content based on user URL requests. "Template" refers to the actual HTML file that defines the layout presented to the user on the client side. Django is typically best supported with relational databases like MySQL due to its build in support for Object Relational Mapping (ORM), a technique used for working with relational databases using an object-oriented language like Python. NoSQL databases can be used with Django but require additional packages to be added alongside the standard Django framework [70].

Table 10: *Comparison of Full Stack Frameworks*

	LAMP	MEAN	MERN	DJANGO
Open Source	✓	✓	✓	✓
Native Primary Language	PHP	JavaScript	JavaScript	Python
Frontend Framework	Native HTML, CSS, JS	Angular	React	Django Page Templates
Backend Framework	Native PHP	Node.JS / Express. JS	Node.JS/ Express.JS	Django
Database	Traditionally SQL Based	NoSQL Based	NoSQL Based	SQL Based
Server Environment	Apache	Node.JS	Node.JS	Nginx
Operating System	Linux	Cross-Platform	Cross-Platform	Cross-Platform
Primary Rendering Style	Server – Side Rendering	Client – Side Rendering	Client – Side Rendering	Server – Side Rendering
Ease-of-Use	Simplest	Simple	Simpler	Simpler
Community Support	Large / Mature	Large / Actively Growing	Large / Actively Growing	Large
Support For Mobile Development	No Native Support	Angular PWA	React Native	Backend Support / Requires additional Frontend Framework

3.5.2 Database Selection for Time-Series Data Management

3.5.2.1 Requirements for Time-Stamped Sensor Data Storage

The monitoring functionalities of the Smart Breaker produce a continuous, high-velocity flow of time-series data. A database designed especially for chronological data intake, quick range queries, and effective aggregation across large datasets is needed to manage it.[88]

3.5.2.2 Comparative Analysis of Time-Series Database Options

Although specialized Time-Series Databases (TSDBs) like TimescaleDB and InfluxDB provide better performance in data compression and complex analytical queries, the project needs to store a variety of flexible data types, including event logs, device metadata, and user configuration, in addition to large volumes of sensor data.[106]

MongoDB is chosen as the main data persistence layer because of its high degree of flexibility, which is frequently preferred in agile development settings, and its ability to manage a variety of workloads. The system benefits from using MongoDB's Time Series Collections functionality, which is appropriate for this purpose, and it helps that we have prior experience with it.

3.5.2.3 Features:

1. **Flexibility and Unified Modeling:** A single ecosystem can easily store a variety of data kinds, including telemetry, event logs, user profiles, and configuration settings, thanks to MongoDB's flexible design. Compared to maintaining distinct relational (for users) and specialized time-series databases, this streamlines the architectural stack.
2. **Horizontal Scalability:** MongoDB is inherently designed for horizontal scaling (sharding), which is important for supporting the modular scalability stretch goal of managing multiple breakers in a panel and potentially millions of deployed units for our project.
3. **Development Velocity:** Because Node.js was chosen for the backend, MongoDB easily connects with the well-liked MERN/MEAN stack, speeding up development and using team knowledge.[107]

MongoDB offers the most overall flexibility for the whole digital ecosystem and, when correctly configured, delivers acceptable performance for time-series data storage, even though dedicated TSDBs frequently exhibit greater write speed and storage compression, particularly for high-cardinality workloads.

Table 11: *Comparative Analysis of Data Storage for Smart Breaker*

Metric/Feature	MongoDB (NoSQL)	TimescaleDB (PostgreSQL Extension)	Selection Rationale
Query Language	Flexible (BSON/JSON, MongoQL)	Full SQL, Window	Flexible NoSQL structure simplifies storage of

		Functions, Joins [90]	mixed data (users, config, telemetry).
Data Model	Flexible/Dynamic Schema	Rigid Relational Schema	Best for accommodating rapid changes in sensor telemetry and metadata.
Scalability Focus	Horizontal (Sharding)	Vertical and Partitioning (Hypertables)[73]	Excellent foundation for scaling out to millions of managed devices.
Disk Storage/Compression	High (Compared to dedicated TSDBs)	Low (Optimized compression)	Flexibility and a consistent data structure are acceptable trade-offs for higher storage costs.
Complex Query Performance	Slower for complex analytical queries (joins/aggregation)	Vastly Superior (x - x faster) [90]	Requires careful optimization to support future Machine Learning/Fault Prediction goals.

3.5.2.5 Database Schema Design for Breaker Telemetry and Event Logging

The MongoDB implementation utilizes two primary collections:

1. **Telemetry Time Series Collection:** High-frequency sensor data are the focus of this collection. It is made with MongoDB's Time Series Collections feature, which automatically partitions data by the "time" and "device_id" columns and internally optimizes storage and query speed for time-stamped data. Current, voltage, power, and temperature are among the fields that are indexed.
2. **Event Log Collection:** Discrete, low-volume, but extremely important events and user activities are stored in this standard collection. Records like "arc_fault_detected", "overload_trip", "remote_trip_issued", and "breaker_reset" are included in this category. Compliance, diagnostics, and user openness about the device's safety history depend on this record.

3.5.2.6 Data Retention Policies and Down sampling Strategy

Since MongoDB has a larger storage footprint than specialized TSDBs, a tiered data retention technique is used to control storage costs and preserve query speed over extended periods of time. For a certain amount of time, raw, high-resolution sensor data will be kept, enabling thorough diagnostics of recent occurrences.

This raw data will be automatically down sampled into coarser aggregates by ongoing background jobs. The long-range queries needed for monthly consumption reporting and historical trend analysis are significantly sped up by storing these aggregated datasets in a distinct, aggregated collection for all time.[73]

3.5.3 Backend API Selection and Real-Time Data Delivery

3.5.3.1 Backend Language and Framework Selection

In order to process asynchronous data streams that are sent from the IoT Hub and maintain permanent client connections, the backend must act as a high concurrency middleman. The best implementation stack is determined to be Node.js with the Express framework.[96]

The V8 engine of Chrome serves as the foundation for Node.js, which employs an event-driven, nonblocking I/O approach. Because it enables the server to manage thousands of concurrent, long-lived connections (both MQTT and Web Sockets) with minimal overhead and effectively conduct I/O-bound operations without causing the main thread to stall, this architecture is intrinsically better suited to the needs of an IoT API.[76]

Node.js offers a notable edge in development pace, even while compiled languages like Go (Golang) offer better raw computing performance and extremely effective concurrency control.[97] It offers a perfect balance between development speed and required performance for this project because to its vast npm ecosystem and the unified language stack (JavaScript/TypeScript), which enable quicker prototyping and deployment.[98]

3.5.3.2 API Gateway and Routing Architecture

An API Gateway is used by the API architecture to control external traffic and implement initial authentication. Two kinds of traffic are logically separated by this gateway:

- **REST Endpoints:** used to retrieve reports from the TSDB, adjust configurations, and access historical data.
- **WebSocket Endpoints:** Dedicated to managing essential control instructions (remote trip/reset) and real-time data streams.

The Node.js backend functions as a collection of processes that distribute load and provide high availability. It effectively routes requests according to whether they call for permanent real-time communication or database involvement.

3.5.3.3 Bidirectional Communication via Web Sockets

The primary interface for real-time client interaction must support communication in both directions: server-to-client and client-to-server. Server-Sent Events (SSE) does not natively handle client-to-server communication beyond the initial request, while providing a more straightforward, HTTP-based protocol that is intended for unidirectional server-to-client data streaming (monitoring).[75] A bidirectional connection is necessary because the Smart Breaker needs safety-critical remote actuation.

Thus, the required protocol for client-facing real-time applications is Web Sockets. [100]

The architecture is made simpler by using Web Sockets for both crucial control command intake and real-time telemetry push. This removes the need to handle two different permanent connection types (a separate channel for control commands and SSE for data). The command execution path can meet the low-latency requirements thanks to this single-protocol method, which also retains excellent efficiency.[101]

3.5.3.4 Server-Side Processing for Alerts and Notifications

In order to handle alerts instantly, the Backend API is essential. The Cloud IoT Hub manages high-priority alert topics that are subscribed to by implemented Node.js APIs. These APIs evaluate the message instantly once the IoT Rules Engine routes it and recognizes a critical event (such as an arc fault or prolonged overload).

After that, the API broadcasts a push notification command to the linked mobile clients over the persistent WebSocket connections. This solution satisfies a crucial project need by guaranteeing immediate notice of safety occurrences. Once the notifications are sent, with little apparent delay since this procedure is asynchronous and depends on the low-latency MQTT/WebSocket pipeline.

3.5.4 Frontend and Mobile Development Frameworks

3.5.4.1 Selection of Cross-Platform Mobile Development Framework

Both online dashboards and mobile applications must function flawlessly for a completely digital environment. For the mobile component, a cross-platform framework is necessary to optimize development efficiency and reduce time-to-market.[103]

The principal user application rejects Progressive Web Apps (PWAs) because of basic constraints. PWAs' performance is limited by the browser sandbox; they frequently lack the speed and responsiveness of native applications, and they have limited access to certain device functions (such as strong, high-priority push notifications required for safety alerts).[103]

The top cross-platform frameworks, Flutter and React Native, are the only options left. High-frequency time-series data visualization in real-time charts is a key component of the Smart Breaker program. React Native communicates with native UI components via a JavaScript bridge, which adds quantifiable overhead and may result in "jank" or visual drops when rendering data-intensive charts under heavy demand.[78]

Flutter, on the other hand, is used for data-intensive, real-time rendering because of its better performance profile. Flutter uses its proprietary Skia rendering engine and compiles its Dart code ahead-of-time (AOT) to native ARM or x86 libraries. By completely avoiding the JavaScript bridge, this method ensures that the mobile experience is dependable and responsive for safety monitoring. It also produces quicker animations, greater UI fluidity, and reduced CPU/memory usage while handling high-frequency data.[79]

Table 12: *Comparison of Cross-Platform Framework for Real-Time IoT Applications*

Metric/Feature	**Flutter (Dart)**	**React Native (JavaScript)**	**Progressive Web App (PWA)**
Native Performance	Excellent (Compiled native code, Skia engine) [79]	Good, but latency introduced by JS bridge [78]	Poor (Limited by browser sandboxing) [103]
High-Frequency Charting	Superior UI Fluidity/Responsiveness [79]	Potential performance drops during heavy load [105]	Unsuitable for reliable real-time safety visualization

Remote Control Latency Path	Optimized (minimal overhead)	Elevated latency risk due to bridge communication [79]	Highest latency, relies on web APIs
Development Reusability	High (Mobile/Web/Desktop)	High (Mobile/Web)	High (Browser only)

3.5.4.3 Web Application Implementation Details

Usually accessible through a PC or tablet, the web application functions as the all-inclusive control and reporting dashboard. Its main objectives are configuration management, report generation, and in-depth historical analysis.

React is one of the contemporary JavaScript frameworks that will be used to build the web frontend. It will obtain aggregated reports and historical usage statistics from MongoDB using standard REST API endpoints. Crucially, it will continue to have a specific WebSocket connection for instantaneous system alarm display and real-time metrics visualization.

3.5.4.4 Mobile Application Implementation Details

The main portable interface for instantaneous remote control and alarm receiving is the Flutter application. Performance and dependability must be given top priority throughout deployment. It will keep up the persistent WebSocket connection needed to safely send low-latency control instructions and receive real-time data pushes.[75] To guarantee that safety-critical alerts (such as overload, high temperature, and fault conditions) consistently circumvent system silencing settings and notify the user right away, even when the app is running in the background, the Flutter application must also integrate with native mobile notification systems.

3.5.5 IOT Cloud Computing Platform Comparison

3.5.5.1 Comparison of Leading Cloud Computing Platforms

Selecting a fundamental cloud platform is essential because it offers managed services for scalability, device ingestion, and security technologies that self-hosted alternatives find difficult to duplicate. The assessment centers on Microsoft Azure IoT Hub and Amazon Web Services (AWS) IoT Core, two of the industry's most prominent and established systems.[80]

Market risk is reduced by selecting a core platform over smaller suppliers. The recent closure of Google Cloud IoT Core serves as a clear indication of the instability in the IoT sector, underlining the necessity for optimal long-term support and full ecosystems afforded by AWS and Azure.[72]

As a safety device, the Smart Breaker requires enterprise-grade security and integrated threat detection capabilities, while AWS IoT Core is renowned for its breadth, unparalleled scalability, and dependability. Azure IoT Hub is, therefore, strategically better. Crucially, Azure IoT Hub delivers deep integration with Microsoft Defender for IoT and powerful real-time processing capabilities.[72] By offering advanced, real-time threat detection and security warnings, this security stack goes above and beyond basic encryption and identity management, which is essential for a product used in critical infrastructure or residential settings.[72]

Table 13: Comparison IOT Specific Cloud Computing Platforms

Feature	AWS IoT Core	Azure IoT Hub	Implication for Smart Breaker
Scalability & Maturity	Excellent (Broadest ecosystem)	Excellent (Enterprise focus, SLA) [80]	Both handle large-scale, multi-device deployments.[72]
Real-Time Latency	Optimized for low-latency messaging [72]	Strong real-time processing capabilities [72]	Essential for meeting the critical control budget.
Security Differentiation	Strong encryption, compliance (HIPAA, GDPR) [72]	Microsoft Defender for IoT (Threat detection, real-time alerts) [72]	Advanced threat detection is vital for critical infrastructure security.
Analytics/AI Integration	Kinesis, Sagemaker	Stream Analytics, Azure ML	Supports the future deployment of machine learning for fault prediction.

3.5.5.3 Security and Authentication Implementation

For the Smart Breaker, a strong security implementation is a must. One Access control, data integrity, and device identification must all be covered by the security protocol.[72]

- **Device Authentication:** The Cloud IoT Platform must directly supply and store distinct, robust credentials, such X.509 certificates, for each ESP32 to be validated. This important safeguard stops unauthorized devices from connecting and sending harmful trip orders or erroneous sensor data.
- **Data Encryption:** Transport Layer Security (TLS) encryption must be used for all communications between the client application and the cloud and the device (ESP32). The cloud platform is in charge of making sure that all data in the TSDB is encrypted while it is in transit and at rest.[72]
- **Policy Management:** The security design strictly sticks to the least privilege principle. By enforcing device restrictions, the IoT Hub makes sure that a certain Smart Breaker device may only broadcast data or transmit commands to subjects associated with its unique device ID. Because of its structure, a compromised device cannot affect the entire fleet.

3.5.6 Real-Time Performance and Latency Constraints

3.5.6.1 Latency Analysis for Safety Control Operations

The Smart Breaker's communication latency directly correlates with how well its remote control works. The remote trip function adds a crucial layer of digital control and emergency shutdown capabilities, while the local mechanical breaker offers immediate, hardware-based protection. A longer end-to-end reaction time reduces the usefulness of this digital control. From the user interface to the backend API, the cloud MQTT broker, and ultimately the ESP32 microcontroller, which must decode the message and carry out the SSR switching sequence, the command must successfully complete the full signal route. The tolerable latency budget can be quickly depleted by non-optimized architectural pathways like synchronous database lookups, conventional HTTP polling, or ineffective API processing.[74] Therefore, designing an architecture that prioritizes event-driven, asynchronous data handling is essential for maintaining performance under load.

3.5.6.2 Defining the Target Response Time for Remote Tripping/Resetting

In order to provide a smooth and dependable user experience, industry standards for smart device control, especially in security or transportation systems, recommend that latency be maintained low, ideally between 100 and 500ms.[71] The highest limit is 500ms for a safety-critical device such as the Smart Breaker. This goal requires that time budgets be rigorously distributed among all of the system's critical route components.
By assigning distinct latency budgets to every element in the control flow, the architecture is made to enforce this limit delay. While the Backend API is required to adopt a non-blocking architecture (Node.js) to decrease processing time, the Frontend Layer is budgeted to minimize delays in command initiation. Since the service level agreement (SLA) of the selected cloud provider has a significant impact on this sector, the Cloud MQTT Broker latency is essential. Lastly, the ESP32's firmware needs to be extremely effective in receiving, decoding, and carrying out the physical command while staying within its budget.

Table 14: ***Latency Button for Critical Control Path***

Component/Segment	Process	Latency Budget	Notes
Frontend (Mobile/Web)	Input registration & Network initiation	<=50ms	Using high-performance framework (Flutter) to minimize UI thread block.
Backend API	Authentication, Routing, Command Processing	<=50ms	Utilizes non-blocking architecture (Node.js).
Cloud MQTT Broker	Publish/Subscription Latency (Cloud-to-Device)	<=100ms	Requires premium, low-latency cloud IoT services.[72]
Device Connectivity (ESP32)	MQTT receipt, command decoding, MOSFET execution	<=200ms	Dependent on firmware efficiency and Wi-Fi quality.
Total Response Time	End-to-End Action Confirmation	<=500ms	Alignment with high-end smart device responsiveness.[71]

3.5.6.4 Architectural Impact of Low-Latency Requirements

All significant technological decisions are significantly impacted by the strict low-latency target:

1. **Protocol Selection:** It is now required to adopt persistent, low-overhead protocols, particularly Web Sockets for client communication and MQTT for device communication. Compared to conventional REST/HTTP polling methods, these protocols drastically lower the cost involved in creating new connections.[75]
2. **Framework Selection:** Frameworks designed for high concurrency and non-blocking operations must be used by the backend processing layer. This makes Node.js a great choice because of its event-driven design, which is perfect for managing thousands of concurrent persistent connections.[76]
3. **Frontend Selection:** Reducing internal processing delays is another requirement for the mobile application framework. When handling high-frequency data graphing or instantaneous control instructions, the JavaScript bridge that is built into frameworks like React Native sometimes introduces performance problems. This is why Flutter was chosen since it can compile to native code.[78]

3.5.6 User Interface and Visualization

3.5.6.1 Real-Time Charting Library Selection

High-performance charting tools are necessary for the effective display of high-frequency time-series data. To optimize for both fluid real-time presentation (mobile) and deep analytical demands (web), a hybrid visualization stack is used.
Grafana is used for the customer-facing web dashboard (which necessitates sophisticated queries for historical consumption records), observability, and back-end engineering. Grafana is a monitoring and analytics industry standard that makes it possible to see aggregated data and intricate historical analysis.[94]
Highcharts for Flutter is chosen for the final mobile application. The real-time V/I/P/T charts will be shown with great performance, smoothness, and minimal latency thanks to Highcharts' official, customized SDK for Flutter.[106] This guarantees an outstanding user experience on the mobile platform, especially during times of heavy data volume.

3.5.6.2 Dashboard Layout and Information Hierarchy

The safety-first approach must be included in the design of the online and mobile interfaces.

- **Safety Focus:** The breaker's operating state (Active, Tripped, Warning) must be clearly shown on the main screen. High contrast indicators must make any pending notifications immediately evident.
- **Monitoring Section:** To show current, voltage, power, and temperature data, real-time dashboards must make use of unambiguous visual components (digital gauges and Highcharts time-series graphs). This facilitates the user's quick identification of irregularities.
- **Section on Analytics (Web/Grafana):** This specific reporting section offers resources for long-term energy awareness and analysis, such as the ability to perform custom queries over past data and calculate total consumption costs (which satisfies the stretch goal need).

3.5.6.3 Remote Control Interface Design and Safety Confirmation Mechanisms

The user interface for actuation (Trip/Reset) must incorporate defensive User Experience (UX) methods to avoid inadvertent or malicious action, given the serious safety concerns of remotely managing a home's electrical panel.

1. **Confirmation and Authorization:** A secondary confirmation step (such as a prompt inquiring, "Are you sure you want to trip the breaker?") must be triggered before a remote Trip or Reset command is initiated.
2. **Real-Time Status and Feedback:** The application must give prompt, clear feedback in order to adhere to the latency budget. The user interface must change to a pending state when the control command is issued, and the application must instantly offer visual and haptic feedback to validate that the operation was successfully completed after receiving the execution confirmation from the ESP32 over the WebSocket channel.[71]

Conclusion

The architecture of the Smart Breaker Digital Ecosystem is rigorously engineered to prioritize safety, security, and performance. The commitment to a maximum end-to-end latency for the remote trip function mandates the selection of persistent, low-overhead protocols (MQTT/WebSockets) and a highly concurrent backend architecture (Node.js). The choice of Azure IoT Hub provides a foundational layer of advanced security, critical for managing high voltage residential infrastructure. Furthermore, the selection of MongoDB ensures that while the immediate requirements for real-time monitoring are met.

We initially considered an FPGA for its average cost, power consumption, integration capabilities, and available documentation; however, due to its limitations in performance, flexibility, and parallel processing, we ultimately chose the ESP32 microcontroller for its high versatility and ease of integration. For communication, Wi-Fi was chosen as the primary protocol due to the ESP32 board being capable of wifi communication so long as an appropriate antenna was attached, and the ESP32 was programmed using a threshold-based algorithm to manage breaker operations.

For the switching element, we opted for a solid-state relay (SSR) over MOSFETs and mechanical relays because of its superior performance in high-power applications. Specifically, the TLP3547 SSR was selected for its low cost and fast switching characteristics. A varistor was included in handling low-voltage protection needs. Branch circuit wiring was implemented using 16–18 AWG stranded copper wire with PVC insulation, providing a balance of flexibility and safety for the testbench setup. For load line current measurement, the ACS712-30A Hall effect sensor was used due to its affordability, suitable current range, and adequate output resolution. Voltage scaling was achieved with a TR100VA001 transformer, chosen for its high efficiency despite a higher cost. Voltage regulation was handled by the LM5180NGU buck converter, while a full-wave rectifier converted AC to DC for consistent power supply to the system.

Overall, the combination of these design choices resulted in a versatile, cost-effective, and efficient smart breaker system, leveraging the strengths of modern microcontrollers, solid-state switching, sensor technology, and cloud connectivity.

Chapter 4 - Related Standards and Design Constraints

4.1 Industry Standards

4.1.1 Electrical Standards

4.1.1.1 High Voltage Standards

Since this is an electrical-power based project, the most important constraint we face is the safety of our product. Because the system will be accessible for demonstration and review by our committee and grading personnel, we must ensure that no user ever receives an electric shock while interacting with or observing the device.

For this reason, our project has been limited to a 24 V supply with a maximum of 5 A on the output side of the breaker. This constraint was specified by our professor and serves two primary reasons:

1. User and operator safety: Mains voltages (e.g., 120 V or 240 V) carry significantly increased risk of injury or fatal shock. According to standard studies, currents as low as 9–30 mA can cause involuntary muscle contraction or inability to let go of a conductor. [reference]Voltages above about 50 V AC or DC have been described as carrying significant risk of injury. [reference]By limiting our system to 24 V, we operate within a range considered extra-low voltage (ELV), which greatly reduces the chance of harmful current flowing through a human body.
2. Limited experience of the team: As undergraduate students with limited exposure to high-power electrical installations, we acknowledge that design errors can lead to serious accidents. By operating at 24 V / 5 A, we reduce the severity of any fault and thereby increase the margin for safe development, testing, and demonstration.

Because our system may be handled, inspected, or tested by members of our committee, teaching assistants, and other students, we must ensure that there is no realistic risk of "getting zapped." All connections will use safe wiring practices, insulation will be verified, and all exposed conductors will be rated for the voltage and current used. We will also enforce proper grounding, use protective covers where required, and follow documented wiring and protective-device standards.

In summary, the safety constraint of limiting our system to 24 V and 5 A is fundamental to our project. It aligns with industry practices for extra-low voltage systems and ensures that the Smart Breaker can be developed, demonstrated, and evaluated safely in an educational environment.

4.2 Design Constraints

4.2.1 Personal Constraints

4.2.1.1 Time Constraints

One of the primary practical constraints of the Smart Circuit Breaker Sabre project is time. As a senior design project, we are given a limited academic timeframe to research, design, fabricate, and test a fully functional prototype. This limitation requires careful planning and prioritization to ensure all milestones are achieved within the academic year.

Our team has approximately two semesters to develop the Smart Circuit Breaker Sabre; from conceptual design to a working prototype ready for demonstration. Within this period, we must conduct research, source and test components, design and fabricate the printed circuit board (PCB), integrate hardware and software systems, and perform extensive testing. Each of these phases introduces potential delays that can cascade if not properly managed.

A significant challenge under this time constraint is component sourcing and fabrication. The ordering of electronic parts and PCB manufacturing can be delayed due to shipping issues, tariffs, international politics and supplier shortages, or fabrication errors. Any delay in receiving key components, such as sensors, MOSFETs, or the ESP32 microcontroller can interrupt our development schedule and force design adjustments or substitutions.

Additionally, testing and debugging represent a major time-consuming stage. Electrical systems often present unforeseen issues such as signal noise, voltage drops, or interference, which require detailed troubleshooting. Since none of our team members have prior experience with circuit protection hardware at this scale, extra time must be allocated for testing each subsystem safely.

To mitigate these constraints, we established a time management strategy early in the project. This includes weekly meetings, detailed Gantt chart tracking, and milestone-based reviews with our faculty sponsor, Dr. Qun Zhou Sun. We also adopted an iterative development approach: instead of waiting for all components to arrive before testing, we test each subsystem independently to parallelize progress.

Our guiding principle is the senior design motto “Do What You Say You Will Do” (DWYSYWD). By maintaining accountability, communication, and consistent documentation, our team aims to stay ahead of schedule. Proper planning, early procurement, and realistic goal setting will allow us to deliver a reliable and well tested Smart Breaker prototype within the given academic timeline.

4.2.2 Physical Constraints

4.2.2.1 Manufacturing Constraints

The final constraint that must be considered for the Smart Circuit Breaker SABRE is manufacturability. As an undergraduate student team, our ability to fabricate and assemble components is limited by the tools, materials, and equipment available through the university laboratories. This limitation constrains the complexity of the overall design and encourages a more modular and straightforward approach to system construction.

A key advantage of this project, however, is that the SABRE design allows for the integration of commercially available components. Many of the required mechanical and electrical parts can be purchased online and assembled using standard lab techniques, significantly reducing the need for custom mechanical fabrication. This strategy helps ensure that our design remains feasible within the scope of our academic environment while maintaining safety and functionality standards.

4.2.2.2 Sustainability

Sustainability is an important consideration in the design of the Smart Circuit Breaker SABRE, particularly in relation to energy efficiency, component longevity, and user accessibility. Although the primary focus of this project is reliable and safe operation in an AC branch circuit, several design decisions have been made to improve the product's long term environmental and practical sustainability.

A central sustainability decision for SABRE is to favor resettable protection over sacrificial protection elements. Because the device is conceived as a circuit breaker, not a disposable protective device, we intentionally avoid using single use fuses as the primary overcurrent protection. Fuses require replacement after a trip, generate consumable waste over time, and reduce user convenience; these outcomes conflict with SABRE's goals of long life, low maintenance, and ease of use. Instead, SABRE is designed to interrupt and restore power electronically (via solid-state switching and/or a mechanical reset mechanism), enabling the device to be reused after a trip without component replacement. This design choice reduces electronic waste and supports a more user friendly product.

Energy consumption is also considered. SABRE operates as an AC branch circuit device (prototype scale: 24 VAC, up to 5 A) and is optimized so that the control and sensing electronics draw minimal standby power. Components and regulators are selected to minimize idle energy use while preserving rapid fault detection and reliable communication. Future iterations could further reduce consumption by incorporating lower power microcontrollers, more efficient gate drive architectures, or adaptive power states (dynamic power aware scheduling).

Component longevity and repairability contribute to sustainability. Key modules (control board, sensors, communication module, and switching stage) are designed to be modular and serviceable, allowing individual parts to be repaired or upgraded without discarding the whole unit. Choosing widely available, standardized parts also improves the likelihood of future replacement and repair, extending the useful life of each device.

Chapter 5 – Application of ChatGPT and Other Similar Platforms

Since the launch of ChatGPT back in 2022, the advent and adoption of Large Language Models and other AI tools have grown exponentially and completely revolutionized how information can be gathered and conglomerated for one's use. While ChatGPT was initially only limited to initial datasets used during the training phase, current models have now been equipped with the ability to search through new information on the internet and perform more complex reasoning when answering user questions. ChatGPT was found to be a valuable tool for conducting initial research into locating specific components and providing specific information regarding these components. However, utilizing these LLMs was not a perfect endeavor, and even with being thorough on specific desires during prompting, a few issues were encountered along the way. For one, there were instances that seemed as if either ChatGPT rushed to provide an answer to a prompt, or that it weighted certain aspects of the prompt more than others to the point of disregarding the additional information entirely. Correcting involved additional input from a user, pointing out the details that it had glossed over and having to inform the AI that it needed to reperform its reasoning with this new context included. Another example is that if questions were asked with little specificity involved, it was very common to see the LLM spit out a wall of text covering what seemed to be every aspect relating to the prompt at hand. This in itself is not necessarily a bad thing, or the fault of the LLM itself, but it was something to keep in mind when prompting ChatGPT or other AI tools.

While ChatGPT served as the primary AI tool consulted throughout the development of this project, we made it a point to incorporate additional AI tools to ensure balanced perspectives and comprehensive research. Among these tools, Google's Gemini was utilized for its seamless integration with online sources and its strong contextual understanding of recent technological advancements, making it particularly helpful during background research. Microsoft's Copilot was employed as a coding assistant, streamlining the process of generating and debugging code within our ESP32 and web interface development.

Out of all the AI systems explored, ChatGPT proved to be the most effective and reliable, primarily due to its strong reasoning capabilities, structured explanations, and adaptability across both technical and creative domains. It offered the most consistent performance in generating accurate, context-aware responses that aligned with our engineering needs. While Gemini and Copilot each excelled in their respective areas, web-based insights and code generation, ChatGPT provided a broader and more flexible foundation for critical analysis, documentation writing, and real time problem solving, making it our preferred AI system for this project.

In essence, using generative AI can be both a tool that can be detrimental to one's learning experience, and it can be one of the greatest tools available to use if used correctly. If one were to use an artificial intelligence such as ChatGPT in a lucrative manner such as simply formulating an idea by themselves and asking ChatGPT to generate an entire paper based on this, then this would be considered one of the worst ways to use an artificial intelligence especially when formulating a paper in a senior design project. The point of senior design is to be a learning experience for when the student enters the world of engineering and must form research of their own accord without the help of others. Asking artificial intelligence to accomplish this task takes away most of the burden. Yes, however, it takes away the entire point of senior design. An individual must be able to conduct their own research based on experiments, prototyping, and various other methos to procure results. Artificial intelligence cannot test these research values on its own. For example, artificial intelligence cannot go out, experiment on separate circuits, grab the values from them, determine the results, and come up with a logical conclusion based on these results. One may ask the generative AI for this kind of testing; however, they will not get correct results.

Certain generative AIs have their advantages and disadvantages. Where some AIs falter in specific areas, others may shine in. For example, ChatGPT excels at generating coherent natural responses aross many domains, handling different topics such as coding, writing, and very basic mathematical extremely well. This makes ChatGPT usable for everyday tasks and questions giving back quick response times. The AI is very user friendly and gives free access to its most advanced engine, giving you a few free responses with the most advanced engine. After these responses are used up the artificial intelligence simply downgrades itself from the most advanced feature to the second most advanced feature and gives you a few free responses from there, and so on and so forth until we are at its most basic engine. However, the amount of questions and tasks you can give ChatGPT until you are no longer able to give any more is enough to keep you going on with your task until the AI replenishes its timer resetting you back to the most advanced engine giving you some more free responses. As a result, an individual should never have to pay for ChatGPT responses so long as they are using their response sparingly. The most advanced engine is nothing to gloss over either, it is able to generate images based on the users prompt, dissect images that the user provides, calculate partial differential equations to a certain extent, give you very understandable summaries of extremely complex topics taught at the university level, as well as give you advice on niche topics such as in the realm of psychology. A university student would be able to go and research very far if they were to use ChatGPT in their research paper. However, if one were to use ChatGPT by itself, they would find that they do not learn anything. As students go to university to understand topics for future employment, if an artificial intelligence is able to accomplish this same task, what good would studying at university be?

Though it is very revolutionary in its intelligence, ChatGPT has its own drawbacks as well. It is not capable of true understanding, though the AI can give extremely quick responses. However, the answers may not be as concrete as they are meant to be. ChatGPT works on a pattern-based engine, isolating each word you write inside a probability matrix where it will then formulate a likely conclusion. This method, while extremely effective, can cause the information the AI outputs to be plausible sometimes. The information that ChatGPT grabs its information from can be accessed from anywhere on the internet and though this information is likely to be checked from the most logical areas possible, sometimes, the AI can generate information from incorrect places leading to information that is plausible or incorrect altogether. Its lack of long-term memory may cause it to struggle with long and deep nested topics, for example coding or complex mathematical processes is where ChatGPT tends to struggle. Though in most instances ChatGPT can give you correct responses in short coding examples and simple mathematical instances but when given a long math question or entire program, ChatGPT will tend to suffer as it cannot store each new piece of information and perform operations based on this. However, other programs tend to be better at analyzing problems such as these.

Gemini being created by google, a large corporate enterprise, is a large-scale model and in the artificial intelligence world is described as multimodal which means it is capable of text, image, and other modalities, so in terms of productivity in the world of AI, it is higher up there. Furthermore, because Gemini is interconnected with google, it has more access to real-time web information, being able to provide the user with more up to date information on anything the user asks. Also due to it having a large context window, Gemini is more capable of solving large coding programs as well as being to able to debug even the smallest of issues and tell you exactly how to fix it and even come up with an entire program to replace the existing program you may have given Gemini. For mathematical processes, if you don't ask Gemini to solve an extremely long equation that only mathematicians that have years of experience are able to solve, the individual should be able to get a possible answer from this task.

Some of Geminis shining features tend to be its drawbacks. For example, its live integration with its own platform google leads it to being extremely fast in terms of the responses it is able to generate and sometimes the responses can even be extremely accurate due to the amount of resources it has readily available, however, this is also its downfall. Firstly, when integrating AI with its own Google search engine and having the AI search through Google's database every single time a task requires it to be quite intensive for artificial intelligence. This is more of a detriment towards google itself since it costs the data centers for Gemini more to operate, the user can use Gemini free of cost. Furthermore, because Gemini gets most of its information from its own Google search engine which could cause the response to be misconstrued into a completely wrong response, no amount of speed could make up for a completely incorrect response. All in all, Gemini should be treated as an extension of google and not have information be completely used in research papers. Everything taken from artificial intelligence should not be taken at surface value; it should be researched and analyzed before any formal piece can be written about it.

ChatGPT and Gemini are two of the most common artificial intelligences available and as far as other generative artificial intelligences, they significantly amplify productivity by automating routine tasks such as documentation, code templates summarization, and basic question and answering allowing the user to focus on higher-value design work. They also help condense large volumes of text/data quickly for the user to quickly interpret data in a timely manner. Though in terms of draw backs they require careful prompt writing to get the most accurate information possible, sometimes they are not completely correct in their responses, and the amount of information it is capable of analyzing and understanding is limited to the capacity of the computer it is running on as well as the Wi-Fi capabilities of the user and finally the information the AI has access to. A limited artificial intelligence has only so many capabilities. When using such intelligences, they should be used with proper usage so that the user can learn more from the experience as well as have access to ease of information. For this paper, ChatGPT was used more to ask basic questions and some products that could be useful when implementing them in prototyping. Though as a research tool it was also very useful, especially when explaining some concepts behind certain smart breakers and what they are capable of. All in all, it is a powerful tool that should be used responsibly.

Artificial intelligence when used in conjunction with a research paper should be purely used to assist the researcher to answer quick and simple questions that can normally be found through a quick look through a textbook. Quick in this context, meaning one must look through several textbooks and authors to find an answer in a specific page number that can only be found through a few hours of reading, which now can be minimized to a simple search through a generative AI that takes just a few seconds. In this scenario, generative AI truly revolutionizes the way research is conducted so long as the papers that were researched before this are uploaded to the internet beforehand. Questions can be as simple as understanding a basic mathematical concept that is easily taught at the elementary level, or a harder concept that is taught at the college level. Both of these questions can now be answered as fast as your internet speed will take you.

5.1 Case Study 1

Refer to Appendix [E.1] for information regarding this case study. This prompt sequence highlights how ChatGPT can sometimes miss or ignore important information provided within a prompt. This prompt was done to help search and compile a list of suitable standard AC transformers that can step 120VAC mains voltage down to a more suitable voltage of 24VAC, while being able to safely supply 120VA to meet the maximum current draw that may be encountered. While ChatGPT was successful in searching and assembling a list of

AC transformers, it missed a crucial detail in the initial prompt that caused it to source insufficient components. Specifically, ChatGPT failed to account for the fact that it was specified in the prompt to search for a transformer capable of supplying a total of 120VA. The list initially provided only included 1 transformer capable of supplying this value, and instead explicitly included options that it itself stated could only supply between 40VA and 50VA depending on the model. was then questioned whether or not it had even realized it had made an error, albeit in a sort of ambiguous manner that first questioned whether the transformer that was sufficient from the list was actually listed correctly. ChatGPT then made a response clarifying that the transformer deemed sufficient from the initial parameters was indeed correct but never elaborated on why it had included transformers that did not meet the requirements stated in the initial prompt. A third prompt had to be conducted explicitly pointing out the shortcomings of the LLMs' first two responses before finally catching its error, and providing a list of transformers that met the requirements set out from the start. This case study showcases both the importance of reviewing the outputs generated by AI services and in providing thorough, detailed prompts. For comparison purposes, the exact same initial prompt was used with Google Gemini. Gemini gave a long initial response, beginning by going into detail as to the fact that finding a low-cost 120 VAC to 24 VAC supplying 120 VA is difficult to attain, and that transformers in this price range typically have VA ratings between 20 VA - 50 VA. It then provided a list of 5 transformers that met the voltage step-down ratio requested, but that varied in VA ratings from 6 VA - 50 VA. It then mentioned again that coming across a consumer transformer at these specified ratings are difficult but then supplied two that did meet these specifications.

5.2 Case Study 2

After being fed with the primary objective of this project we use this tool to brainstorm some objective to solve with our product here are the prompts used:

"The primary objective of this project is to develop a functional Smart Circuit Breaker capable of remotely monitoring power consumption in real time. The system will provide live power readings, incorporate protection features to safeguard the electrical system, and enable direct communication to enhance safety, efficiency, and user control in both residential and commercial applications.

For safety and demonstration purposes, the project will be implemented at a reduced scale, operating at 24 VAC and 5 A."

GPT Please give me a problem statement that my project should be able to solve:
"Conventional circuit breakers are primarily mechanical, offering only basic overcurrent protection. They cannot provide real-time monitoring, remote control, or communication capabilities that modern smart grids and energy-conscious users require.

As energy systems evolve, there is a growing need for intelligent protection devices that not only interrupt current during faults but also track power usage, communicate with users, and improve system efficiency and safety.

Current solutions in the market are limited, expensive, or not fully optimized for integration at the branch circuit level."

5.3 Case Study 3

“What are some of the switching/Relays technologies that I should consider for this project?”

“Mechanical Relay:

Mechanical relays operate using an electromagnetic coil to physically open or close contacts. They provide strong isolation between control and load circuits and can handle high current levels. However, they suffer from mechanical wear, slower response times, and audible noise, making them less ideal for high-speed or long-term switching applications.

Solid-State Relay (SSR):

Solid-state relays perform the same switching function as mechanical relays but without moving parts. They use semiconductor components such as thyristors or triacs, resulting in faster response, silent operation, and longer lifespan. The main drawbacks include higher cost, small leakage current when off, and potential heat generation during continuous operation.

Back-to-Back MOSFETs:

This configuration uses two MOSFETs in series but in opposite directions to allow bidirectional current flow. They combine the speed and efficiency of solid-state relays with improved control and low on-resistance. Back-to-back MOSFETs are ideal for low- to medium-voltage AC systems and provide precise, fast, and reliable switching with minimal power loss, though they require more complex gate-drive circuitry and protection design.”

This research was used in the project. Very helpful input given by the AI that help the project evolve and give the initial idea for the now 3.xxx Switching/relay technology section of this project

5.x Final Thoughts

While some of the AI-generated responses contained unrealistic suggestions, the recommendations provided were highly valuable. It significantly accelerated the project's realization and contributed to achieving positive results in a shorter timeframe. The tool was an effective method for rapidly translating initial ideas into a tangible document.
In conclusion, ChatGPT and other LLM tools are exponentially being integrated into every part of modern life with no sign of slowing down. The importance of becoming acclimated to such tools will be a critical skill for those looking to succeed in the future, as they represent what might possibly be the largest innovation since the launch of the internet. While the ability for LLMs to compile information, paraphrase content, and break down complex topics on the back of a key stroke, they are not without their own shortcomings. LLMs are still not yet to the point where the output generated can be taken as gospel. These AI models can still provide inaccurate, irrelevant, or even forged information without indication to the user that they have done, so much so that these errors have been colloquially dubbed as hallucinations. So, while these tools serve as great instruments for learning new topics, it remains important to verify the details generated by cross validating from more established sources, and by prompting the model for the source in which in based it’s reasoning off.

Chapter 6 – Hardware Design

6.1 Overview of Hardware Subsystems

The hardware within the SABRE smart breaker is composed of three discrete subsystems: power supply, load monitoring, and the switching element. All of these hardware subsystems are interlinked together primarily through the ESP32 microcontroller, which receives both input and output signals depending on the exact section of the circuit. Depending on measured data, the ESP32 will respond appropriately to facilitate safe operating conditions for the supplied load seen beyond the circuit breaker.

6.2 Power Supply and Delivery

The ESP32 and each subsequent auxiliary component will be powered from the same initial power source as that of the actual load applied across the breaker. Regardless of if current is drawn across the actual load branch, the simulated mains power source will be stepped down and have its polarity converted using a full bridge rectifier fed into a switching buck converter. The primary side input will provide power and enable the flyback controller to begin functioning. In addition, the primary side provides a feedback loop for the controller as well to properly adjust the switching frequency and thus regulate the primary side to a proper voltage adequate to maintain a constant 5 VDC on the secondary side. The primary and secondary sides of the circuit are galvanically isolated from each other using a flyback transformer, which along with the flyback controller, properly steps down the primary signal down to a constant desired secondary signal of 5 VDC. The secondary side is composed of two Zener diodes, two capacitors, and two resistors. The initial Zener diode, resistor, and capacitor in parallel are directly in series to the input of the secondary side of the flyback transformer and are used as a snubber to prevent high-frequency spikes caused by both the switching element and transformer. The capacitor and resistor in parallel to the flyback transformer are used for output filtering to provide a more constant, stable output signal. The additional Zener diode in parallel is used as an over voltage clamp for additional reassurance that the output signal is prevented from rising above the desired voltage level. The flyback circuit utilized can be seen below.

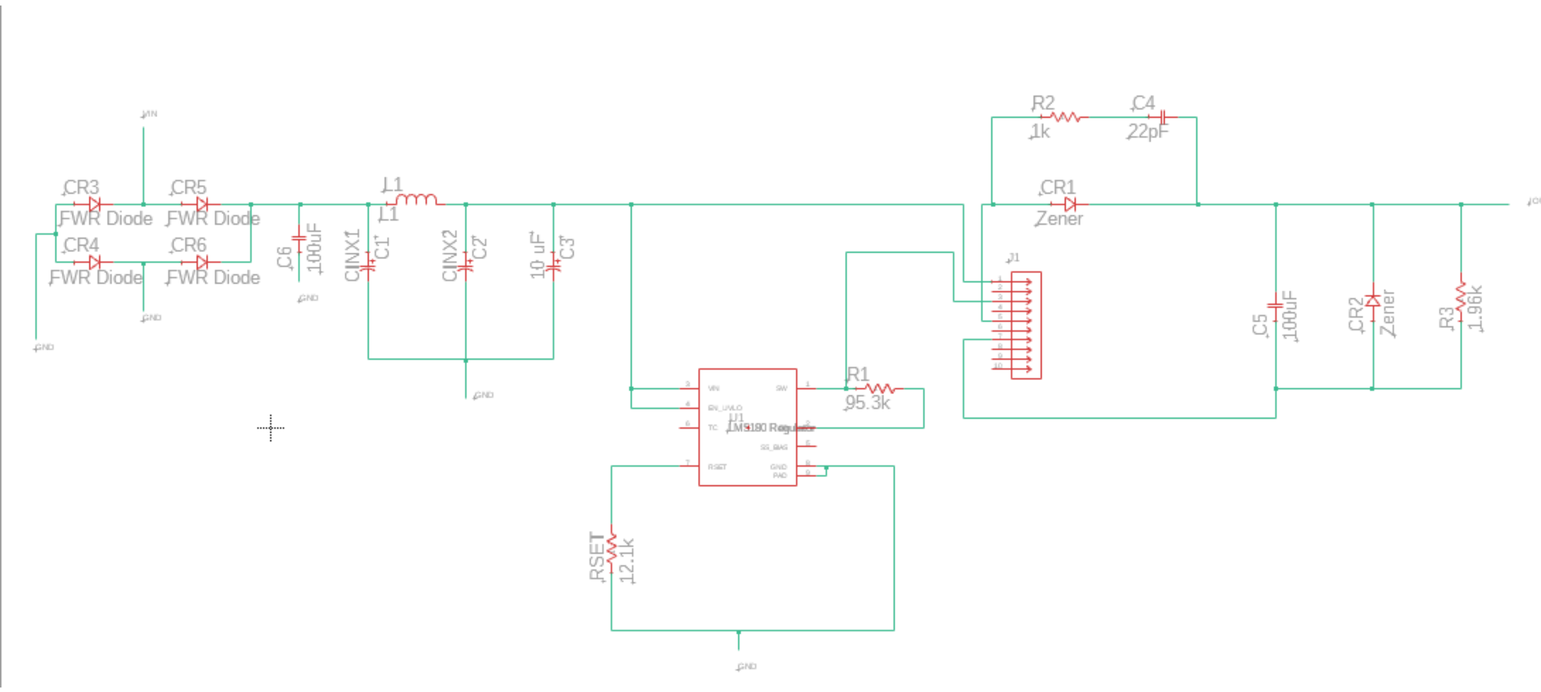

Figure 4: Flyback Buck Converter by Authors

6.2 Load Monitoring and Management

Effective load monitoring is going to be primarily the responsibility of the ACS712 Hall Effect Sensor, providing a linear voltage output proportional to that of the current being drawn from the forementioned load. The output from the ACS712 is then fed through to a LM321 OpAMP to improve the output resolution. By default, the ACS712 provides a proportional voltage signal resolution between 66 - 185 mV/A. With the addition of the LM321 on the output of the sensor assembled how it is seen in the schematic, the voltage gain can be increased up to 610 mV/A, vastly improving the overall output resolution, allowing for more precise measurements between small current fluctuations. In addition to providing a more sensitive output fluctuation, adding the OpAMP helps center the zero-midpoint voltage at a value that is better suited to take full advantage of the ESP32's onboard ADC. The output voltage signal from this subsystem is fed directly to an ADC on the microcontroller for appropriately measuring current in real time to determine actions that should be taken based on the read value. The circuit for providing constant circuit measurements to the microcontroller can be seen below.

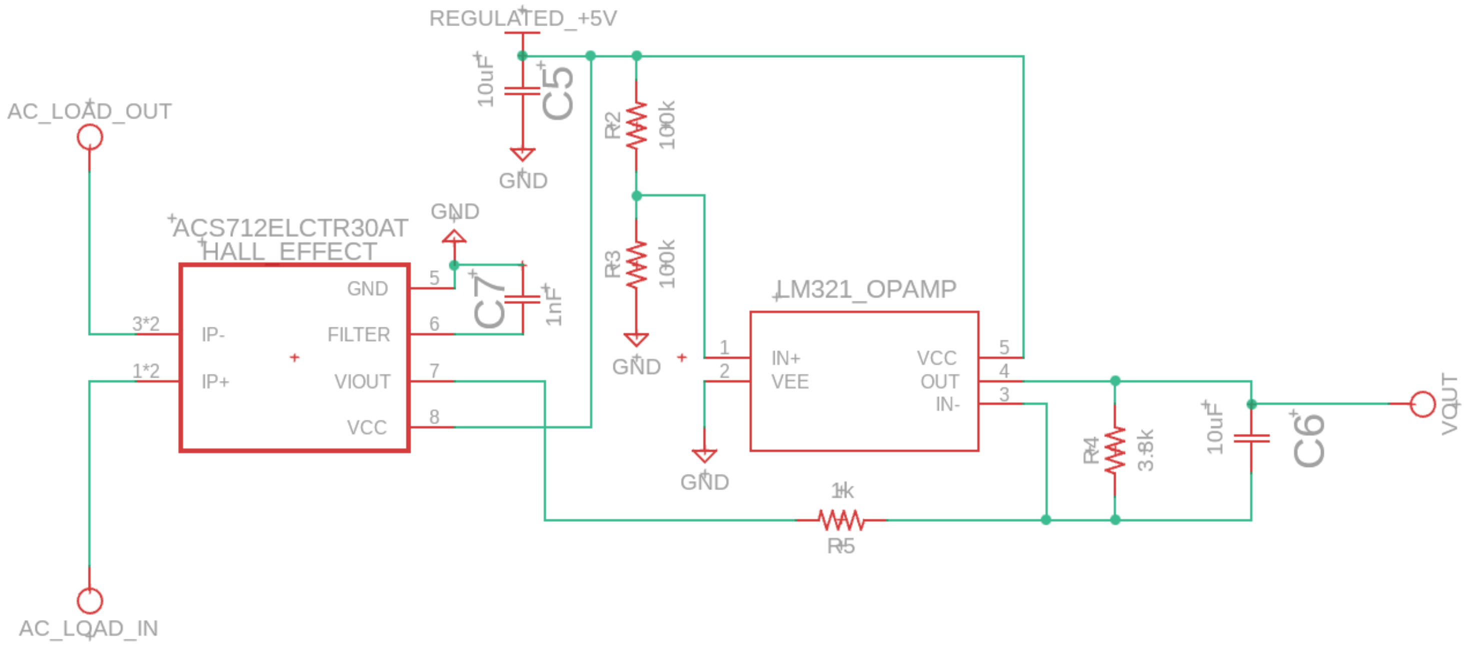

Figure 5: Current Measuring Subsystem by Authors

6.4 Switching and Breaking

The switching from the main supply to the attached load will be facilitated by the ESP32 microcontroller and performed by a TLP3547 solid-state relay (SSR). The ESP32 is programmed to continuously monitor the output of a Hall Effect current sensor through its integrated ADC. When the measured current exceeds a defined safety threshold, the microcontroller disables the control signal driving the SSR, causing it to open the circuit and stop current flow to the connected load. The TLP3547, is a photo relay-type SSR, meaning it uses an optically isolated input stage where an internal LED activates a photo-sensitive MOSFET array on the output side. This optical coupling provides galvanic isolation between the low-voltage control circuitry and the high-voltage AC load, enhancing safety and noise immunity. Unlike traditional mechanical relays, the TLP3547 employs back-to-back MOSFETs to allow bidirectional current flow, enabling it to handle AC loads up to 60 Vrms at 5 A. This makes it particularly suitable for switching low-voltage AC signals, such as those found in this 25 VAC design, while providing low on-resistance and silent, bounce-free operation. Because it has no moving parts, the photo relay offers excellent durability, fast response times, and high reliability under repetitive switching conditions. Additionally, a physical manual switch will be mounted on the chassis to provide the same user functionality as a conventional circuit breaker, allowing the operator to manually enable or disable power flow to the load. The circuit for implementing the switching mechanism can be seen below.

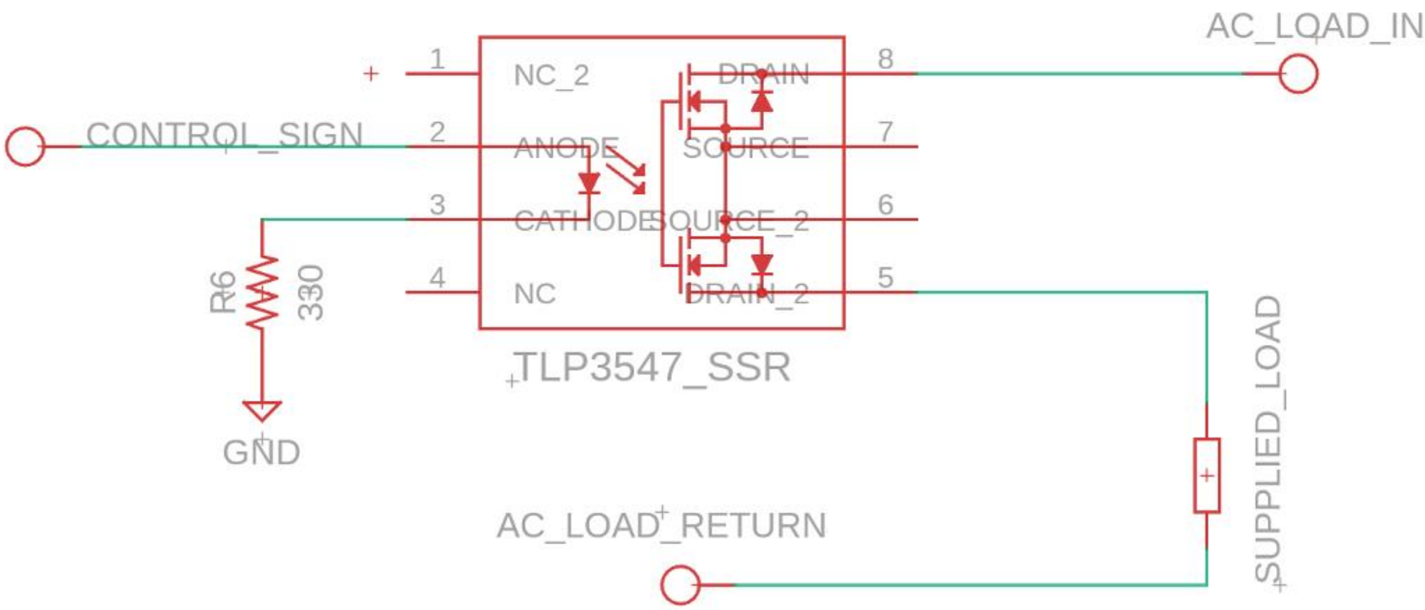

Figure 6: Current Measuring Subsystem by Author

6.5 Full Logic Schematic

Each of the forementioned subsystems interact with the ESP32 to perform their respective operations. The switching buck regulator for the primary step down only lowers the voltage to a 5 V signal, too high for the onboard power pin on the ESP32. As a result, a 3.3 V linear regulator is placed between the power pin and the buck regulator output to step down and maintain an appropriate voltage for which the microcontroller can function. Concerns arose initially about using a linear regulator to step down the relative high voltage AC signal down to 5 V due to the heat dissipation caused by the inherent inefficiency of linear regulators. However, the minor shift from the 5 V signal down to 3.3 V is a small enough voltage drop to where any heat dissipated is negligible, offering an appropriate method for maintaining a 3.3 V signal without having to create a second switching buck regulator. This 3.3 V signal is used for powering the microcontroller, for providing a HIGH signal for the manual switch for the ESP32 to read when the switch has been engaged and to shut off the signal controlling the SSR, and for the onboard programming interface circuit used to convert USB to UART. The output from the current measuring subsystem is fed into GPIO34 on the ESP32, a pin that can be configured for use with onboard ADC1 which is the required ADC to use as ADC2 is disabled for use during Wi-Fi operations. The current is

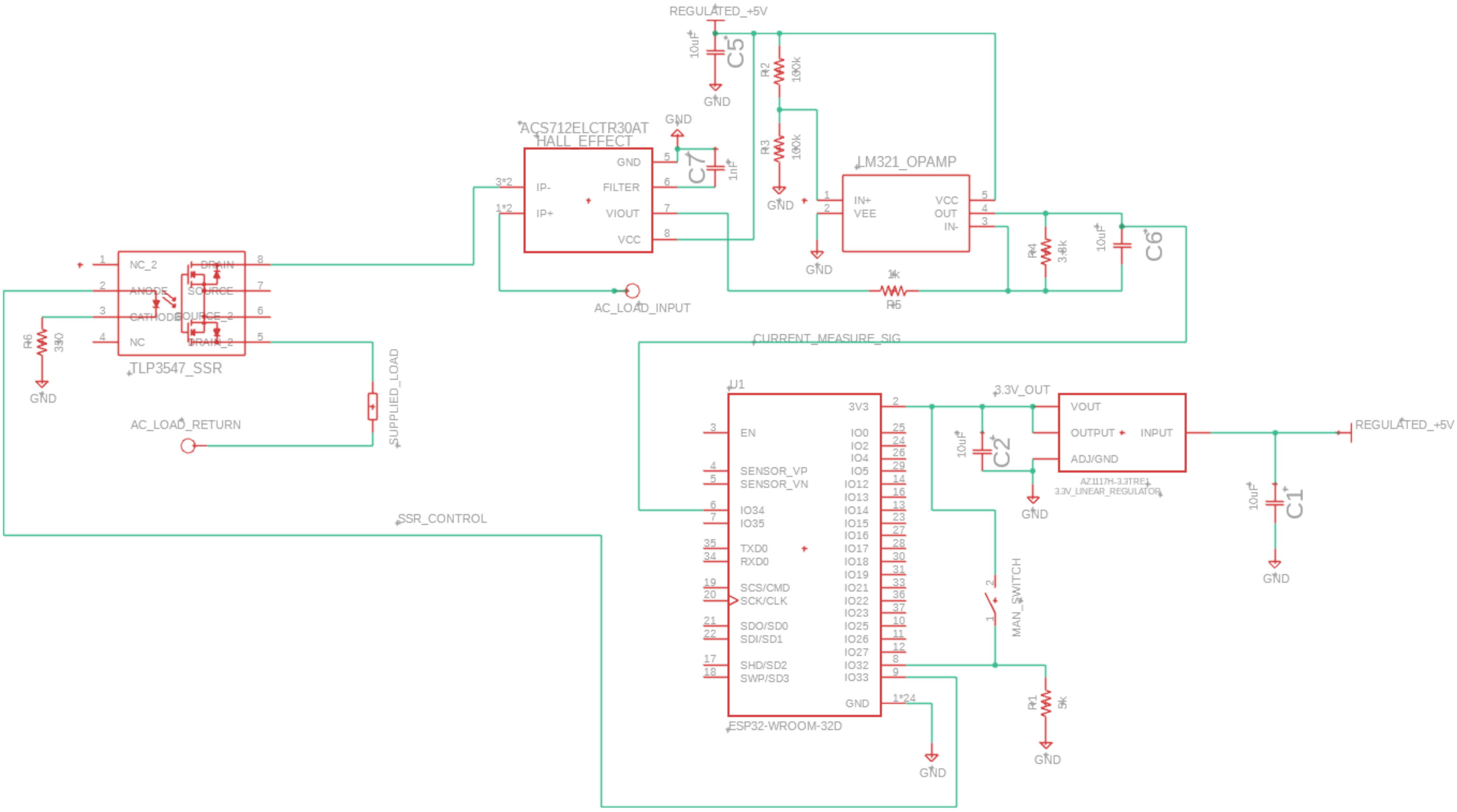

Figure 7: Full Logic Side Schematic by Authors

6.6 Programming Interface

The programming interface looks to implement a similar circuit topology to what can be found on the majority of ESP32 development kits. The circuit looks to convert the compiled program coming in from the USB header and converts it over the UART bridge to allow the computer to send the code straight to the onboard serial interface. In addition, it implements easy access buttons to both manually reset the ESP32, and to hold strapping pins low during reset to boot up in programming mode.

6.6.1 USB Header

The USB header is used for the initial input for sending over program data to the ESP32. The important lines to pay attention to are VCC, D-, and D+. The VCC line is the power received externally over the micro-USB cable, a 5 V signal. To ensure additional safety to the ESP32, a Schottky diode is placed along this trace to ensure that if the microcontroller is being powered externally when USB power is applied (I.E. 5 V signal from the buck regulator), the external source won't back feed power back over the USB and vice versa. D+, and D- are the signals that transfer data between the PC and the USB header. All three of these lines contain additional TVS diodes in parallel to the signal facing each other. These diodes are purposed with clamping voltage spikes that can be caused when first plugging in the cable to the header. In typical operation, these diodes are negligible, but during a high voltage spike relative to what is expected, the diodes are able to shunt this excess spike to ground safely without effecting the subsequent components. The schematic for the USB input header can be seen below.

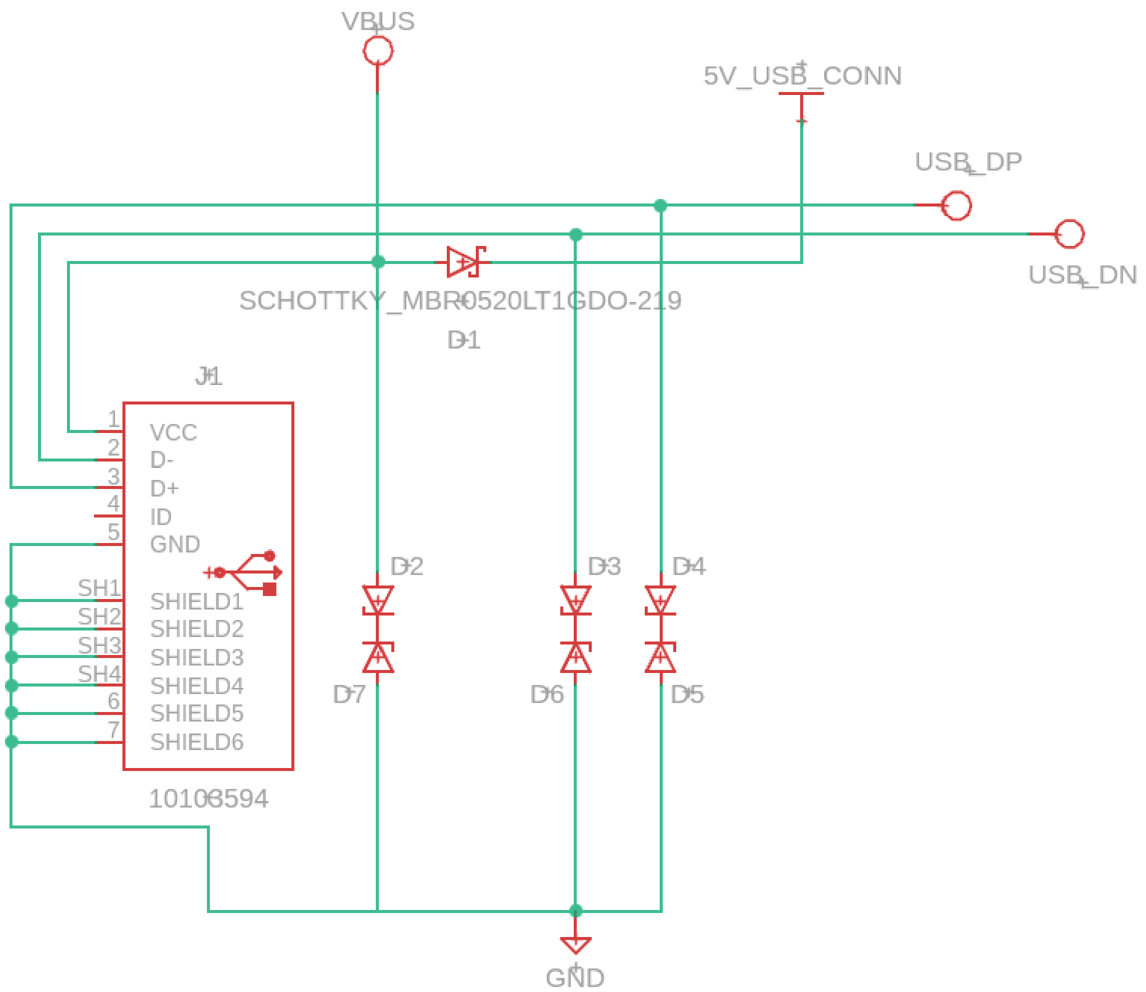

Figure 8: USB Header Schematic by Authors

6.6.2 UART Bridge

The UART bridge is the link between the ESP32's serial interface and the USB header. The IC controller used to facilitate this transfer is the CP2102N-A01-GQFN28 and is the go-to controller used in the official ESPRESSIF datasheet for implementing this schematic. The D+ and D- pins labeled on the controller are for taking in input transmitted from the USB header and then the TXD and RXD pins are connected to the opposite respective pins on the ESP32 for transmitting data to and from the PC to the microcontroller. The controller takes two voltage sources for both powering and setting up a reference voltage for the logic signals to use. The controller itself is powered from the 5 V signal from the USB cable and then receives a 3.3 V reference voltage so that the communication signals are stepped down to a proper voltage for the ESP32 to utilize without being damaged. The RTS and DTR pins are used for determining and setting up the ESP32 in a state ready for receiving programming data. The schematic for the UART bridge IC can be seen below.

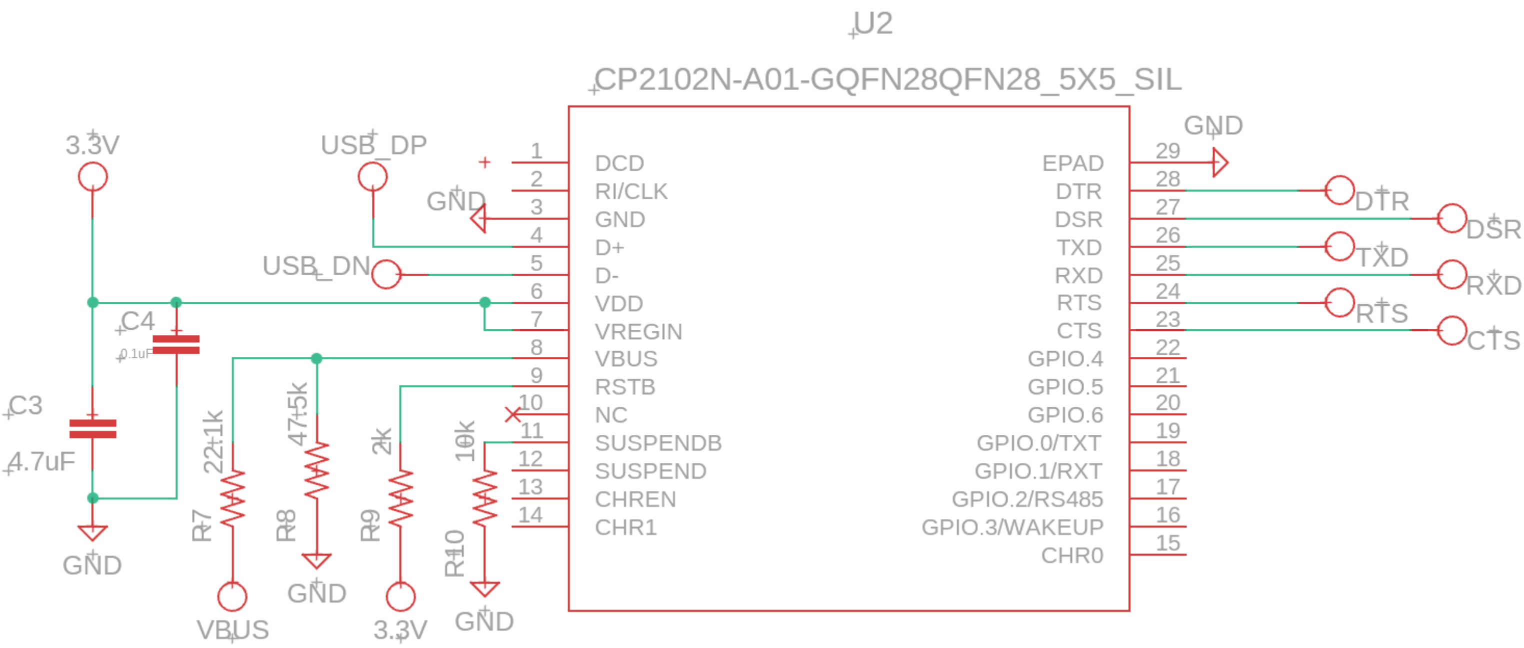

Figure 9: UART Bridge Controller Schematic by Authors

6.6.3 Automatic / Manual Programming Interface

The RTS and DTR pins are attached to a pair of BJTs to automatically boot the ESP32 into programming mode when the code is uploaded from the IDE. When the CP2102N begins receiving data from the USB header, the RTS and DTR pins momentarily pull both strapping pins, GPIO0 and EN LOW to reset the microcontroller. The RTS pin then releases so that the EN can switch HIGH to properly put the ESP32 into bootloader mode. The program is then flashed onto the chip and then resets the controller again to reboot in standard mode to execute the newly uploaded program. In addition, there has been a separate circuit included to manually reset and control the GPIO0 pin for manual resetting and debugging purposes. Both circuit schematics can be seen below.

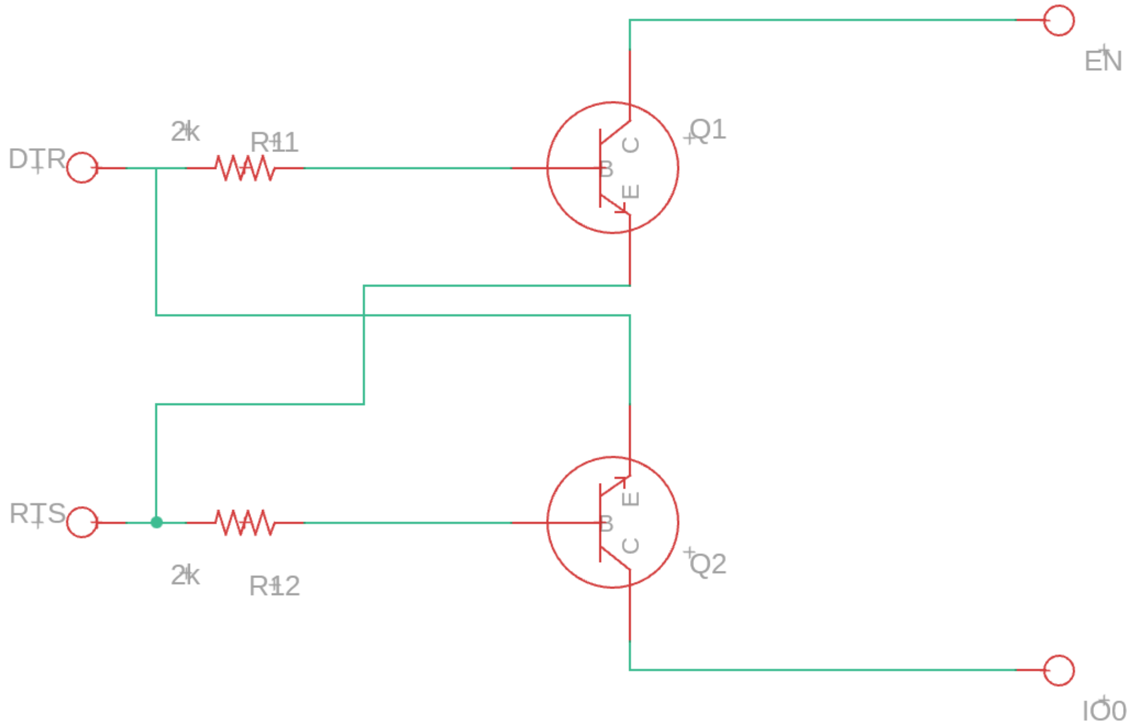

Figure 10: Automatic Programming Schematic by Authors

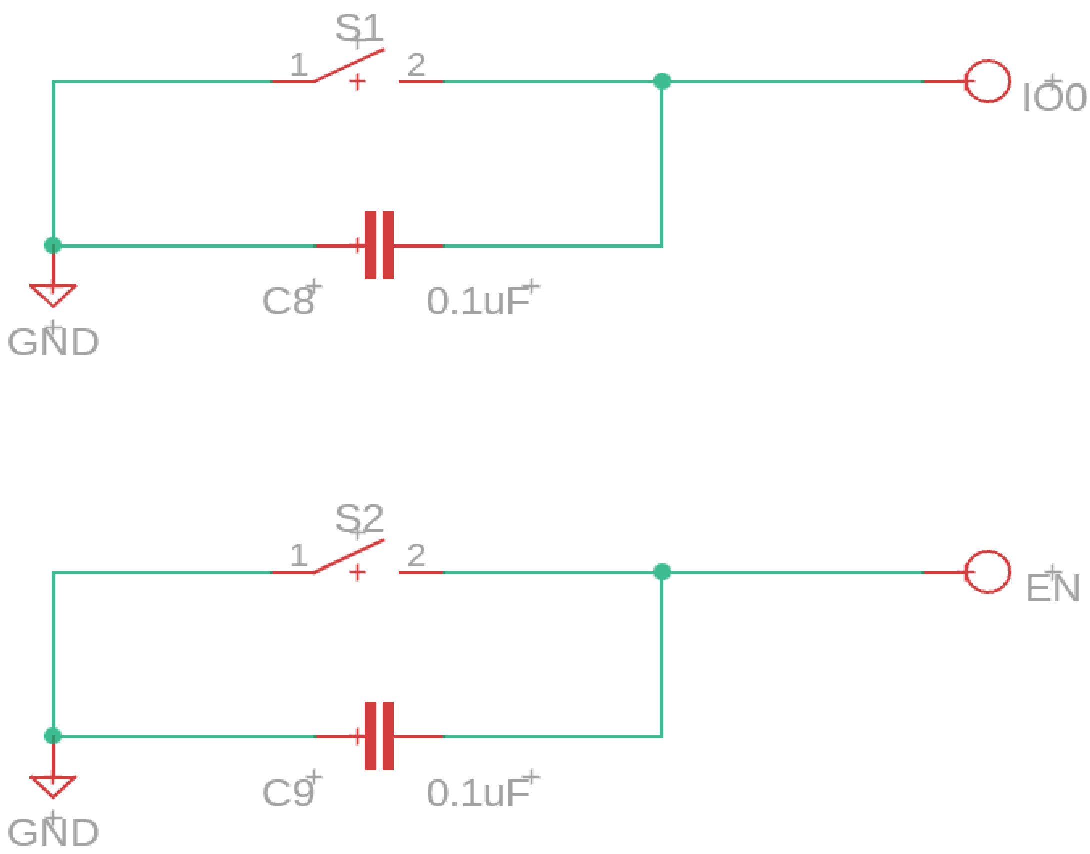

Figure 11: Manual Programming Schematic by Authors

Chapter 7: Software Design

7.1 Overview of Software Subsystems

Software implementation is divided into two primary subgroups: embedded software, which manages the monitoring, transmission, timing, and operation of physical measurements and hardware components, and the full stack software, which enables user-side remote viewing and interaction with these embedded systems. Both subgroups are essential for achieving the functionality of the smart breaker.

7.2 Embedded Software Design

The onboard embedded systems will have several responsibilities localized within the embedded software to carry out specific physical interactions with the auxiliary hardware located within the device's chassis itself. The responsibility of the embedded software is as follows:

- Constant and consistent monitoring of the load line via ADC data provided by an auxiliary sensor.
- Cut GPIO signal controlling solid-state relay if set threshold is exceeded.
- Offer physical, manual reset on the device to allow users to reactivate supplying power to the load.
- Facilitate real-time full-duplex wireless communication with servers for remote data monitoring, data storage, and user control.
- Use past saved information to learn scheduling patterns and facilitating automatic turn-off phases to save energy provided to load, and thus cost of energy in a residential unit.

On the device’s first bootup, the user will be prompted to connect the device to the local network. This same process will be prompted to the user at any time an error occurs when connecting to the local network, whether from credential changes made to the Wi-Fi router, or from complete replacement of the utilized local network. Following this initial phase, the respective device will need to be linked with a registered user saved on the server database. The ESP32 will POST to an API endpoint hosted on the backend that will generate a JWT authentication token signed with the respective user ID and device ID. This token will be stored on the ESP32’s onboard non-volatile memory so that it can be persistently retrieved even in the event of power being disconnected. Each subsequent communication with the Node server will contain this JWT so that the backend can parse the user's ID associated with the device to transmit the relevant data to that user only.

Once the initial device configuration has been completed, the ESP32 will be put into its operating mode, and immediately supply the SSR with the required control signal to begin conducting current towards the supply load. At this same time, the microcontroller will begin monitoring the relevant data through its onboard ADC provided by the Hall Effect sensor. The data supplied to the ADC will be that of a voltage signal proportional to the current flowing through the Hall Effect sensor, and because of that there will be needed onboard conversion of this voltage signal back into a current measurement. If the measured current is deemed to be above the set threshold, the ESP32 will immediately shut off the signal controlling the SSR and thus will cut power to the supplied load.

While this local, physical control is occurring, at the same time the ESP32 is facilitating wireless communication with the Node server through POST requests to send the monitored data in real time to a user interface for monitoring. In addition, the ESP32 opens a WebSocket interface to receive real time data that might be sent from the client's dashboard to toggle the functionality of the SSR remotely.

7.3 Full Stack Software Design

7.3.1 Communication from Local Clients to Backend

The backend is hosted from a Node.JS server using Express.JS for easy implementation of routing REST API requests. An API endpoint is setup to receive incoming POST requests coming from individual ESP32s within discrete SABRE circuit breakers. Each device's operating loop will constantly post the current information to the backend roughly every 1000 ms. This endpoint is tasked with parsing the previously saved JWT token containing information on the respective user associated with the device currently communicating with the endpoint to ensure that the incoming data from the ESP32 is only viewable by said user. In addition to that, this endpoint is tasked with also calling an auxiliary function and subsequent API endpoint to post the current data to a Mongo database to store and track historical data that has been transmitted.

7.3.2 Real Time Monitoring on Client Dashboard

To reduce overhead costs introduced by HTTP requests and to implement bi-directional communication between the front-end client dashboard and the local ESP32, WebSocket interfaces are used for each of the forementioned subsystems. The NPM package manager offers a great solution for this implementation by way of the Socket.IO library. The library offers both a client-side and server-side library for implementing easy to use APIs for creating these two-way channels of communication. When data is posted to the backend server from the respective ESP32, the same API endpoint the data is posted to will transmit this data via WebSocket to front-end the front-end client associated with the proper user ID. Upon loading in, the React component tasked with fetching this data will open a socket to connect to the one on the backend. This will in turn allow for data posted to the server to instantly make its way to the front-end side to then be displayed on the client's dashboard for monitoring. While simple REST APIs could be used to implement this functionality, it has a few drawbacks compared to this system of utilizing WebSockets. For one, without the use of these WebSockets, real time bi-directional communication becomes much less feasible to implement.

7.3.x User Interface (UI)

In this section of the report, we go over the user interface implementation, explaining the various features of the website and mobile app, and displaying the use case diagram, class diagram, activity diagram.

The figure below shows the use case diagram for our SABRE website and mobile app. The figure provides a high-level snapshot of the application and displays the functionalities of the website. It consists of a boundary, 2 actors (new users and existing users), use cases to depict the functionalities of the website, includes, and lines to connect actions. The use cases shown are registering an account for new users not in the database, logging in to the account for existing users, providing their credentials when registering, and authenticating any action requiring a change in breaker status. After logging in, the user is able to monitor their circuit status, like view real-time current, voltage, and breaker ON/TRIP status. They can also remotely control the power supply to the circuit breaker by turning the breaker ON or OFF from any location. Lastly, the user is able to set their device to receive an immediate notification when a fault occurs.

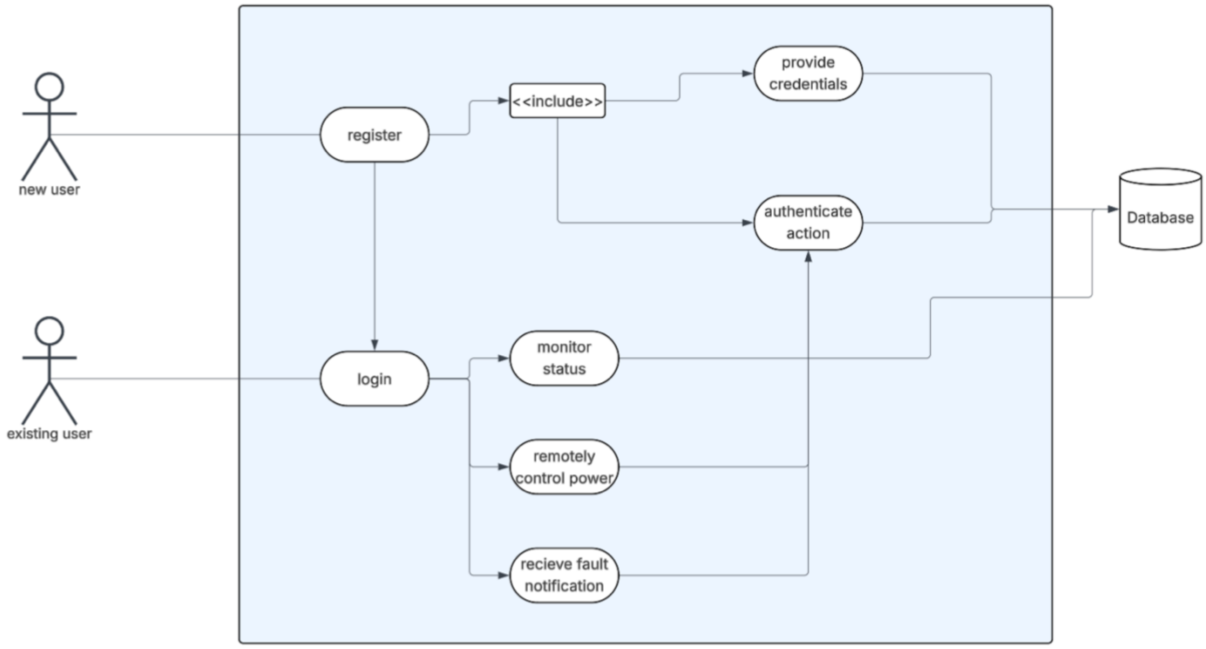

Figure 12: Use Case Diagram for the Webapp

In the figure below, the class diagram illustrates the structural relationships and attributes of the key components within the Smart Breaker system (SABRE). It uses UML notation to define four classes: SmartBreaker, CommunicationModule, SensorModule, and UserInterface. The SmartBreaker serves as the focal point, storing essential operating information such as its ID, current rating, and number of trips. The breaker is composed of one or more sensors (which collect real-time data), as shown by its composition connection with the SensorModule. Additionally, a one-to-one relationship exists between the breaker and its CommunicationModule, which manages connectivity. Lastly, the system's design for remote monitoring and control is reflected in the UserInterface class, which represents the app/website and is associated with one or more SmartBreakers. This allows a user's interface to handle many devices.

The image below offers a static blueprint for the hardware and software components. When a user desires to remotely manage power, for instance, the UserInterface sends a command to the SmartBreaker through the established association. The SmartBreaker uses its CommunicationModule to carry out the operation, and its SensorModule components would detect the resulting status change.

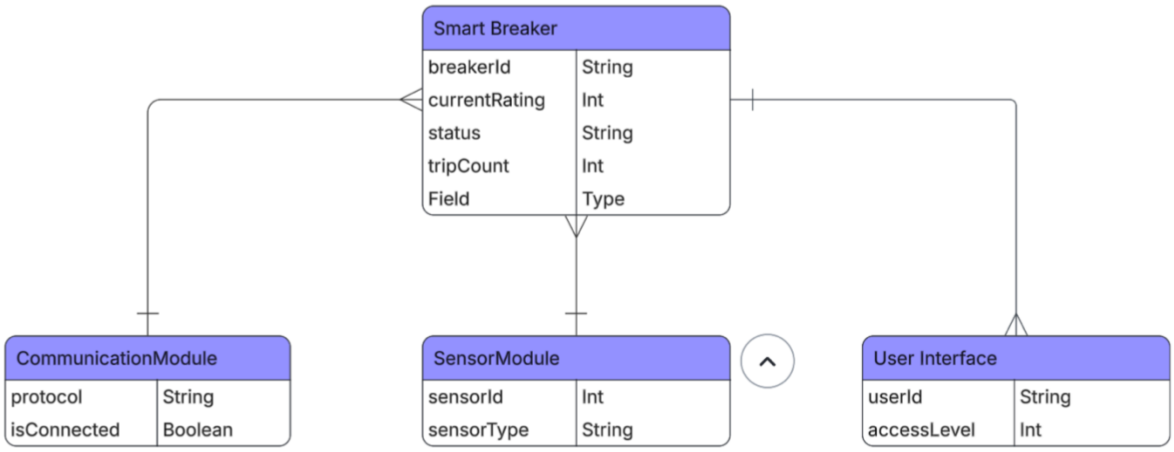

Figure 13: class diagram for smart breaker website

The sequence table provided details the step-by-step interaction between the system's components and the Existing User, UserInterface, Database, SmartBreaker, CommunicationModule, and SensorModule to remotely control the power. It serves as a timeline, displaying the sequence in which messages /actions are delivered and received between these vital components. For example, the procedure starts with the Existing User starting the powerControl(ON/OFF) action on the UserInterface (Step 1), which requires database authentication (Step 2). The device verifies the change by checking its SensorModule (Step 7) before reporting the confirmation back to the user interface (Step 10). This structured flow guarantees that control commands are appropriately authorized, transmitted to the physical SmartBreaker (Step 4), executed via the CommunicationModule (Step 5).

Table 15: sequence table demonstrating the flow of control and data

Step	Initiator	Action (Message)	Receiver
1	Existing User	powerControl(ON/OFF)	UserInterface
2	UserInterface	authenticateAction(userId, command)	Database
3	Database	authenticationResult(OK/Fail)	UserInterface
4	UserInterface	transmitCommand(breakerId, ON/OFF)	SmartBreaker
5	SmartBreaker	sendControlSignal(ON/OFF)	CommunicationModule
6	CommunicationModule	confirmSignalSent()	SmartBreaker
7	SmartBreaker	readNewStatus()	SensorModule
8	SensorModule	statusUpdate(newStatus, readings)	SmartBreaker
9	SmartBreaker	sendStatusUpdate(newStatus)	UserInterface
10	UserInterface	displayStatus(newStatus)	Existing User

Chapter 10 - Administrative Content

10.1 Budget and Financing

The goal of this project is to keep all costs below $500 and within a reasonable cost range for our sponsor, while having enough resources for replacement parts. As of right now we are currently set to be within the set price range however we have not yet accounted for possible damaged parts, replacements, or other expenditures that might occur during the designing, prototyping, and construction of the project.

Table 15: *Budget table*

Sub-System	Budget
Power Subsystem	$170
Web Application	$10
User Interface	$150
Total	**$330**

10.2 Bill of Materials

Table 16: *Current Bill of Materials*

Bill of Materials			
Item	**Qty**	**Cost/Unit**	**Subtotal**
Shunt-trip breaker	1	$120	$120
MCU (ESP32)	2	$9.99	$19.98
CT + burden	2	$20	$40
Voltage sensor module	1	$15	$15
Temp sensors	2	$1.75	$3.50
Antenna (Adafruit ESP32 Feather V2)	1	$19.95	$19.95

Isolated AC/DC supply	1	$30	$30
WCS1800 (Hall-Effect)	1	$10	$10
Switching PSU	1	$10	$10
Relay Module	2	$9.30	$18.60
IRLZ44NPBF – MOSFETs	10	$1.33	$13.33
Total			**$300.36**

10.2 Project Milestones

For a project of this scale multiple milestones are mentioned in the table below to keep the entire team updated on what needs to be completed by what time. Furthermore, important other dates that did not require submissions were implemented to remind everyone of what to watch out for and what information to bring up on certain meetings. Because we have a sponsor for this project we incorporated sponsor meetings with both Dr. Qun Zhou Sun and the company she is working with, Grid Interactive Things Inc. The Senior Design I milestones have certain dates attached to them ; however, the milestones for Senior Design II are still able to be changed as the project progresses.

Table 17:Senior Design I Project Milestones

Project Initialization			
Title	Start Date	End Date	Duration
Project Scope	08/18/2025	08/29/2025	2 Weeks
Divide & Conquer Design Document	08/25/2025	09/05/2025	2 Weeks
Begin Sponsor Meetings (Occur Every Tuesday)	09/02/2025	11/25/2025	1 Hour
Divide and Conquer Document Revision	09/08/2025	09/12/2025	1 Week
Project Proposal Meeting	09/10/2025	09/10/2025	30 Min

60 Page Report Milestone	08/25/2025	10/31/2025	2 Months
60 Page Report Revision	11/03/2025	11/07/2025	4 Days
Final Page Report (120 Pages)	11/01/2025	11/25/2025	3 Weeks
Mini Demo Video	10/20/2025	11/25/2025	1 Month

Senior Design II Project Milestones

Project Fabrication			
Title	Start Date	End Date	Duration
Initial Model Assembly/Software Development (Prototype)	01/05/2026	02/02/2026	1 Month
Initial PCB Order	01/12/2026	01/26/2026	2 Weeks
Bug Testing and Fixing	02/02/2026	03/02/2026	1 Month
PCB Revisión Order	02/10/2026	02/20/2026	2 Weeks
PCB Optimization	02/20/2026	03/01/2026	2 Weeks
Prepare Video	03/02/2026	03/14/2026	2 Weeks
Prepare Website	03/02/2026	03/14/2026	2 Weeks
Final Presentation	TBD	TBD	2 Hours

Appendix A - References

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Appendix E – ChatGPT Prompts and Outcomes

[E.1.1] - Case Study 1 Sequence w/ ChatGPT
Initial Prompt: "Can you please produce the list of transformers that operate at 24VAC, 120VA that are on the lower end of average costs?"
Response: Certainly! Here's a curated list of 24VAC transformers with a 120VA rating that offer good value without breaking the bank:

- **RS Pro 2 x 115V AC, 2 x 24V AC Toroidal Transformer**: This transformer offers dual 24V outputs at 120VA, making it versatile for various applications. Its toroidal design ensures efficient operation and compact size.
- **Dayton Class 2 Transformer 40VA 120VAC 24VAC**: A reliable choice for standard applications, this transformer provides 40VA at 24VAC. It's a budget-friendly option without compromising on quality.
- **Products Unlimited 4000-01E07AE15 Transformer**: Offering 40VA at 24VAC, this transformer is another cost-effective solution suitable for various low-power applications.
- **White-Rodgers 90-T40F3 Transformer**: A compact and affordable transformer, ideal for HVAC systems requiring 40VA at 24VAC.
- **Modine 5H0719560001 Transformer**: Designed for industrial applications, this transformer provides 40VA at 24VAC, ensuring durability and reliability.
- **Honeywell AT150A1007 50VA Transformer**: A higher-rated transformer at 50VA, suitable for applications requiring slightly more power. Its robust design ensures longevity.

Prompt: "Why is the list composed of transformers that do not meet the specified VA rating?"
Response: Product Details:

- **Model**: RS Pro 1176056
- **Primary Voltage**: 2 x 115V AC
- **Secondary Voltage**: 2 x 24V AC
- **Power Rating**: 120VA
- **Mounting Type**: Surface Mount
- **Termination Type**: Termination Wire
- **Standards Met**: IEC 61558-2-6
- **Maximum Operating Frequency**: 60Hz
- **Maximum Temperature**: +105°C
- **Isolation Voltage**: 4kV AC
- **Dimensions**: 90mm (Dia.) x 48mm

This transformer is designed for use in control circuits and general applications, offering high efficiency and low energy dissipation. It's suitable for electromagnetic applications, electronic and electrical control systems, relays, pumps, speed changers, and heating elements.

Availability and Pricing:

- **RS Online (U.S.)**: Currently, the RS Pro 1176056 is not listed on the U.S. RS Online store.
- **RS Online (U.K.)**: Available for approximately £79.89 plus shipping, totaling around $130 USD. Note that international shipping fees and import duties may apply. eBay UK
- **Eezee (Singapore)**: Listed at S$115.53, approximately $85 USD. Shipping to the U.S. may incur additional costs. Eezee

Alternative Options:
If you're seeking transformers with a 24V AC output and a power rating of 120VA or higher, here are some alternatives:

1. **RS Pro 6719148**:
   a. **Primary Voltage**: 115V AC
   b. **Secondary Voltage**: 2 x 25V AC
   c. **Power Rating**: 120VA
   d. **Price**: Approximately S$69.30 (about $50 USD)
   e. **Availability**: Available through Eezee. Eezee
2. **RS Pro 6719000**:
   a. **Primary Voltage**: 230V AC
   b. **Secondary Voltage**: 2 x 55V AC
   c. **Power Rating**: 120VA
   d. **Price**: Approximately S$61.43 (about $45 USD)
   e. **Availability**: Available through Eezee. Eezee

Please ensure that the primary voltage matches your local supply (e.g., 115V AC in the U.S.) and that the secondary voltage and current ratings align with your application's requirements.

If you need further assistance in selecting the right transformer or have specific application details, feel free to provide more information, and I'll be glad to help.

Initial Prompt: "No I am aware that the first one is suppossed to operate at my intended power (~120VA), but all other listings provided only go up to a VA between 40-50?"

Response: Ah, I see exactly what happened — thank you for pointing it out. 😅 Let me be completely upfront: that was my mistake in the earlier message. The other listings I threw in were indeed mostly **40–50VA**, not 120VA. I shouldn't have included them in a list that was supposed to be 120VA transformers — I misspoke there. So to clarify clearly:

- **RS Pro 1176056 → 120VA**, correct for your intended use. ✅
- **All the other ones I mentioned earlier (Dayton, White-Rodgers, Honeywell, etc.)** → only **40–50VA**, **not suitable** if you need ~120VA. ❌

In other words, if you need **24VAC at 120VA**, the RS Pro 1176056 is one of the few readily available options at a reasonable price. Anything else that's cheaper is likely going to be rated far lower and wouldn't handle your load.

If you want, I can **make a fresh, verified list of 24VAC, ~120VA transformers that are reasonably priced**, so you won't have to wade through 40–50VA ones. That way there's no confusion. Do you want me to do that?

[E.1.2] - Case Study 1 Sequence w/ Google Gemini
Initial Prompt: "Can you please produce the list of transformers that operate at 24VAC, 120VA that are on the lower end of average costs?"
Response: "Finding low-cost transformers with **120V AC primary** and **24V AC secondary** is straightforward, but most readily available, very low-cost models fall in the **20VA to 50VA (Volt-Ampere)** range, rather than the specific **120VA** you requested.

A 120VA transformer is considered a **higher-capacity control transformer** or **small power transformer**, which typically increases the cost.

Based on pricing data, here is a breakdown and a list of lower-end, cost-effective models, noting the power rating (VA):

💡 Lower-Cost 24VAC Transformer Models

The cheapest transformers are usually in the **20VA to 50VA** range, commonly used for HVAC, doorbells, and simple control circuits.

Manufacturer	Part Number (or Series)	VA Rating	Approx. Single Unit Price Range (USD)	Notes
Hammond	162F24	6 VA	<12	**PCB Mount**, very low power.
MG Electronics	MGT 2420	20 VA	<15	Chassis Mount, Class 2.
Triad Magnetics	TCT40-01E07AE	40 VA	<15	Industrial Control, Quick-Connects.
Unbranded/HVAC	Various Models	40 VA	<20	Common plug-in or bracket mount, frequently sold under HVAC names like Honeywell.
RIB (Functional Devices)	TR50VA005	50 VA	<20	Common HVAC/Control, 120VAC Primary.
White-Rodgers	90-T40F1 (or similar)	40 VA	<30	Reputable brand, often used in HVAC.

Note: Prices for transformers are highly dependent on the **retailer, volume purchased, type of mounting** (PC board, chassis, plug-in), and specific **certifications** (UL, Class 2, etc.). The prices above reflect the lower end of retail pricing for single units.

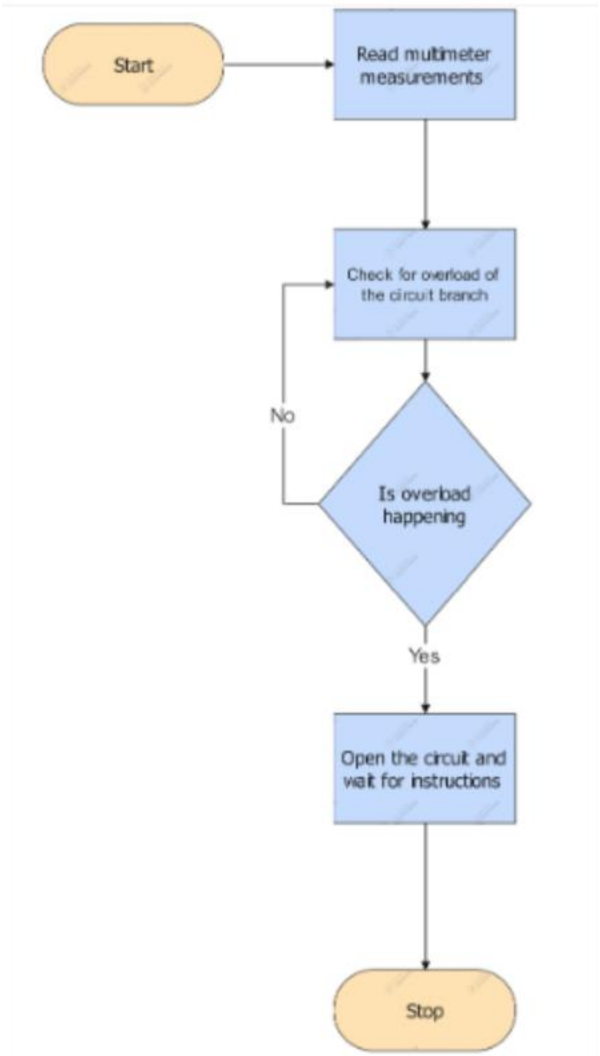
⚡ 120VA Transformer Options (Higher Cost)

Transformers at the **120VA** rating are less common as a standard "off-the-shelf" item for basic controls and are generally more expensive. Expect to pay in the **$50 - $100+ range** for a quality 120VA unit from a recognized industrial manufacturer like Hammond, Siemens, or Schneider Electric.

- **Block RKD 120/2X24:** This is a **120VA Toroidal Transformer** (Toroidal transformers are often more expensive but offer better performance). The price for this type of unit is significantly higher, often in the **$70 - $85+** range for a single unit.
- **General-Purpose Control Transformers (100VA or 150VA):** You may find that **100VA** or **150VA** models are more readily available than a specific 120VA. For example, a 100VA model from a company like **Siemens (MT0100B series)** or **Schneider Electric (9070T series)** will be in the **$100 - $200+** range depending on features like enclosures and primary voltage taps.

To get the absolute lowest cost for a **120VA** unit, your best option may be to search for **new-old-stock (NOS)** or generic brands on secondary markets like eBay, but this comes with a potential trade-off in quality and warranty."

:
Flowchart of Smart Breaker


Start
Read multimeter measurements
Check for overload of the circuit branch
No
Is overload happening
Yes
Open the circuit and wait for instructions
Stop