Smart Assessing Breaker for Residential Estates (SABRE)

EEL4915 - Senior Design II

University of Central Florida
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Chapter 1 – Abstract

The modern circuit breaker began to be widely adopted in residential buildings during the 1950s and 1960s. This innovation was built upon earlier designs stemming from the 1920s that utilized bimetal strips, which take advantage of the temperature-sensitive characteristics of metals to bend and disengage the flow of current. Additionally, the introduction of the thermal magnetic component during this era utilized fundamental principles of electromagnetism to trip the breaker when a specific threshold was exceeded. These two fundamental elements of circuit breakers have remained unchanged for the past six decades. The SABRE smart breaker was developed in partnership with Grid Interactive Things Inc. to integrate modern sensors to provide a more efficient and safer means to properly protect residential electrical systems while also providing readily available data from any Wi-Fi source in the world. SABRE is designed to allow the user to trip the breaker remotely, provide live readings of energy usage on the webapp, and provide information on past disturbances, allowing the user to determine if their electrical system is at risk of being jeopardized.

The SABRE smart breaker system operates in a similar manner to that of protective relays utilized in substations. The protective relay scales down both voltage and current via step-down transformers to safely transmit through overcurrent relays and over/under voltage relays. Rather than using step-down transformers, the smart breaker instead takes an input signal and is read by one of two components: a Hall-Effect sensor to provide an analog voltage signal proportional to the current going across it, and a microcontroller to effectively process the signal. The antenna embedded within the microcontroller will then communicate with the web application to provide live readings of the power flowing through the transmission line, and so long as the SABRE smart breaker is within fifty meters of a Wi-Fi connection, communication through the entire system is viable.

Due to constraints of the project enforced by the University of Central Florida, the SABRE smart breaker will operate a load line voltage level of 25 VAC at 5 amperes for the safety of the research team, students, and staff during testing and demonstration. The current tripping mechanism was employed using a solid-state relay interconnected along the main signal line. The Hall-Effect sensor will monitor and detect any potential disturbances produced from the load signal and communicate this information to the microcontroller. This allows the microcontroller to assess whether the solid-state relay should be deactivated to prevent current flowing to the load.

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, code 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.

Chater 2 - Project Description

2.1 Background and Motivation

Electricity is everywhere in the modern world. In North America the rating at which conventional outlets operate 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 in it of itself but if improperly regulated, could burn down an entire building. When electricity is put into nearly every home in the country, safety standards must be in place. In comes the modern circuit breaker. A device that not only protects the electronics inside your home from receiving irreparable damage but also prevents intense heat from generating inside the wirings that can lead to 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 electronics damage, insulation burns, and even fires [14]. Furthermore, with the modern digitizing age, there is an increasing demand for every electrical grid in the world requiring an upgrade from the old. With the Smart Assessing Breaker for Residential Estates (SABRE), these issues are a thing of the past.

This smart, single-phase, circuit breaker acts 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 within the home. The prototype also allows for a solid-state approach to trip power rather than causing strain over time on the mechanical aspect of a conventional breaker by including a microcontroller into the hardware making the breaker more reliant on circuitry giving it a safer, more robust, and fast acting switching than traditional means [5]. In addition, 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, allowing the user to monitor 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 primary functionality, 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 newly developed large scale data centers which are being invested in 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 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 Assessing Breaker for Residential Estates design was 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 interface. To expand this idea, Dr. Zhou tasked our team to design a Smart Circuit Breaker that innovated 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 served as the intended customer for this project.

2.2 Goals & Objectives

The primary objective of this project was to develop a functional Smart Circuit Breaker capable of remotely monitoring power consumption in real time. The system was designed to 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 was implemented at a reduced scale, operating at 24VAC and 5A.

2.2.1 Goals

2.2.1.1 Basic Goals

- Designed a Smart Circuit Breaker capable of protecting against overcurrent and short circuit conditions while also being able to meet standard electrical safety code [14].
- Created a built-in communication system allowing for remote controlled access via a web application to allow for real-time monitoring, remote control operation, and predictive maintenance insights through a user-friendly interface.
- Provided predictive fault detection analysis to inform the user of irregularities during power consumption of a home allowing them to respond accordingly.
- Minimized power consumption of devices to less than 10W.

2.2.1.2 Advanced Goals

- Incorporated components capable of withstanding surges to prevent replacements and repairs at later times.
- Created a user-friendly, easy to install system mimicking that of standard circuit breakers that were able to be installed within conventionally available load centers. Forgoing the need to require a proprietary breaker box to mount the device.
- Implemented temperature monitoring to warn users of potential heat surges or fires within the system and trip the branch accordingly.

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

- Utilized a mechanism to convert current measurement into a proportional analog voltage that can be properly read and assessed by the microcontroller.
- Implemented signal analysis to predict fault detection within the entire power system of residential homes.
- Integrated power consumption regulations to minimize overall power consumption in a scaled down simulated residential load.

2.2.2.1 Advanced Objectives

- Removed reliance on mechanical aspects of conventional breakers and replaced it with a combination of solid-state components, current monitoring sensors, and a microprocessor.
- Incorporated persistent storage through a database to allow for multiple months' worth of data to be stored and analyzed at any given point.
- Keep data password protected inside website and smartphone to ensure data privacy using two-factor authentication

2.2.2.1 Stretch Objectives

- Replace microcontroller boards with faster FPGA to implement into residential and commercial areas for faster real-time monitoring and reaction capabilities.
- Incorporate a local LCD display to facilitate real-time monitoring and provide visual feedback regarding the status of the breaker. This display should show relevant measurements when the current draw remains within the designated range, allowing users to quickly ascertain the device's performance. Additionally, it should feature a clear indicator to confirm that the breaker is operational. In the event of a trip, the LCD should present a distinct visual alert, ensuring users are immediately aware of the change in status.
- 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 goal behind the project was to design a device capable of preventing an overload from occurring along a given branch circuit within a building, preventing damage to electrical loads connected, and to the building itself. Instead of using a mechanical component, which is what standard circuit breakers use, the SABRE smart breaker uses an entirely solid-state digital design. The prototype provides real-time monitoring over a residential building's energy usage, providing information on any irregularities and predicting potential disruptions to the website if 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. If Wi-Fi is not present, the device continues to function as that of a standard circuit breaker but will not transmit any of the measured data captured during this time.

2.3.1.2 MCU

The Microcontroller Unit that the team used was the ESP32 microcontroller which carries a dual-core processor up to 240 MHz and 520 KB of SRAM. The processor also introduces Wi-Fi connectivity of up to 2.4 GHz and Bluetooth. Furthermore, the processor processes onboard digital to analog and analog to digital converters. Lastly, the board contains an ultra-low power co-processor to allow for sensor monitoring while operating in sleep modes [5]. The dual-core processor cascaded with the solid-state relay in conjunction with the ultra-low power co-processor allows the ESP32 board to monitor live power readings in case of any power fluctuations and if triggered, the processor "activates" and reacts accordingly. The dual-core processing speed and RAM allowed for trip times in the microsecond range. The Wi-Fi capabilities of the SoC assisted in the need for live readings and transmission of the electrical load data to the website

2.3.1.3 Solid-State Relay

The solid-state relay served as the tripping mechanism in the SABRE smart breaker, employing a small DC voltage signal to regulate the current flow between its terminals. The team explored both a explicit MOSFET array and individually packaged solid-state relays. Ultimately, we chose the latter due to the compact size of the SSR components and their ability to implement the desired circuit configuration effectively.

The concept of the solid-state relay was first introduced by Dr. Qun Zhou Sun during the team's sponsor meeting on September 2, 2025. This idea emerged from the research performed on previous smart breakers designed for high-power applications. Although such technology had not been previously applied in these contexts, it became evident that innovative tripping methods were necessary to stay within the size constraints.

2.3.1.4 Temperature Sensor

The implemented temperature sensor serves as an additional tripping mechanism for the circuit breaker. In conventional circuit breakers, the mechanical tripping mechanism heats up in response to the current flowing through it; once it reaches a certain temperature, the breaker trips, interrupting the current and preventing further faults in the circuit. In this scenario, users can establish temperature thresholds during the initial setup phase. If the temperature detected by the sensor surpasses the predetermined limit, the smart breaker will automatically trip, ensuring enhanced protection against potential issues.

2.3.1.5 Switching PSU

As opposed to linear power supplies that look to step down higher voltages through linear transformers, switching PSUs makes this conversion by utilizing pulse width modulation generated from an integrated circuit and other circuit elements. Switching PSUs tend to be noisier components as opposed to their linear counterparts, but they can be stuffed in a much smaller form of factor while also operating at higher power efficiency, both were huge factors in being an effective method of stepping down voltage for use within the embedded components of the SABRE Smart Breaker. An example of a classic small form factor switching PSU is the circuit used for the 5W block for Apple chargers. This exact same premise is what was utilized to step down the 25VAC signal to a 5VDC signal to provide appropriate power to our MCU and auxiliary sensors.

2.3.2. Software

2.3.2.1 Website/App Interface

The web application interface played a crucial role in delivering a "smart", and user-friendly experience throughout the system. It enables users to monitor real-time metrics, such as current drawings, and identify any anomalies that may occur during operation. If these irregularities lead to a system trip, the application promptly notifies the user and provides a straightforward method for resetting the breaker to restore normal operating conditions. Additionally, the application utilizes a database service for persistent storage, allowing users to track and analyze metrics over time for their personal use.

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 upgrading to these systems requires the installation of a completely new proprietary load center, in addition to the circuit breakers, which significantly raises the upfront cost needed for the upgrade. Some products from Luton in particular 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: Overall Design Specifications

Overall System Specifications		
Specification	**Target Value**	**Tolerance**
Operating Voltage	25 VAC (single phase)	±10%
Rated Current Capacity	5 A	±5%
Wireless Trip Response Time	< 3s	±1%
Interrupt Rating	500 AIC	Scaled Down Proportional to the UL 489 Standard
Continuous Load Rating	95% 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)	< 10 W	±10%

Dimensions (HxWxD)	≤ 75 × 40 × 76 mm	Stand. Size - 0 tolerance

Table 2 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
Current Sensor	Measurement Range	0 - 10 A	Overcurrent Detection
	Accuracy	±2%	
Voltage Sensor	Measurement Range	0 – 24 VAC	For Monitoring
	Accuracy	±2%	
Temperature Sensor	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	Control Continuity	5 V	Logic signal for switching the relay between on and off
	UL Certified Load Capacity	5A 25VAC	Signal being controlled by MCU
	Operating Time	1 ms	Switching Time
	Power Consumption	~0.45w	Energy Usage
	Ambient Operation Air Temperature	-40 °C to 55 °C	Operating Temperatures
Hall-Effect Sen.	Operating Voltage	3V - 12V	Converts high current into low volt. signal for MCU
	Output Operating Current	0A - 35A	
	Sensitivity	72 mV/A	
Switching PSU	Input Operating Voltage	24VAC	Converts 24VAC into constant 5W output
	Output Operating	5VDC, 3A	

2.6 Hardware Block Diagram

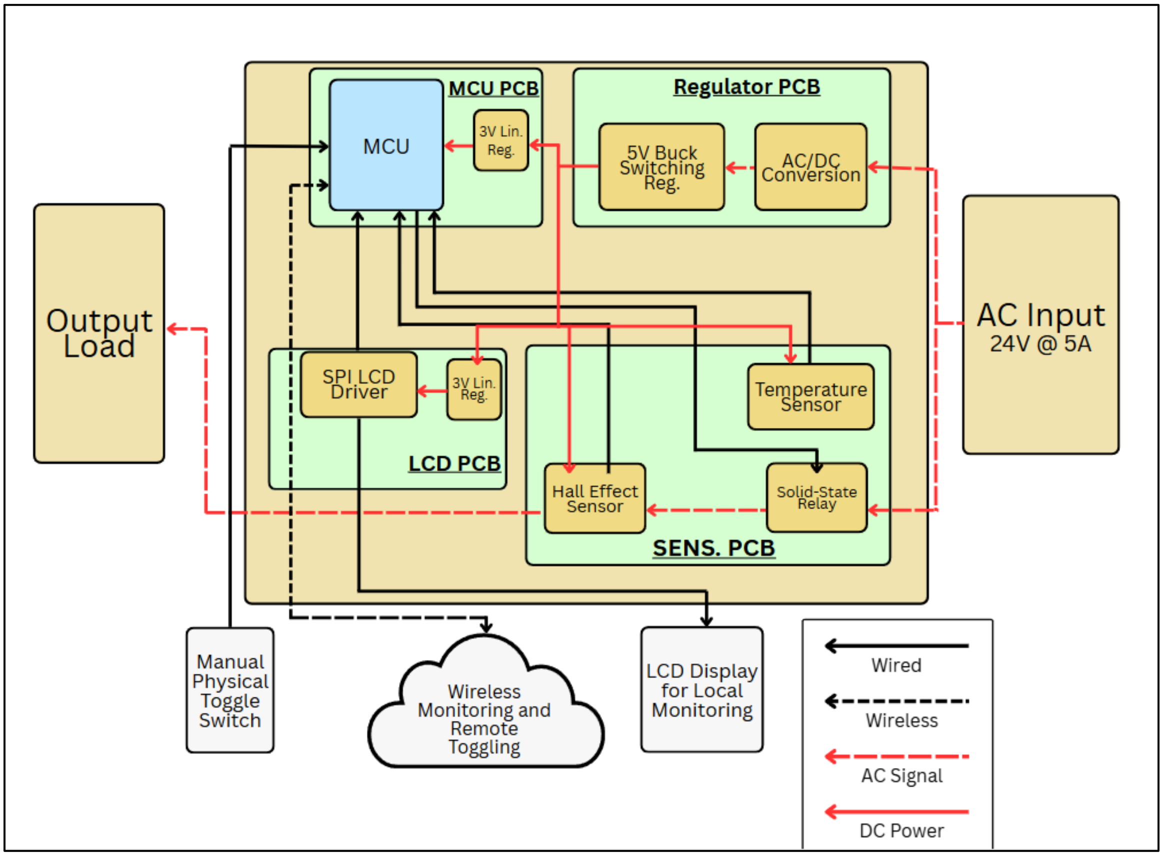

Figure 2.1: Hardware Block Diagram

2.7 Software Block Diagram

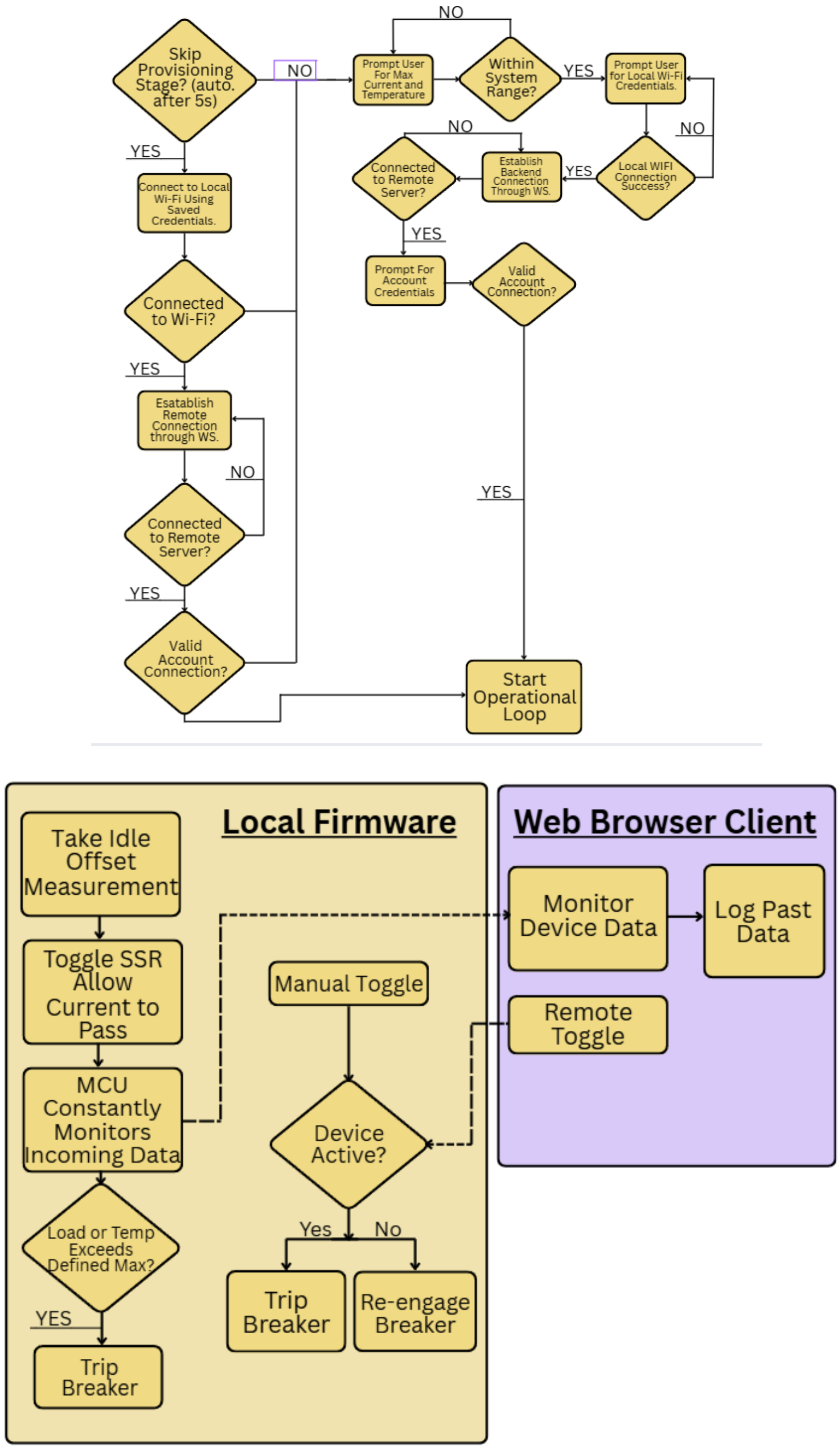

Figure 2.2: Software Block Diagram

2.8 House of Quality

The House of Quality provided 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 individually.

Figure 2.3: House of Quality by Authors

From our analysis, we found that cost was the most impactful factor when compared to 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.

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 mechanical breakers, but they include additional features such as electronic sensing and wireless communication. 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 manages 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 can 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 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 must 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 can 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 like 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 an 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, MOSFET-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 interruption 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 be 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 as an 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 63A version, it provides functionality that rivals high-end models that cost 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 63A 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 35mm 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 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 smart breaker, we looked to make the device entirely solid-state. 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 was to be taken instead, and for the device to be self-assessing and predictive, we needed it to be digitized. The approach was to have something that could take our high-power signal and output a proportional analog voltage signal and then feed that through the ESP32's onboard analog-to-digital converter (ADC) to be able to appropriately interpret the magnitude of the current being drawn from the load connected to the breaker.

The ESP32 contains an onboard ADC with a maximum analog voltage input of 3.3 volts, effectively satisfying our requirements. The only caveat the team found is that there are only two analog channels for the ADC, and whenever we are running communication through Wi-Fi, the chip prevents any usage from the second ADC channel. Because the device is communicating with the web application constantly, the team had to decide on only using a single ADC channel at a time. Luckily, multiple analog signals can be read and converted along a single channel, and thus the single ADC channel ended up being more than sufficient.

As for speed, the frequency that the SABRE Smart Breaker operates at is the same as in residential buildings which is 60 Hz [17]. For ADC conversion, we required around 100 samples per cycle, and fortunately the ESP32's ADC can operate at 6000 samples per second, which was more than sufficient for our needs. 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 when reduced from 12-bit resolution to 9-bit resolution. 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.

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 it 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 can 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 cheap 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 embedded components. 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 the smart breaker is able to trip the breaker in 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 threshold that will then determine if the signal is permitted 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 can 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 can combat this issue by using embedded sensors with extreme accuracy to correctly determine the current draw at a given time. 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.

3.2 Embedded Systems

3.2.1.1 The Brains of The System

The embedded systems within the implementation were crucial to both the functionality and performance of the breaker that was 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 particularly well-suited 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 Wi-Fi 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.) made 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 is 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 the SABRE smart breaker needed to make use of constant wireless communications protocols, it was going to be imperative to choose a solution that is able to be easily implemented, offers strong error handling, and high redundancy. For this reason, the obvious solution was 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 does exist 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		✓

3.2.1.3 ESP32

The ESP32 series from ESPRESSIF 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 and 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 of 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 that all the above features are packed into a chip that is sold for 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 for $10 [22].

3.2.1.4 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 several 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 are 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 offers 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 regarding 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 several 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 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
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 required 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 determined the speed, efficiency, durability, and ease-of-implementation of incorporating the actual switching of the actual current flow 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 like 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 entice 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 was deemed to 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 occur during switching operation are further disadvantages. Mechanical relays, though reliable for a range of applications, were 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 were introduced when using SSRs. For one, the use of some semiconductor components can lead to voltage drops being introduced across the semiconductor junctions. This aspect could have resulted in additional power dissipation and therefore increased heat generation throughout the device, but through testing the team found little to no additional power dissipation when testing these components. Depending on the current drawing, 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 it’s not conducting. Despite these limitations, SSRs present a robust solution in providing controlled switching while minimizing the number of moving components.

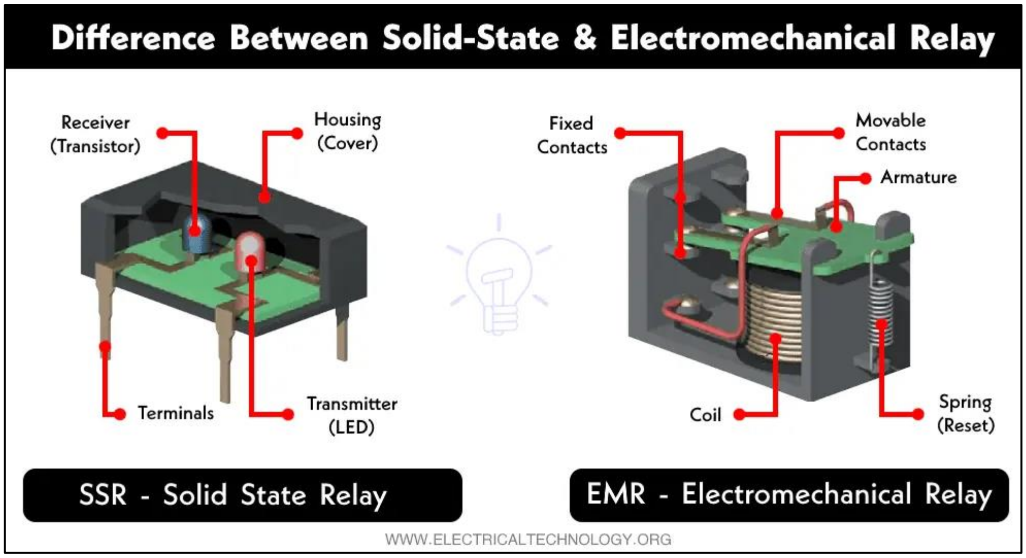

Figure 3.1: Comparison of Solid-State Relay vs. Conventional Relay, From Difference between solid-state electromechanical relay (SSR) & EMR, by ElectricalTechnology.org n.d. [124]

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 issue 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

Metrics	Mechanical Relay	Solid-State Relay	MOSFET Configuration
Avg. Cost	**$5.00**	**$25.00**	**$2.00**
Avg. Switching Speed	10 ms	1 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	Low: µA range	Low: µA range
Form Factor	Bulky: Coil, Contacts, Housing	Very Compact: SMD	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 480VAC load signal operating at 5A, giving more than enough headroom 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 3VDC and 32VDC, 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 280VAC 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 3VDC and 15VDC, which is within the range for a microcontroller such as the ESP32 to be able to properly control it at 3.3V, 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 4.5A. 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 4.5A, the G3VM-31 WR might just be short of safely controlling the supply of a maximum 5A 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 30VAC load at 5A, perfectly within the parameters chosen with the SABRE smart breaker. The relay is controlled through a 1.2VDC 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 60VAC signal operating at 5A, 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 5mA maximum, which should be acceptable for a microcontroller GPIO and resistor in series [40].

Table 6: Comparison of Solid-State Relays

Metrics	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	100 mA	5 mA
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 the reliability of electronic components. Several technologies were considered, each with distinct advantages and limitations.

3.2.3.2 Varistor

To safeguard the circuit against voltage surges, a Metal Oxide Varistor (MOV) was integrated into SABRE's design. A varistor is a voltage-dependent resistor that remains highly resistive under normal operation but rapidly decreases resistance when voltage exceeds a defined threshold. This allows excess energy from transients or spikes to be safely diverted to the ground, preventing damage to sensitive components.

For the prototype, the MOV provides an excellent balance of cost, reliability, and response speed. Its main strengths lie in its ability to respond almost instantly to surges, tolerate repeated small transients, and require no maintenance. However, its energy absorption capacity is finite, and repeated exposure to large surges can degrade its performance over time.

3.2.3.3 Fuse

A fuse is one of the oldest and most reliable protection devices, consisting of a thin metallic element that melts when current exceeds its rated value for a sustained period. This creates a permanent open circuit that prevents overheating or fire hazards. Fuses serve as the final line of defense against prolonged overcurrent conditions.

While traditional fuses are inexpensive and highly reliable, they are single-use and must be replaced after operation. Resettable fuses, or polyfuses (PTC devices), overcome this limitation by increasing resistance when heated and automatically resetting after cooling. However, polyfuses respond more slowly to faults and exhibit higher resistance once tripped. Both devices are effective for preventing sustained overcurrent but are less suitable for protecting against high-speed transient voltages.

3.2.3.4 Transient Voltage Suppression Diode

A TVS diode provides rapid voltage clamping within nanoseconds, making it ideal for protecting sensitive low-voltage circuits such as microcontroller inputs or communication lines. Unlike the MOV, which absorbs bulk surge energy, the TVS diode limits the voltage to a precise threshold, providing accurate and immediate protection for delicate components.

While TVS diodes are small and extremely fast, they have limited energy-handling capability and are better used in combination with MOVs for complete surge protection. In SABRE, this complementary approach ensures that both high-energy and high-speed transient events are mitigated effectively.

3.2.3.5 GFCI / RCD (Ground Fault Protection):

Ground fault protection devices, such as GFCIs or RCDs, are designed primarily for user safety. They detect leakage current from the live conductor to ground and disconnect the circuit within milliseconds to prevent electric shock. These devices are common in residential installations where user protection is paramount.

While GFCIs are extremely effective for preventing shock hazards, they do not protect equipment from voltage surges or transient spikes. Therefore, they are considered a complementary form of protection rather than a substitute for surge suppression or overcurrent devices in SABRE.

3.2.3.6 Selection

After evaluating multiple technologies, the MOV was selected as the primary protection element for the SABRE Smart Circuit Breaker. It provided a strong balance between response speed, protection level, and cost-effectiveness for a low-voltage AC prototype. Its ability to absorb surge energy and clamp voltage transients ensures that sensitive electronics remain safe under abnormal operating conditions, while maintaining a compact and affordable design.

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 25VAC and 5A, 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 was used. Stranded conductors provide better flexibility and were 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 followed a structured sequence:

1. Input supply
2. Protection devices (varistor and fuse)
3. Switching element (SSR or MOSFET)
4. Sensing stage (current/temperature 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.

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 were explored, 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 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 came with some immediate drawbacks. The biggest disadvantage in this approach is that to get a proper measurement across the shunt resistor required 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 of 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 was still not be a full proof solution of protecting the processor or providing an accurate measurement. Shunts are designed to have their resistance minimized 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 presented 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 improved the standalone shunt for a number of reasons. For one, this allowed for constant proportional output current to that being supplied to the load on a separate isolated signal line, something that a single shunt resistor failed 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 component that allows a signal to pass through it. The current's magnetic field is measured and converted into a proportional analog voltage signal that is supplied from one of the sensor pins [41]. This pin can be connected directly to one of the ADC 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 provided 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 was great as it provided 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 was 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].

Table 7: 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 12mA and 3.3V. Our signal is expected to be 24V and 5A, 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 required a 5:1 potential transformer that can step down from a 120V mains input to 24VAC while being able to supply 5A, resulting in a total power delivery of 100VA. 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 met a few of the criteria required to properly evaluate the functionality of our breaker technology. This transformer featured a single primary winding rated for 120VAC at 50/60 Hz, making it directly compatible with standard mains voltage. On the secondary side, it provided a single 24VAC output capable of supplying approximately 4.2A, resulting in a total power delivery of 100VA [47]. This capacity was slightly less than the desired rating for simulating the maximum operating conditions expected in our system and might have required 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 was that, since it only included a single input and output terminals, using this transformer alone made constructing the circuit much simpler than that of other options that included multiple input and output terminals. The transformer was rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input were accurately represented at the output. This level of accuracy was critical for reliable overload detection and measurement during testing. In addition, the price of the unit at $54.99 made 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 met several of the specified criteria that were required to properly assert the functionality of our breaker technology. The transformer featured two primary voltage windings rated for 115VAC, allowing them to be configured in parallel for a single 115VAC input or in a series configuration of 230VAC. The transformer came equipped with two output terminals, each supplying 24VAC and each capable of driving a total 60VA load. This meant that, to properly assess the maximum power capability of the breaker technology, the transformer secondary windings needed to be wired in parallel so that each was able to supply about 2.5A under maximum load conditions, successfully supplying 100% of the load current [49]. The transformer was rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input were accurately represented in the output. This level of accuracy was critical for reliable overload detection and measurement during testing. One of the most compelling aspects of this unit was its 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 was an adequate solution for meeting the demands needed to properly assess the functionality of the breaker. The transformer featured primary input terminals rated for 120VAC with two secondary output terminals rated for 24VAC at 100VA and 12VAC at 50VA, respectively. The transformer was rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input were accurately represented in the output. The single 24VAC output terminals were a reliable option for driving a signal. At 100VA, it could drive approximately 83% of the maximum load specified by our breaker. The additional 12VAC output terminals at 50VA might have initially seemed like a good inclusion, but further investigation showed that this was not the case. Attempting to use the 12VAC output in parallel with the 24VAC output to drive a higher load would not have worked as it might initially have seemed. Combining voltage supplies that did not share the same value caused the less powerful of the two to act more as an additional load rather than as an intended supply. Because of the low impedance that transformers were intended to exhibit, this essentially created a short circuit between both transformers, leading to overheating and/or damage to both transformers. In addition, the price tag of almost $200 made this one of the least compelling options of the bunch, as it had by far the highest pricing among the array of selections to pick from [51].

3.2.7.5 Chemscan 96VA Transformer

The Chemscan 96VA Transformer was another satisfactory solution for providing the main power for assessing the breaker technology. As suggested by the name, this transformer had a single 120VAC, 50/60 Hz primary input and a single 24VAC secondary output capable of supplying 96VA to a load. With a maximum power output of 96VA, this meant that the maximum current that could be supplied was 4A, or 80% of the specified threshold of the breaker. This capacity was slightly less than the desired rating for simulating the maximum operating conditions expected in the system and might have required 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 benefited from a single set of input and output terminals that allowed 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 was rated for high precision with an accuracy of 0.1%, ensuring that even minor fluctuations in the input were accurately represented in the output. This level of accuracy was critical for reliable overload detection and measurement during testing. In addition, the price tag of only $65 placed it in a competitive price range with the other selections mentioned previously [52].

Table 8: Comparison of AC Transformers for Simulation Purposes

Metrics	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	120VAC	115VAC	120VAC	120VAC
Primary Output Rating(s)	24VAC	24VAC	24VAC 12VAC	24VAC
VA Rating	100VA	60VA (Per Output)	100VA 50VA	96VA

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 was 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 was 25VAC, and for a future implementation was expected to operate at mains 120VAC. This was incompatible with the majority of commercially available microcontrollers that typically functioned within a voltage range of 2VDC–5VDC. This discrepancy not only highlighted the significant difference between the supply voltage value and the operating voltage value of the microcontroller but also emphasized the need for a direct current signal as opposed to an alternating one. Due to this fact, it was essential that a portion of the circuit facilitated 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 on, allowing for the inclusion of capacitive and inductive 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 a resistor connected in series to achieve a voltage drop. The impedance of the capacitor is determined by the formula Zc = 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 them. 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 simple 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 of 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 constant voltage output using OP-AMPs and transistors. The OP-AMP is used to compare a reference voltage to the output voltage and, based on 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 9: Comparison of Voltage Step-Down Methodologies

Metrics	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	Best
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 4.5V - 65V, with its own integrated 100V-rated, 1.5A 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 250mm².

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 4.5V and 42V and integrates a 65V-rated, 1.5A 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 250mm².

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 4.5V to 65V 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 255mm².

3.2.8.3.3 LM2576HV

The LM2576HV switching regulator was selected as a step-down DC/DC conversion solution for the prototype power architecture. It operated over a wide input voltage range, supporting up to 40V for the standard version and upwards of 60V for the HV variant, making it suitable for regulating the rectified 25VAC supply. Unlike newer synchronous converters, the LM2576 utilized an internal switching transistor and required an external Schottky diode, output inductor, and filter capacitors to complete the buck regulator topology. The device operated at a fixed switching frequency of 52 kHz and provided up to 3A of output current, enabling reliable regulation of a 5V rail for the microcontroller and supporting circuitry. A major advantage of the LM2576 was its relatively simple implementation and low component count while still maintaining high efficiency, often in range of 70%–85% depending on loading and component selection. In addition, its tried-and-true design, robust protection features, and compact support circuitry made it a practical and cost-effective candidate for integration, with a PCB footprint competitive with other candidate regulators considered.

Table 10: Comparison of Flyback Controller ICs

Metrics	LM5180NGU	LM25180NGU	LM5160DNT	LM2576HV
Avg. Cost	$4.50	$1.50	$5.00	$2.35
Efficiency	88%	88%	85%	80%
Size	4mm x 4mm	4mm x 4mm	4mm x 4mm	TO-263 SMD
Max Power Capability	7 W	7 W	130 W	36W
Max Input Voltage	65 V	42 V	65 V	60V
Max Input Current	1.5 A	10 mA	2 A	10mA

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 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.

Table 11: Comparison of AC/DC Conversion Methodologies

Metrics	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	Lower 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 the SABRE Smart Breaker, 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 negligible in a breaker that is continuously powered from the grid itself instead of an external supply.

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 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 10ms 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 capable 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 previously the ESP32 board is a dual-core processor and due to the Wi-Fi constraints, that were set earlier, there would only always be one core available, 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

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 always operate. However, with the Dynamic-Power Aware scheduling algorithm it can put either core to sleep whenever that core is not required for major processing data. During operating hours, the smart breaker should monitor 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 SABRE Smart Breaker 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: 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 SABRE Smart Breaker 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 SABRE breaker 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 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 12: Comparison of Algorithm Implementations

Algorithm Type	Description	Advantages	Disadvantages	Suitability
Threshold-Based Algorithm	Uses fixed voltage and current limits to trigger	Simple, fast, and requires minimal processing	Cannot predict overloads; only reacts to events after they occur.	High for baseline protection control.

	protection or alert conditions.	power. Ideal for real-time protection.		
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).

3.5 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 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 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 built-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 13: Comparison of Full Stack Frameworks

Metrics	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 was 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 needed 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 was 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 was appropriate for this purpose, and it helped that the team had prior experience using 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 14: Comparative Analysis of Data Storage for Smart Breaker

Metric	MongoDB (NoSQL)	TimescaleDB (PostgreSQL Extension)	Selection Rationale
Query Language	Flexible (BSON/JSON, MongoQL)	Full SQL, Window Functions, Joins	Flexible NoSQL structure simplifies storage of 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)	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)	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 [173].

3.5.3 Backend API Selection and Real-Time Data Delivery

3.5.3.1 Backend Language and Framework Selection

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 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 [176].

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 of its vast npm ecosystem and the unified language stack (JavaScript/TypeScript), which enable quicker prototyping and deployment [78].

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 [75].

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 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 15: Comparison of Cross-Platform Framework for Real-Time IoT Applications

Metric	Flutter (Dart)	React Native (JavaScript)	Progressive Web App (PWA)
Native Performance	Excellent (Compiled native code, Skia engine)	Good, but latency introduced by JS bridge	Poor (Limited by browser sandboxing)
High-Frequency Charting	Superior UI Fluidity/Responsiveness	Potential performance drops during heavy load	Unsuitable for reliable real-time safety visualization
Remote Control Latency Path	Optimized (minimal overhead)	Elevated latency risk due to bridge communication	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

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 used to build the web frontend. It obtained aggregated reports and historical usage statistics from MongoDB using standard REST API endpoints. Crucially, it maintained a dedicated 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 keeps 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 16: 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)	Both handle large-scale, multi-device deployments
Real-Time Latency	Optimized for low-latency messaging	Strong real-time processing capabilities	Essential for meeting the critical control budget.
Security Differentiation	Strong encryption, compliance (HIPAA, GDPR)	Microsoft Defender for IoT (Threat detection, real-time alerts)	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 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

To provide smooth and dependable user experience, industry standards for smart device control, especially in security or transportation systems, it is vital that latency be maintained low, ideally between 100 and 1s [71]. The highest limit is 1s for a safety-critical device such as the Smart Breaker. This goal requires that time budgets be rigorously distributed among all 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 17: 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.
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.

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].

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.

Chapter 4 - Related Standards and Design Constraints

4.1 Industry Standards

4.1.1 High Voltage Standards

Since this was an electrical power-based project, the most important constraint we faced was the safety of our product. Because the system would be accessible for demonstration and review by our committee and grading personnel, we had to ensure that no user would receive an electric shock while interacting with or observing the device.

For this reason, our project was limited to a 25VAC supply with a maximum of 5A on the output side of the breaker. This constraint was specified by our coordinator and served two primary purposes:

1. User and operator safety: Mains voltages (e.g., 120V or 240V) carry significantly increased risk of injury or fatal shock. According to standard studies, currents as low as 9–30mA can cause involuntary muscle contraction or inability to let go of a conductor. [119] Voltages above 50V AC or DC have been described as carrying significant risk of injury. [123] By limiting our system to 24V, 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 might be handled, inspected, or tested by members of our committee, teaching assistants, and other students, we had to ensure that there was no realistic risk of "getting zapped." All connections used safe wiring practices; insulation was verified, and all exposed conductors were rated for the voltage and current used. We also enforced proper grounding, used protective covers where required, and followed documented wiring and protective-device standards.

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

4.1.2 IEEE Standards

IEEE standards were some of the most important standards when it came to safety in developing this project. Standards used by IEEE enforced strict codes and regulations to maintain the safety of both the developers and the consumers of the product. Furthermore, within the electrical engineering community, IEEE served as one of the benchmarks for electrical engineering development. With more than 486,000 members, IEEE was one of the most useful resources for meeting standards and protocols. The organization held the following principles to maintain its standards: direct participation, due process, broad consensus, balance, transparency, broad openness, coherence, and development dimension. The most important of these were due process, where "Decisions are made with equity and fairness among all participants in a transparent manner and no party dominates the process"; broad consensus, where every viewpoint was considered; and balance, which ensured that no single step was dominated by one individual, but rather every decision was given equal opportunity for all participants to vote upon and assess its correctness. For the purposes of this project, the power and energy section of the IEEE standards and codes was used to assess the safe use of our devices.

4.1.2.1 National Electrical Safety Code

The first standards book used was the IEEE C2-2023, 2023 National Electrical Safety Code (R) (NESC(R)). This book provides safety rules for utility systems such as transformers, switchgear, and batteries. Though this book was intended for use with higher order electrical systems, the project developed acted within the same principle though on a smaller scale. The following are a list of some of the key points associated with the scope of the design:

1. Section 14 – Batteries/Energy Storage: This section was considered to accommodate the fact of backup power and how to incorporate it with the smart breaker appropriately if we needed to use one.
2. Section 19 – Grounding Methods: These are new updated methods for power and communication systems directly relevant to the SABRE smart breaker that uses Wi-Fi technology to communicate directly from the ESP32 micro controller unit to the website that has direct access to information brought by the system.

3. Rule 320B – Conduit Separation: Relevant to communication systems how the wiring between the cables of the antenna and original signal must be separated to avoid noise and distortion when communication occurs.
4. 410A – Arc-Flash/Worker Safety: This involves the risk of using radio frequences that could cause sudden arc flashes or RF exposure could cause health risks to individuals. Though not an immediate threat to our team due to the power constraints of the system, on a larger scale this could be brought up.
5. Units Format: The current 2023 version of the National Electrical Safety Code now uses units and inches-feet-pounds which now need to be converted back to the metric system accordingly.

The focus here was on the codes related to arc-flash protection, grounding methods, and communication protocols. The SABRE smart breaker incorporated Wi-Fi in its communication with the website, and it was required to continuously send information; hence, upholding the smart breaker to these regulations was a necessity if we wanted the system to remain viable at all times. Furthermore, operating at radio frequencies could be quite dangerous at higher voltages; therefore, it was imperative that we followed these regulations to ensure the safety of anyone who used this device.

4.1.3 Standard for Trip Systems for Low-Voltage Circuit Breakers

IEEE C37.17-2022 defined how a trip system inside a low-voltage circuit breaker had to operate, perform, and protect electrical equipment. In essence, this was one of the most important standards incorporated within the SABRE smart breaker system. The standard covered overload protection to protect the device from high-voltage threats, short-circuit protection similar to how conventional breakers operated, but without the mechanical tripping aspect used in traditional breakers like the approach included in our project. Ground-fault protection also had to be implemented if ground could not be found or had been removed in some capacity. Lastly, coordination rules had to be implemented for complex devices, as multiple aspects of the smart breaker needed to operate at the same time; without proper communication, this could not occur. The entire scope of this standard applied to low-voltage circuit breakers operating below 1000V AC and below 1500V DC. The scope specifically stated that breakers falling within this category had to incorporate electronic or electromechanical trip systems.

To classify as a protective system, the device had to fulfill basic protection requirements, and it also had to comply with performance requirements. Clause 5 demonstrated that the functional and performance requirements had to include:

- Overload protection Rules – Defined how a trip system had to respond to overcurrent above a continuous rating but not exceeding the level classified as an immediate fault. The key requirements of overload protection included a Long-Time Pickup Setting, where the breaker had to allow a selectable pickup setting, and the pickup had to remain accurate within defined tolerances. Because the scope of SABRE was an electronic smart breaker, the breaker had to emulate thermal heating behaviors seen in traditional breakers. Lastly, because we used a microcontroller-based breaker, SABRE had to implement a programmable inversetime curve consistent with the timing windows and tolerances defined within this standard.

- Instantaneous Protection – High fault currents had to be handled immediately within a smart breaker. This included having an instantaneous pickup range, no intentional delay—where the maximum response time governed by Clause 6 required that the trip time be no longer than a few milliseconds—accuracy of pickup level, and override prevention, meaning that regardless of whether another trip had occurred within the system, the fault-current protection had to remain active regardless of what was occurring within the system. Lastly, full fault spectrum coverage was required, meaning that the sensor implemented within the system had to be able to detect any changes in current associated with hard faults. Nothing could be incorrectly detected or monitored.
- Ground-fault Protection Functions – This part covers protection against phase-to-ground faults. Key requirements for this clause first included Residual or Zero-Sequence Sensing which means that the sensing method must accurately detect ground-fault current either by measuring residual current through mathematical operations of the vector sum of the phases or the system can also use a dedicated zero-sequence CT. False tripping within the system is not allowed at all, the SABRE project must be immune to: Harmonic distortion, Neutral Currents, and Transient inrush, the rules define that the system must have stable operations at all times. Coordinate Requirements are also specified to ensure that proper coordination between subsystems occurs when high voltage or fault-currents occur, all aspects must operate at stable levels regardless of if a trip were to occur.
- Environmental Performance – Also under Clause 6 environmental factors must be considered. The system must perform correctly when exposed to: Extreme temperatures, Humidity, Vibration, Mechanical shock, and conducted and radiated electromagnetic interference. Proper precautions must be taken to ensure that the smart breaker must perform under extreme environments.
- Reset and Reclose Characteristics – To classify as a properly functioning breaker, the trip system had to reset properly after tripping, prevent reclosure until internal sensors were stabilized, and avoid nuisance tripping after resets or power loss. To achieve this smart behavior, a microcontroller unit had to be used in conjunction with the device to accurately and properly assess the state of the components with which it was operating.
- Power Supply Requirements – The components associated with the electronic trip units had to be powered by either internal current transformers, control power supplies, or auxiliary sources. This was required to protect the tripping mechanism from overloading and failing during extreme scenarios, thereby protecting the structural integrity of the load.
- Display and Indication Requirements – When a trip occurs the trip systems must provide a clear indication on what was the cause of the trip, a status indicator to provide a clear indication that device was tripped, a method to verify settings, and troubleshooting indicators.
- Communication and Data Requirements – Because the SABRE smart breaker includes Wi-Fi in its communication systems, communication rules had to be implemented. First, any communication systems could not interfere with protection

speed, so when communicating with the microcontroller unit, the tripping mechanism had to remain the highest priority. Second, the system had to perform frequent integrity checks to ensure that nothing had degraded or been damaged due to previous faults. Lastly, the communication system had to preserve settings during communication failure to prevent any lost data while the trip was occurring.

To ensure the highest safety standards are met by the SABRE smart breaker, IEEE protocols and standards were used to properly prototype and research into the device. Other standards and rules were used in this research paper, however, IEEE was held to be at the forefront of engineering standards in this system.

4.1.4 IEC 61558 – Transformer Safety

IEC 61558 is an essential safety standard from the International Electrotechnical Commission governing the design and usage of generic transformer architectures. It sets critical metrics for transformer insulation, creepage, clearance distances, and adequate safety testing. It defines how transformers must be constructed, tested and validated under varying conditions, and standardizing the thermal behavior, dielectric strength, and types of overvoltage categories to ensure that transformers can maintain long term operational safety and reliability in electrical applications.

Insulation Requirements

The IEC 61558 standard classifies insulation into several categories based on the system they are integrated in and the effectiveness of said insulation in the given scenario. The different insulation types are as followed:

- Functional Insulation: For operational reliability, ensures that the primary and secondary windings are isolated from one another. Provides little to no user safety protection.
- Basic Insulation: Fundamental level of protection for electric shock between the primary and secondary windings.
- Supplementary Insulation: Additional independent layer of insulation used in tandem in the event that the basic insulation layer fails.
- Reinforced Insulation: Shock protection at the level of supplementary insulation while only requiring a single layer of a thicker, more robust material [109].

Clearance and Creepage Distance Requirements

The IEC 61558 standard defines clearance as the shortest, open-air distance between two conductive points at a specified voltage level. Creepage is defined as the maximum allowed shortest distance on the surface of an insulated material between two conductive traces to prevent arcing. Creepage is important for preventing faults during long-term steady operations, while clearance is intended for providing protection against short-term voltage spikes. Proper clearance within a system is based on air pressure and pollution. Depending on altitude, an additional coefficient will need to be multiplied into the original formula to account for the difference in air pressure. Pollution is classified into four different categories based on the amount and conductivity of said contamination and varies the safe clearance distance accordingly. Creepage is a function of four variables within a given system, that being the maximum RMS voltage, pollution degree, material group, and operating frequency [109].

Thermal and Electrical Safety Requirements

The IEC 61558 standard lays out safety requirements for mechanical, electrical, and thermal variances. The bobbin material, the support structure for the windings to be wrapped around, whether plastic or ceramic, determines the spacing and isolation required to safely manufacture and operate a transformer. The windings themselves also play a factor in the performance and operational safety of the transformer. Insufficient spacing between the windings can lead to arcing between windings, not only leading to core saturation which can damage the transformer but also can lead to a safety hazard for those using it. Proper spacing between windings is also important to ensure adequate heat dissipation and to minimize chances of core saturation. Performance of the magnetic coupling is also a function of the configuration of the windings; improper winding configuration can either lead to poor magnetic coupling, and thus poor performance, or the magnetic coupling can be too much and again lead to core saturation and degradation of the internal insulation material [109].

4.1.1.4 IEC 61558-2-16 – SMPS Transformer Safety

IEC 61558 – 2 - 16 is a safety standard that outlines safety and operating specifications in switch-mode power supplies such as flyback, forward, and resonant isolated power supplies. The standard outlines requirements and tests for switch-mode power supplies and safety descriptions to be implemented in the transformer used for isolation. The standard outlines a lot of the same material present within the generic transformer standards seen in IEC 61558 including insulation, clearance distance, and creeping distance. Isolation standards are divided into the same tiered hierarchy as IEC 61558 but include tests to account for stress on the insulating layers from high-frequency switching introduced by the flyback controller.

Adequate Marking and Labeling of Terminals

The standard outlines that proper markings or labeling that makes proper distinction between the input and output terminals located on the transformer. This should be properly noted physically on the chassis, or within the included data sheets the proper pinout for both primary and secondary windings on the transformer to ensure correct operation when integrated into a larger SMPS circuit [111].

Output Voltage w/ No Load & w/ Applied Load

The output voltage had to be tested under both no-load conditions and with an applied load appropriate for the rated current draw of the SMPS. This was performed with varying primary-side input voltages that remained within the desired range to ensure that the output voltage under no-load conditions maintained proper levels while staying within acceptable deviation limits. With the load applied, it was important to verify that the current drawn by the applied load maintained proper values while operating within the rated range, while also not adversely impacting the output voltage [11].

Insulation

Proper insulation was required with sufficient protection against contact with live elements within the circuit. It defines that hazardous live parts are those that fail to be separated from the transformer with proper insulation and that their voltage exceeds a 35VAC peak or a 60VDC signal [110]. Class I transformers, those that include windings rated for about 70 kV and below, must be separated from these hazardous elements with a minimum of basic insulation. Class II transformers, with windings from 115kV to 765kV must be separated from the elements through reinforced insulation [112].

4.1.2 PCB Design Standards

4.1.2 IPC - 2221

IPC – 2221 standard is a generic design guideline outlining the proper assembly of printed circuit boards through information regarding conductor spacing, trace width, clearance, creepage, material selection, mounting methods, and general layout principles. The guideline established best practices for designing a PCB that is functional, manufacturable, and robust against the environment that it is to be present in.

PCB Conductor Spacing

The IPC – 2221 layouts guidelines regarding safe spacing between conductors based on the peak AC or DC voltage said conductors may produce. As voltage between conductive elements increases, the required spacing between the conductors must be increased to minimize chances of arcing within the PCB to provide safe and robust delivery of electrical signals. The standard provided guidelines for spacing for whether or not the conductive elements are directly exposed or embedded between layers of insulated material. In addition, it provided guidance on the safe clearance of component leads up to 50V (0.13 mm), clearance for conductive mechanical hardware (0.75 mm), and maximum protrusion of mounting hardware for assembling the PCB (6.4 mm) [113].

Table 18: Safe Spacing for Conductors [113]

Peak Voltage Potential Between Conductors	Min. Spacing Internal Conductors	Min. Spacing External Conductors
0 – 15 V	0.05 mm	0.1 mm
16 – 30 V	0.05 mm	0.1 mm
31 – 50 V	0.1 mm	0.6 mm
51 – 100 V	0.1 mm	0.6 mm

101 – 150 V	0.2 mm	0.6 mm
151 – 170 V	0.2 mm	1.25 mm
171 – 250 V	0.2 mm	1.25 mm
251 – 300 V	0.2 mm	1.25 mm
301 – 500	0.25 mm	2.5 mm
> 500 V	0.0025 mm / Volt > 500V	0.005 mm / V > 500V

Conductive Trace Sizing

IPC – 221A outlined that the minimum width and thickness of conductive traces on a PCB is to be primarily determined by the current capacity seen across it. Specifically, it outlined the following equation to be used to determine the safe operating current across the trace:

$$I = k \cdot \Delta T^{0.44} \cdot A^{0.725}$$

Figure 4.1: Safe Spacing for Conductors [113]

Where I is defined as the safe operating current across the trace, K is the constant that is either set as 0.048 or 0.024 depending on if the trace is external or internal respectively. ΔT is defined as the rise in temperature above ambient conditions measure in Celsius, and A is the cross-sectional area of the trace measure in mm. Using this equation, it can be determined the safe current draw across a trace given the sizing of the conductive trace [113].

4.1.3 Wired Communication Protocols

4.1.3.1 UART Protocol

The UART wired commutation protocol is a non-standardized asynchronous communication protocol originally derived from RS-232, which standardizes a serial communication interface between a host and peripheral device [114]. The UART protocol is used for converting parallel data into a full-duplex asynchronous serial communication between two devices; each device is equipped with dedicated lines for transmitting and receiving data. The asynchronous nature of the protocol implies that the data transfer is not facilitated by a dedicated clock pin between the two devices. Instead, the two communication devices are both preassigned a BAUD rate that specifies to the two of them the expected rate at which data will be transmitted. Each transmitted string of data is appended with a start and stop bit to signal to the receiver when to begin and end reading from its receiver line. In addition, it is common for both devices to be configured to expect a parity bit to be appended to the end of the data packet as well to ensure correct transmission of the given data [115]. UART is widely utilized in programming firmware due to its simple implementation, low pin count, and straightforward serial communication between devices. Consumer microcontrollers are designed to have an onboard ROM bootloader that listens to the UART by default before any other subsystem is powered on, making it an ideal candidate for flashing firmware onto a device from a separate source.

4.1.3.2 USB Protocol

The USB protocol is an asynchronous serial communication protocol that standardizes structured data transfer and power delivery across a master-slave architecture. Originally design to normalize a common communication interface between a host and peripheral devices, the USB standard defines the physical interface, voltage characteristics, device tally, transfer speeds, and power delivery for a variety of unique USB types. The protocol defines the host and peripheral devices aligned in a tree hierarchy that assigns priority based on when the peripheral was plugged in while still allowing for fast communication with devices near the bottom of the priority stack. The host itself contains two components for initiating transmission. The first is the host controller, which is integrated with firmware that oversees all actions taken over the bus, such as recognizing new devices, management of transferred data, and power delivery [116]. The second is the root hub, which provides an initial point of contact between the host and the first peripheral recognized by the controller. Each subsequent device starts at this root hub and is distributed down the tree structure. The standard characterizes devices on a 7-bit address allowing for a total of 127 devices to communicate with the host independently [116][117]. Over the years, the standard has defined a variety of different physical interfaces, with different pinouts depending on the data transfer capability of the connector, but the general architecture of data transmission remains similar amongst all of them. Data is transmitted through a process called differential signaling; using two lines labeled D+ and D- respectively. The difference in voltage between these two lines, whether positive or negative, is what determines the logical signal that is read for the given bit. This is an improvement from that of just using a signal transmission line, that measures voltage difference relative to ground signal, as it eliminates concerns of incorrect data introduced by electromagnetic interference or ground noise [118].

4.1.4 Wireless Communication Protocols

4.1.4.1 IEEE 802.11x

IEEE 802.11x is a family of standards defining the necessary components that make up the architecture for implementing wireless local area networks that allow devices to communicate without being physically interlinked. The original standard set communication across a 2.4 GHz radio frequency band with speeds up to 2 Mbps and has iteratively improved upon this since with later renewals of the standard to include an additional operating frequency of 5 GHz with network speeds up to 1300 Mbps. The protocol is facilitated by a Wireless Access Point that provides the RF interface for devices to communicate wirelessly with, and with modern implementations, typically offer routing to external networks that make up the internet. Devices communicate locally amongst each other through their unique MAC addresses, a 48-bit identifier that acts as a name for determining which device on the network is doing what.

4.2 Design Constraints

As a smart circuit breaker system is designed to protect the well-being of the user and the area that the breaker encompasses, the design constraints of the SABRE Smart Breaker system had to be strict and precise. Conventional breakers do not incorporate complex electrical wiring or coding algorithms in their designs; in fact, their designs are rather simple, hence the number of limitations that can be enforced upon them are very few. Due to the design of the SABRE Smart Breaker, this number increases the more we have to introduce a complex subsystem such as the use of transformers, coding algorithms, communication systems, tripping technology, and more. Furthermore, due to the project being designed as a senior design project, there are some constraints that the university has enforced upon the research team as well. One of which being the time constraints being split into roughly nine months or sustainability constraints. Though the intellectual property of the smart breaker is held by us students, the university has control of the access of the website and will eventually have to send it to another network, though this will be far into the future. Other constraints discovered were by our own agreement and will be discussed further.

4.2.1 Personal Constraints

Due to this being a 4-person research focused project there were some apparent constraints on everyone having their work ready by a certain deadline, especially due to this research having to be conducted as if it were another class. Other classes within the semester had to have been completed as well so this research was not our only focus throughout the semester. For some of the researchers within our group we took as few as twelve credits within the semester though this does not also account for a part-time job that some of us had to endure alongside being a full-time student. Others had to take as much as 15-17 credits with academically rigorous coursework causing us to spend hours at a time on this courseload. In terms of academic rigor, this senior year is one of the most difficult.

In addition to having coursework with this research paper, employment had to be considered causing the researchers to have to work around specific deadlines to ensure the paper was not only completed but completed with the standards of an academic research paper. Applications had to be sent out, and interviews had to be conducted with potential employers; career fairs had to be attended, and trips had to be taken to ensure that employment after graduation could be fulfilled. Though this research project is a helpful steppingstone towards reaching our goal of full-time employment, it cannot be the saving grace, as there are certain things that could happen such as what if the project fails in the end? What if the project is not up to the standards of the companies that will be viewing our project come presentation time? What if our project is not done on time? All these aspects were considered in the constraints of the individual, and we had to work with each other in this respect.

Team meetings were conducted every Friday with the advisor of the project Dr. Qun Zhou Sun, which allowed us to inform her of any new updates that occurred within the week.

Due to personal constraints, some individuals had to miss these meetings and had to inform other members of the group of what they accomplished during the week while they are absent. Group coordination was key, it didn't matter that an individual was missing work, what mattered was that someone else was there to pick up where they had left off. Teamwork was the major aspect that allowed us to overcome these personal constraints, without the team we would have surely failed.

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 SABRE Smart Breaker 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, was 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 fact helped ensure that our design remains feasible within the scope of our academic environment while maintaining safety and functionality standards.

One strong issue with the manufacturing of this device became apparent early on when research began on the components available that pertained to the smart breaker. When research began the intention was to design the smart breaker to actual scale at 120V and 20 A, however, due to safety regulations within the university we were scaled down to 25 V at 5A, which became more manageable but harder to ensure proper scaling back up to proper residential voltages were possible as this was a company-funded project, and was required to work seamlessly with residential buildings. In this respect, devices that could change easily need to be incorporated into our design. For example, the transformer that begins at the very start of our smart breaker allowing the high voltage of a simulated residential building to enter our microcontroller unit without damaging the processor needed to be scaled down to an appropriate level, this became a constraint of ours firstly because the transformer needed to scale down this high voltage effectively enough without becoming damaged and secondly, it needed to scale down efficiently enough so that the further scaled down signal could reach the microcontroller unit could effectively analyze the voltage and determine when the breaker should trip.

4.2.2.2 Sustainability

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

A central sustainability decision for SABRE was to favor resettable protection over sacrificial protection elements. Because the device was conceived as a circuit breaker, not a disposable protective device, we intentionally avoided using single-use fuses as the primary overcurrent protection. Fuses required replacement after a trip, generated consumable waste over time, and reduced user convenience; these outcomes conflicted with SABRE’s goals of long life, low maintenance, and ease of use. Instead, SABRE was 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 reduced electronic waste and supported a more user-friendly product.

Energy consumption was also considered. SABRE operated as an AC branch circuit device (prototype scale: 25VAC, up to 5A) and was optimized so that the control and sensing electronics drew minimal standby power. Components and regulators were 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.

Component longevity and repairability contribute to sustainability. Key modules (control board, sensors, communication module, and switching stage) were 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.

4.2.2.3 Political Constraints

An unexpected constraint on the research project was that of the political constraints. Firstly, because our project is being sponsored by an independent company known as Grid Interactive Things, it was imperative that we kept an up-to-date log of everything that we have accomplished every time we met. Though, during the time of the research paper, we did not meet with the sponsors in person, we did meet with the advisor of the project and kept in contact with her. She did in fact have contact with the sponsors of the project and kept them up on all of the recent information that had been going on. These meetings serves as a groundwork to keep everything up to standard so long as we were sponsored under this specific company.

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 across many domains, handling different topics such as coding, writing, and very basic mathematics extremely well. This makes ChatGPT usable for everyday tasks and acquiring answers to 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 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 Switching/relay technology section of this project.

5.4 Case Study 4

Refer to Appendix [E.4] for information regarding this case study. This was an example of ChatGPT providing valuable and concise information in response to a given prompt sequence. Current measurement was initially to be carried out through the use of a current transformer over a shunt resistor into the microcontroller's onboard ADC. However, there came a couple of reasons why this seemed to be a less than adequate approach. For one, current transformers fail to measure a direct current due to the lack of variance in the magnetic field produced by the current. While for a final implementation this would not be an issue, as the intended current to measured would be an alternating one, the use of it introduced challenges regarding the prototyping stage, an any current measured would have to be supplied off the back of the simulation transformer. This alone would not be a severe issue, but it would introduce inconveniences of having to perform initial testing forced at a higher voltage level than would be desired, removing the ability to utilize the output of a microcontroller GPIO pin or even just using a 9V battery. In addition, the current transformer would require a shunt resistor to be placed between the output of the transformer and the input to the ADC to get a usable measurement. A microcontroller's ADC pins do the measurements with respect to voltages, not current, so the calculated current would have to be a result of the voltage drop across the resistor. It was determined that there was likely a better method of providing current measurements to the microcontroller, so ChatGPT was consulted on some methods to perform minimally invasive, galvanically isolated current measurements. When prompted, ChatGPT was able to compile a list of a number of methods to perform current measurements in the context of an embedded project, with comparisons between the pros and cons of each implementation. This case study showed a great example of when ChatGPT can be a useful tool to utilize. With only a couple of prompts, it was able to compile a useful list of current measurement implementations that eventually led to a selection to be used within the SABRE smart breaker.

5.5 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

This chapter provides a detailed examination of the major subsystems that make up the SABRE Smart Breaker. Each subsection expands on the design principles, hardware selection, and integration considerations required to create a functional and reliable smart breaker prototype capable of sensing, reacting, and controlling electrical loads safely.

6.1 Overview of Hardware Subsystems

The SABRE smart breaker design was built upon four fundamental, interconnected hardware subsystems that worked in conjunction to achieve safe, intelligent load control all of which spread across 4 separate PCBs respectively. These included the Power Supply, Load Monitoring and Management, Switching and Breaking Elements, and the Programming Interface. All systems were centrally controlled and coordinated by the ESP32 microcontroller, which processed sensor inputs and drove control outputs.

The power supply subsystem was responsible for safely and efficiently generating the required DC voltages for the microcontroller and auxiliary components from the AC mains signal that also powered the load. This was achieved through a multi-stage process that emphasized safety and voltage stability. First, the power supply subsystem performed initial conversion and isolation. The AC mains signal was first processed through a full-bridge rectifier and then fed into a switching regulator, which regulated the input to maintain a constant 5 VDC output. This 5V rail was stabilized using output filtering components (capacitors and resistors) and was protected by Zener diodes that served as over-voltage clamps and snubbers, preventing high-frequency switching spikes from damaging the downstream circuitry. The last stage was the final step-down. The ESP32 and its I/O components required a 3.3V operating voltage. The 5V output from the switching circuit was passed through a linear regulator to provide the final regulated 3.3V supply. Because the voltage drop from 5V to 3.3V was small, the heat dissipation was negligible, allowing for the use of a simple and less complex linear regulator over a second switching regulator.

For load monitoring and management, this subsystem provided the real-time data necessary for the smart breaker's intelligence. It involved sensing the load current and conditioning the signal for the ESP32's Analog-to-Digital Converter (ADC). The core component for current sensing was the ACS712, which was connected in series with the load. It produced a linear voltage output directly proportional to the AC current flowing through the load branch. The sensor's conditioned analog output was fed into an ADC pin on the ESP32 (specifically GPIO34, configured for ADC1 use, as ADC2 was disabled during Wi-Fi operation). The ESP32 digitized this signal, enabling the microcontroller to monitor the current load continuously and make immediate decisions regarding the safety of the operating conditions.

The switching and breaking subsystem acted as the actuator. It was responsible for physically interrupting the current flow to the load based on commands from the ESP32. A TLP3547 solid-state relay (SSR) was used to switch the AC line. This was a photo relay that provided galvanic isolation between the low-voltage ESP32 control signal and the high-voltage AC load through an optical barrier and was crucial for protecting the control circuitry. The SSR used back-to-back MOSFETs to handle bidirectional AC current flow (up to 60Vrms and 5A), offering a silent, fast, and durable alternative to mechanical relays. The ESP32 continuously monitored the current data. If the measured current exceeded a safety threshold, the microcontroller disabled the control signal to the SSR, causing the relay to open the circuit and safely cut power to the load, thereby simulating a circuit breaker trip. A manual switch was included on the chassis to provide the user with the conventional ability to physically enable or disable power flow, mirroring the functionality of a standard breaker switch.

The final subsystem is the microcontroller and its associated programming interface, which facilitates communication between a host computer and the ESP32 for firmware upload and debugging. This interface is built around a USB-to-UART Bridge (CP2102N) that translates the computer's USB protocol into the UART serial signals (TXD/RXD) required by the microcontroller. This block also includes robust Transient Voltage Suppression (TVS) diodes on the USB data lines (USB_DP/USB_DN) and a Schottky diode on the VBUS line to ensure electrical protection and prevent back-feeding of power.

The SABRE Smart Breaker is realized by these. The Power Supply converts the high-voltage AC source into the stable 3.3VDC required for the control plane, utilizing a galvanically isolated switching regulator for simplicity. The Load Monitoring subsystem, centered on the Hall-Effect Sensor, provides accurate, conditioned current data which is fed directly into the ESP32's ADC. The ESP 32 analyzes this data in real-time and uses the Switching subsystem (the TLP3547 Solid-State Relay) to electronically interrupt the load current if a safety threshold is exceeded. Finally, the Programming interface subsystem ensures the system can be easily updated and debugged via a protected USB-to-UART link which in turn also communicates with the LCD driver and display. This comprehensive architecture allows the ESP32 to function as an intelligent controller, continuously sensing, deciding, and acting to ensure safe operating conditions for the supplied load, thus defining the core functionality of the smart breaker.

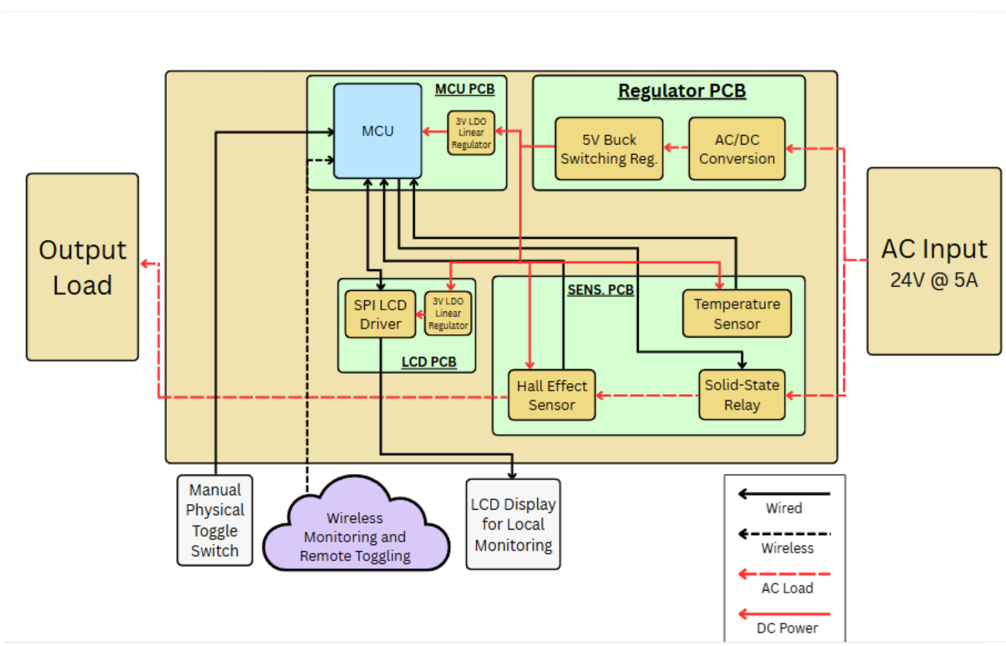

Figure 6.1: Hardware Block Diagram by Authors

6.2 Power Supply and Delivery

The ESP32 and each subsequent auxiliary component were powered from the same initial power source as the load applied across the breaker. Regardless of whether current was drawn across the actual load branch, the simulated mains power source was stepped down and its polarity was converted using a full-bridge rectifier fed into a switching buck regulator. The circuit itself was simple in design, yet its components had to be researched and selected to withstand the large power flowing through the line. For example, the Schottky diodes shown on the left side were able to withstand at least 60V, which was more than double the expected line voltage. Furthermore, the regulating capacitor had a value of 4700 µF, and its purpose was to smooth out the signal before entering the LM2576 buck regulator.

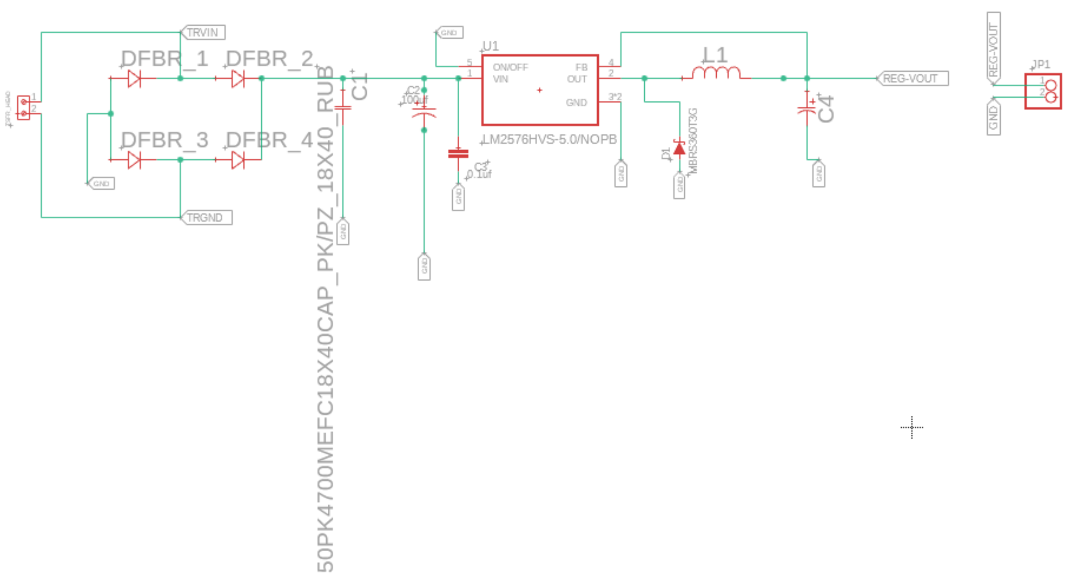

Figure 6.2: Rectifier and Switching Buck Regulator by Authors

6.3 Load Monitoring and Management

Effective load monitoring was primarily the responsibility of the ACS712 Hall-effect sensor, providing a linear voltage output proportional to the current being drawn from the aforementioned load. By default, the ACS712 provided a proportional voltage signal output resolution between 66–185 mV/A. The output voltage signal from this subsystem was 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 measured value.

The Hall-effect sensor and temperature sensor were also integrated in conjunction with the solid-state relay, as seen in Fig. 6.3. Precise monitoring from the sensors and tripping from the relay was achieved through this topology. In addition, the microcontroller was connected to these components to deliver precise sensor data readings. The circuit for providing constant circuit measurements to the microcontroller can be seen below.

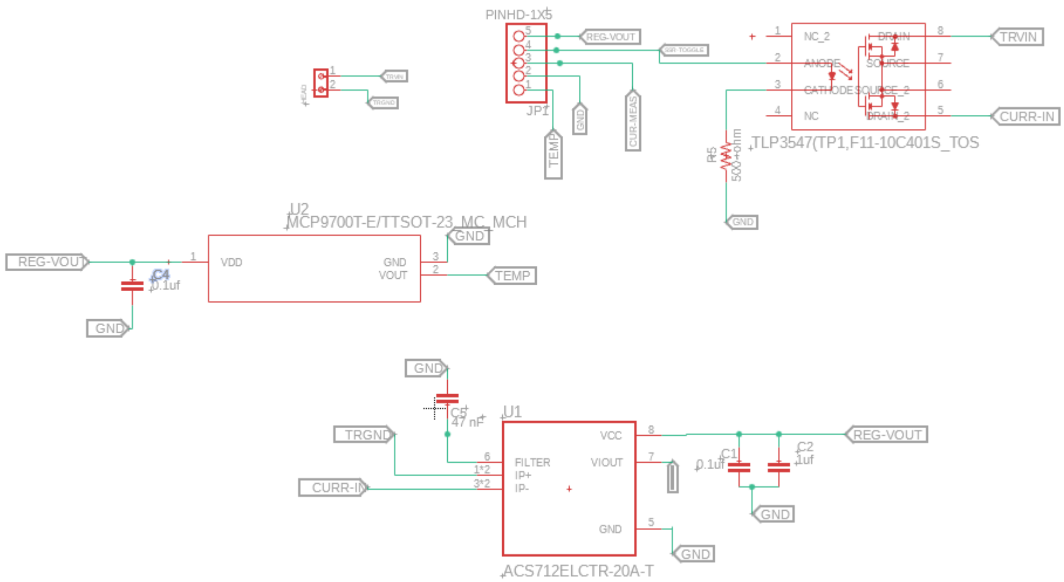

Figure 6.3: Current Monitoring and Tripping by Authors

6.4 Switching and Breaking

The switching from the main supply to the attached load was facilitated by the ESP32 microcontroller and performed by a TLP3547 solid-state relay (SSR). The ESP32 was programmed to continuously monitor the output of a Hall-effect current sensor and temperature sensor through its integrated ADC. When the measured current exceeded a defined safety threshold, the microcontroller disabled the control signal driving the SSR, causing it to open the circuit and stop current flow to the connected load.

The TLP3547 was a photo relay-type SSR, meaning it used an optically isolated input stage where an internal LED activated a photo-sensitive MOSFET array on the output side. This optical coupling provided 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 employed back-to-back MOSFETs with additional Zener diodes to allow bidirectional current flow, enabling it to handle AC loads up to 60Vrms at 5A. This made it particularly suitable for switching low-voltage AC signals, such as those found in this 25VAC design, while providing low on-resistance and silent, bounce-free operation. Because it had no moving parts, the photo relay offered excellent durability, fast response times, and high reliability under repetitive switching conditions.

Additionally, a physical manual switch was mounted on the chassis to provide the same user functionality as a conventional circuit breaker, allowing the operator to manually enable or disable current flow to the load. The circuit for implementing the switching mechanism can be seen below.

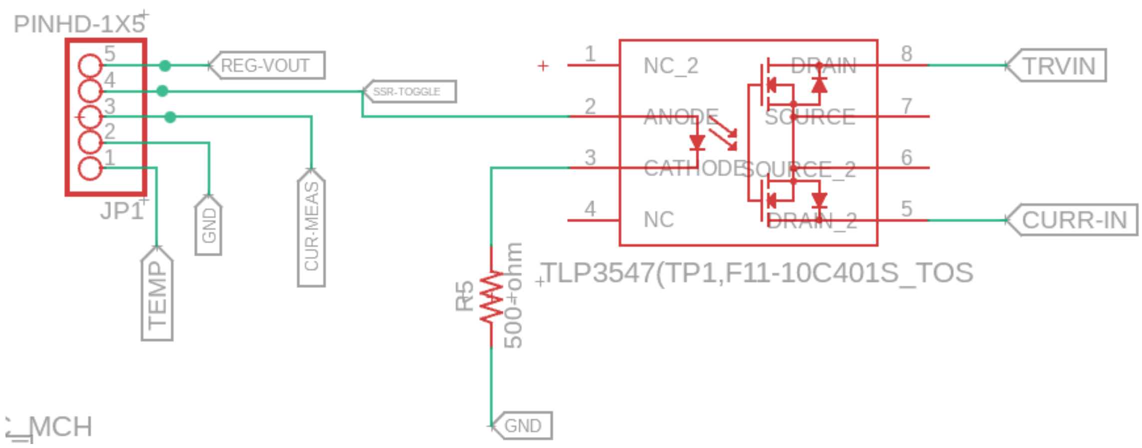

Figure 6.4: Current Tripping Subsystem by Authors

6.5 Full Logic Schematic

Each of the aforementioned subsystems interacted with the ESP32 to perform their respective operations. The switching buck regulator for the primary step-down only lowered the voltage to a 5V signal, which was too high for the onboard power pin on the ESP32. As a result, a 3.3V linear regulator was placed between the power pin and the buck regulator output to step down and maintain an appropriate voltage at which the microcontroller could function. Concerns arose initially about using a linear regulator to step down the relatively high-voltage AC signal to 5V due to the heat dissipation caused by the inherent inefficiency of linear regulators. However, the minor shift from the 5V signal down to 3.3V was a small enough voltage drop that any heat dissipated was negligible, offering an appropriate method for maintaining a 3.3V signal without having to create a second switching buck regulator. This 3.3V signal was used for powering the microcontroller, for providing a HIGH signal for the manual switch for the ESP32 to read when the switch was engaged and to shut off the signal controlling the TLP3547 SSR, and for the onboard programming interface circuit used to convert USB to UART. The output from the current measuring subsystem was fed into GPIO34 on the ESP32, a pin that could be configured for use with onboard ADC1, which was the required ADC to use, as ADC2 was disabled during Wi-Fi operations.

Connected in series were the microcontroller, ACS712 Hall-effect sensor, and the TLP3547 solid-state relay. When working together, the system operated as follows: First, the load signal was sent from the generator unaltered through the solid-state relay, almost acting as if it were a transistor. Two outputs were present at the solid-state relay. One output flowed to an LED indicator; if working as intended, the LED emitted a constant light not dependent on the voltage applied to it. The second output was directed to the Hall-effect sensor, which measured the current of the load signal, and its trace also interfaced with a temperature sensor. The sensors were powered by the load signal itself once it had been properly stepped down via a step-down transformer and buck regulator. In this method, the signal could be properly analyzed by the microcontroller, ensuring accurate decisions were made regarding the operation of the solid-state relay.

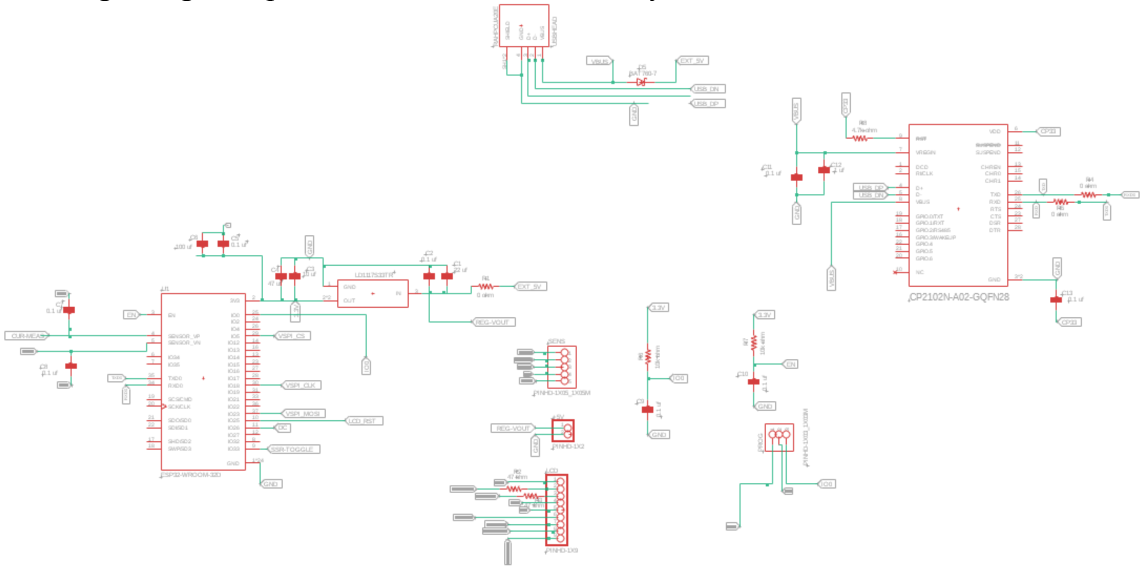

Figure 6.5: Full Logic Side Schematic by Authors

6.6 Programming Interface

The primary function of the programming interface was to bridge the communication gap between a personal computer and the microcontroller. The PC transmitted the compiled program code using the Universal Serial Bus protocol. This digital information entered the system via the USB Header, which, as was discussed, protected the data lines (USB_DP and USB_DN) from voltage spikes; however, the ESP32's onboard serial interface expected data in the Universal Asynchronous Receiver-Transmitter (UART) format. The CP2102N (U2) USB-to-UART bridge component was specifically included to handle this translation. It accepted the USB data packets and converted them into a sequential stream of serial data, which was then sent directly over the TXD (Transmit) and RXD (Receive) lines to the ESP32. This conversion allowed the computer to seamlessly upload the program code, or communicate with the microcontroller for debugging, using its native serial protocol.

A key feature for flashing any ESP32 was the ability to place it into programming mode (or bootloader mode). The circuit implemented two methods for controlling the two critical pins that determined the device's start-up behavior: the Enable (EN)/Reset pin and the GPIO0 (IO0/strapping pin).

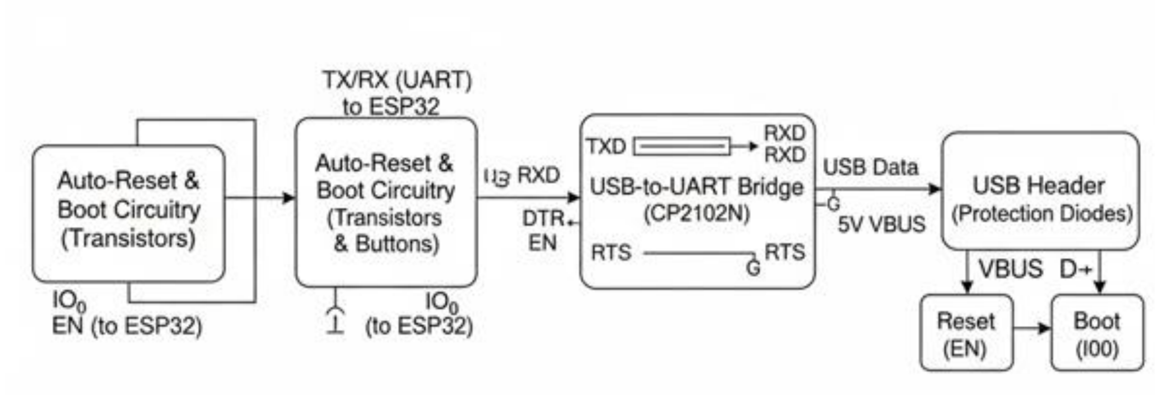

Figure 6.6: Programming Interface Block Diagram

6.6.1 USB Header

Figure 6.5 is the entry point primarily focused on signal integrity. The circuit uses a Schottky diode (D1) on the VBUS line (5 V from the USB cable) to prevent back-feeding of power. This ensures that if the system is powered by an external source (like a buck regulator), the power doesn't flow back into the PC or the USB host, isolating the power rails.

The heart of the communication link is CP2102N USB-to-UART Bridge (U2). The VBUS, USB_DP, and USB_DN signals from the protected header connect directly to this chip. Its fundamental role is to translate the differential USB protocol into the standard serial UART signals required by the microcontroller: Transmit Data (TXD) and Receive Data (RXD). Beyond data, the CP2102N also generates critical handshaking/control signals: Data Terminal Ready (DTR) and Request to Send (RTS). While these lines traditionally control data flow, in microcontroller flashing circuits, they are repurposed to automate the process of entering the bootloader. Various passive components, including pull-up and pull-down resistors (R6 and R7) and decoupling capacitors (C11 - C13) support the chip's operation, ensuring stable power and correct signaling conditions.

The final stage uses the control signals from the CP2102N to manage the microcontroller's boot state. For the ESP32 to enter its programming mode (the bootloader) the EN pin must be pulled HIGH, then LOW (reset), and then HIGH again, while the IO0 pin is held LOW during the reset. This entire chain allows for a seamless, software-drive update and debugging experience over the single USB cable.

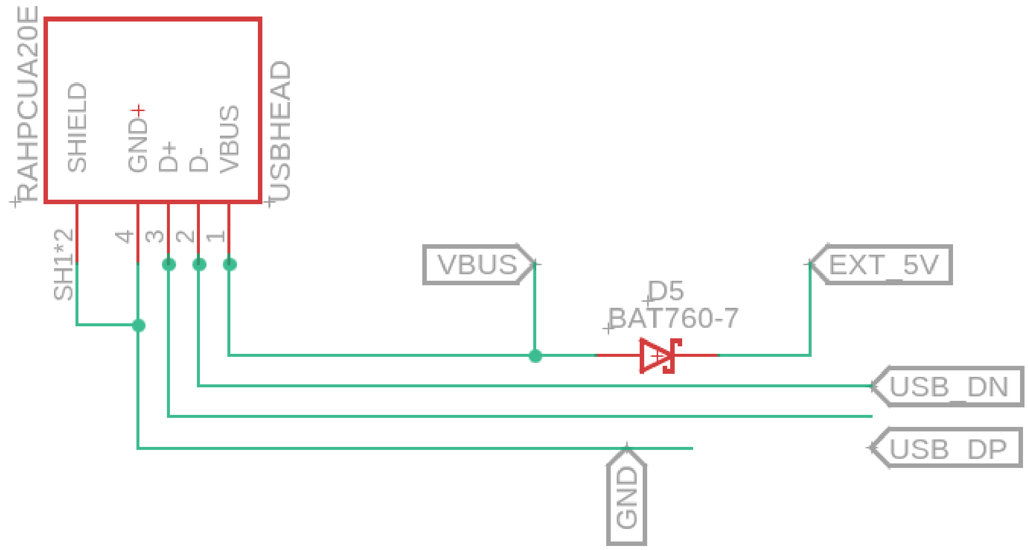

Figure 6.7: USB Header Schematic by Authors

6.6.2 UART Bridge

The UART bridge is the link between the ESP32's serial interface and the USB port of the host computer. In this design, the CP2102N-A01-GQFN28 serves as the USB-to-UART controller, which is the same device recommended in ESPRESSIFs' official hardware design datasheet for USB-based programming interfaces. The D+ and D- lines 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, specifically into pin 4 (D+) and pin 5(D-). These differential data signals are used by the controller to receive USB packets from the host PC. After processing the USB transactions, the CP2102N outputs asynchronous serial data through its TXD (pin 25) and RXD (pin 26), which are cross connected to the ESP32's RX and TX pins respectively. This configuration allows bidirectional transfer of programming data, serial debug logs, and any user-defined UART communication between the ESP32 and the computer. The controller takes two voltage sources for both powering and setting up a reference voltage for the logic signals to use. The primary supply, VBUS, comes from the 5 V rail of the USB cable and powers the internal USB transceiver and regulator. A secondary 3.3 V reference is provided to the CP2102N's VDD pin (pin 6), which defines the logic-level voltage for the TXD, RXD, RTS, and DTR signals. This ensures that all UART signals are safely level-shifted to 3.3 V, protecting the ESP32 from over-voltage damage while maintaining full compatibility with it's I/O specifications. The full CP2102N UART bridge schematic, include USB data routing, voltage conditioning components, pull-downs, and logic-level reference pins are shown below.

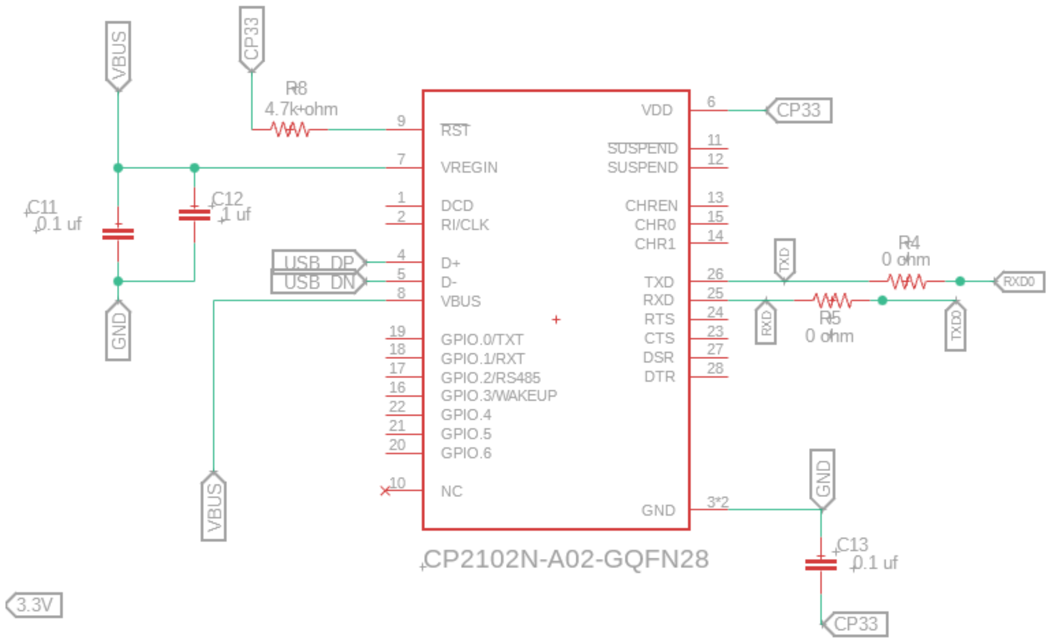

Figure 6.8: UART Bridge Controller Schematic by Authors

6.6.3 Automatic Programming Interface

To streamline firmware flashing and system debugging, the design implements an automatic programming interface driven by the CP2102N USB-to-UART controller. This circuit manages the two ESP32 strapping pins EN (CHIP_EN) and GPIO (BOOT) which determine whether the microcontroller boots normally or enters its serial bootloader. En allows for reset for control and GPIO0 allows for boot mode control. This topology allows the CP2102N to momentarily pull these pins LOW in a controlled sequence whenever the IDE initiates a firmware upload. This mechanism eliminates the need for a manual reset/boot sequence every time code is uploaded, mimicking the behavior used on official ESPRESSIF development boards. In terms of sequence:

In addition to the automated mechanism, the design includes a pull-up resistor circuit shown in figure 6.8. Each port is paired with a 0.1 µF capacitor (C9 and C10) to smoothen the signal and generate a clean falling-edge pulse. Together they provide a robust, dual-method boot control interface for the ESP32.

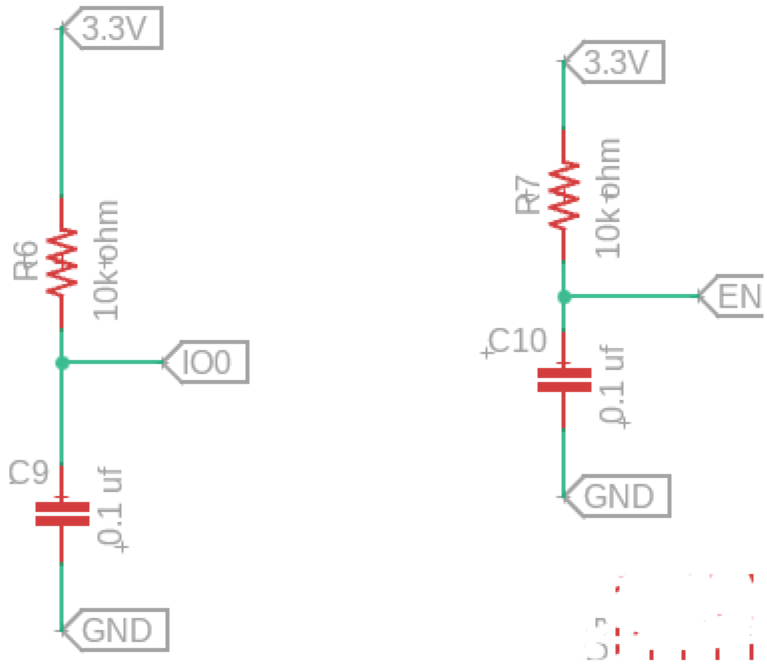

Figure 6.9: Pull-up Resistors Schematic by Authors

6.7 Protection Stage Integration

6.7.1 Purpose of Protective Elements

To safeguard both users and sensitive electronics, SABRE incorporated multiple protection mechanisms that worked cooperatively. While traditional household breakers relied primarily on thermal–magnetic mechanisms that responded only after the current had risen above safe levels, SABRE introduced an advanced electronic protection architecture capable of reacting before a fault became dangerous. This layered approach significantly increased safety and reliability, ensuring that faults were detected, analyzed, and mitigated faster than in conventional mechanical breakers.

The first layer of protection was the sensing system, which continuously monitored the AC waveform in real time. Rather than waiting for heating effects or large current surges, the system digitized the current signal, applied filtering techniques, and calculated key parameters such as RMS current and waveform symmetry. This early monitoring allowed SABRE to identify abnormal conditions, including sudden spikes, sustained overloads, or erratic behavior, at the moment they began. By catching these changes in the waveform rather than relying on slow physical mechanisms, SABRE prevented faults from propagating into the solid-state switching stage.

A second layer of protection was embedded in the decision-making logic implemented on the microcontroller. Using defined thresholds and time-overcurrent logic similar to what was found in professional protective relays, the controller interpreted the sensor data and determined whether the behavior represented a real hazard. This software-based protection provided flexibility, allowing the breaker to distinguish between harmless transient events (such as inrush currents) and genuine dangerous faults. The microcontroller could also enforce more sophisticated trip curves than a mechanical breaker, improving selectivity and reducing unnecessary interruptions.

The third layer of protection centered on the solid-state switch safeguard, which ensured that the semiconductor device, whether MOSFET, TRIAC, or similar AC control element, never operated outside its safe limits. Because solid-state devices could be sensitive to high current or voltage stress, SABRE included fast-acting protection that disconnected the device well before its rated boundaries were exceeded. Current limiting, zero-cross switching principles, and rapid cutoff helped prevent thermal stress that could otherwise degrade or destroy the electronic components. This electronic protection effectively served as a pre-emptive layer that shielded the switching stage from harmful conditions.

Additional safety was provided through hardware redundancy and failsafe behavior. If the microcontroller experienced unexpected failures such as a watchdog timeout or loss of power, the system was designed to default to an open (safe) state. Likewise, surge-protection elements, filtering capacitors, and isolation strategies were incorporated to prevent high-frequency noise, transients, or voltage spikes from reaching critical subsystems. This ensured that SABRE remained reliable even under adverse electrical conditions that commonly occurred in AC environments.

Finally, the system included a user-oriented protection layer, where indicators, reset mechanisms, and clear feedback reinforced safe operation. Users could visibly detect when a fault had occurred, understand the status of the breaker, and restore service only after conditions had returned to normal. This enhanced usability without compromising safety, something that traditional breakers could not provide with the same clarity.

By combining these multiple layers—advanced sensing, intelligent software logic, semiconductor protection, hardware fail-safe behavior, and user-level safeguards—SABRE moved beyond the limitations of traditional thermal-magnetic breakers. This integrated protection architecture not only provided rapid and precise fault response but also extended the lifespan of the device and ensured a safer, more reliable simulation of residential AC branch-circuit behavior.

6.7.2 Metal Oxide Varistor (MOV) Integration

The MOV was mounted at the input of the prototype to clamp high-voltage spikes caused by inductive loads or switching events. Even in low-voltage systems, transient spikes could travel through the AC transformer or be generated internally by rapid MOSFET switching.

At the AC input of SABRE, the protective stage formed the first layer of electrical defense. A Metal Oxide Varistor (MOV) clamped transient overvoltage and suppressed fast spikes, preventing these disturbances from reaching sensitive electronics. Even at a scaled 24V AC prototype level, inductive loads, transformer irregularities, or switching events could generate harmful surges, and the MOV effectively absorbed these disturbances. A fuse served as the final, sacrificial safety element in the unlikely case of catastrophic failure.

6.8 Wiring, Connections, and Physical Layout

Physical wiring and connection techniques directly influenced the safety and performance of the prototype. Copper conductors were used due to their high conductivity, mechanical reliability, and consistent behavior in low-voltage circuits. Proper insulation, cable strain relief, and routing practices ensured stable operation during prolonged testing. The branch-circuit layout mirrored that of full-scale residential wiring: AC input, followed by protective devices, solid-state switching, sensing stages, and ultimately the output load. This structured approach not only enhanced safety and clarity but also maintained alignment with industry wiring conventions.

6.9 Thermal Management and Heat Dissipation

Thermal performance played a critical role in the reliability of AC protection devices. In the SABRE design, all components that interacted with real-world AC loads current sensors, MOSFETs or TRIACs, relays, and microcontrollers generated heat during operation. Even though this project used simulated AC loads rather than full high-current residential currents, the circuit had to consider heat accumulation inside confined enclosures. Without proper airflow or heat-spreading strategies, component temperature drift could alter sensing accuracy or reduce component lifespan. To address this, the design integrated components with low on-resistance and efficient switching characteristics, minimizing thermal losses. Additionally, enclosure ventilation, copper pours on the PCB, and derating strategies were considered to increase system robustness. By planning for thermal limits even at the prototype stage, SABRE remained aligned with industry practices for long-term safety and performance.

6.10 Scalability and Future Expansion

Although this prototype targeted a single branch circuit, the architecture was intentionally designed with scalability in mind. Future iterations of SABRE could monitor multiple AC lines, integrate wireless communication, or even interact with home energy-management systems. The modular PCB layout and microcontroller-based decision engine made it easy to add new features, such as arc-fault detection, ground-fault sensing, or real-time load profiling. By planning for scalability, the team positioned SABRE as not only a standalone prototype but also a foundation for more advanced smart-circuit-breaker systems. This forward-looking perspective demonstrated engineering foresight and underscored the long-term potential of the project.

Chapter 7: Software Design

7.1 Overview of Software Subsystems

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

7.2 Embedded Software Design

The onboard embedded systems had 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 responsibilities of the embedded software were 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 was 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 is prompted to connect the device to the local network. This same process is 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 a change 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 generates a JWT authentication token signed with the respective user ID and device ID. This token is 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 contains 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 had been completed, the ESP32 was placed into its operating mode and immediately supplied the TLP3547 SSR with the required control signal to begin conducting current toward the supply load. At the same time, the microcontroller began monitoring the relevant data through the onboard ADC provided by the ACS712 Hall-effect sensor. The data supplied from the Hall-effect sensor was a shift from the initial reported voltage to one proportional to the current measured across the terminals. Since the current being measured was alternating current, the reported output voltage swung in both directions around the initial midpoint. As a result, the program was needed to sample this swing over a set period and compute the RMS voltage based on the constant variation in order to compute an RMS current through the sensor. Doing this produced a computed alternating current matching what would be measured using a DMM.

o achieve precise RMS current calculations, it was essential to find a balance between the sampling count and sampling frequency during the measuring phase. This balance sought to perform calculations that were both quick and accurate while also not occupying the processor for too long so that it could manage its other tasks. The duration of the sampling phase was a function of both the sampling frequency and the number of samples collected. Increasing the number of samples taken allowed for a more accurate measurement across multiple cycles but came at the cost of extending the time spent within the sampling phase. Conversely, increasing the sampling frequency allowed for taking more samples across a single cycle, but came at the cost of not sampling subsequent cycles if the sample count was fixed. A series of experimental assessments were conducted to optimize both speed and accuracy. The first decision was to find an appropriate sampling frequency, and after trialing a range of different frequencies, it was determined that 10kHz was an appropriate sampling rate, performing a measurement every 100 microseconds. With the frequency determined, the sample count was evaluated across a range of values that were scaled in relation to the number of cycles desired to be captured. From a 60Hz waveform sampled at 10kHz, a single captured cycle required approximately 170 samples, while two cycles required about 335 samples, adding roughly 17ms for each additional cycle. After comparing the ADC's reported measurements with those from a DMM, a sample count of 500 was selected to effectively capture three full cycles during the sampling phase.

If the computed RMS current exceeded that of a set threshold, the ESP32 immediately set the appropriate GPIO pin to LOW, cutting off power to the internal LED within the TLP3547 SSR, and thus breaking the conductive path for the current and shutting off power to the applied load.

While this local, physical control was occurring, at the same time the ESP32 facilitated wireless communication with the Node.js server through POST requests to send the monitored data in real time to a user interface for monitoring. In addition, the ESP32 opened a WebSocket interface to send and receive real-time data from the client's dashboard to toggle the functionality of the TLP3547 SSR remotely.

7.3 Full Stack Software Design

7.3.1 Communication from Local Clients to Backend

The backend was hosted from a Node.js server using Express.js for easy implementation of routing REST API requests. An API endpoint was set up to receive incoming POST requests coming from individual ESP32s within discrete SABRE circuit breakers. Each device's operating loop constantly posted current information to the backend roughly every 1000 ms. This endpoint was 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 was viewable only by that user. In addition to that, this endpoint was also tasked with calling an auxiliary function and subsequent API endpoint to post the current data to MongoDB to store and track historical data that had 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 were used for each of the aforementioned subsystems. The NPM package manager offered a great solution for this implementation by way of the Socket.IO library. The library offered both a client-side and server-side library for implementing easy-to-use APIs for creating these two-way channels of communication. When data was posted to the backend server from the respective ESP32, the same API endpoint to which the data was posted transmitted this data via WebSocket to the front-end client associated with the proper user ID. Upon loading in, the React component tasked with fetching this data opened a socket to connect to the one on the backend. This in turn allowed data posted to the server to instantly make its way to the front end and then be displayed on the client's dashboard for monitoring. While simple REST APIs could have been used to implement this functionality, they had a few drawbacks compared to this system utilizing WebSockets. For one, without the use of these WebSockets, real-time bi-directional communication became much less feasible to implement.

7.3.3 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, and 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 can 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 can set their device to receive an immediate notification when a fault occurs.

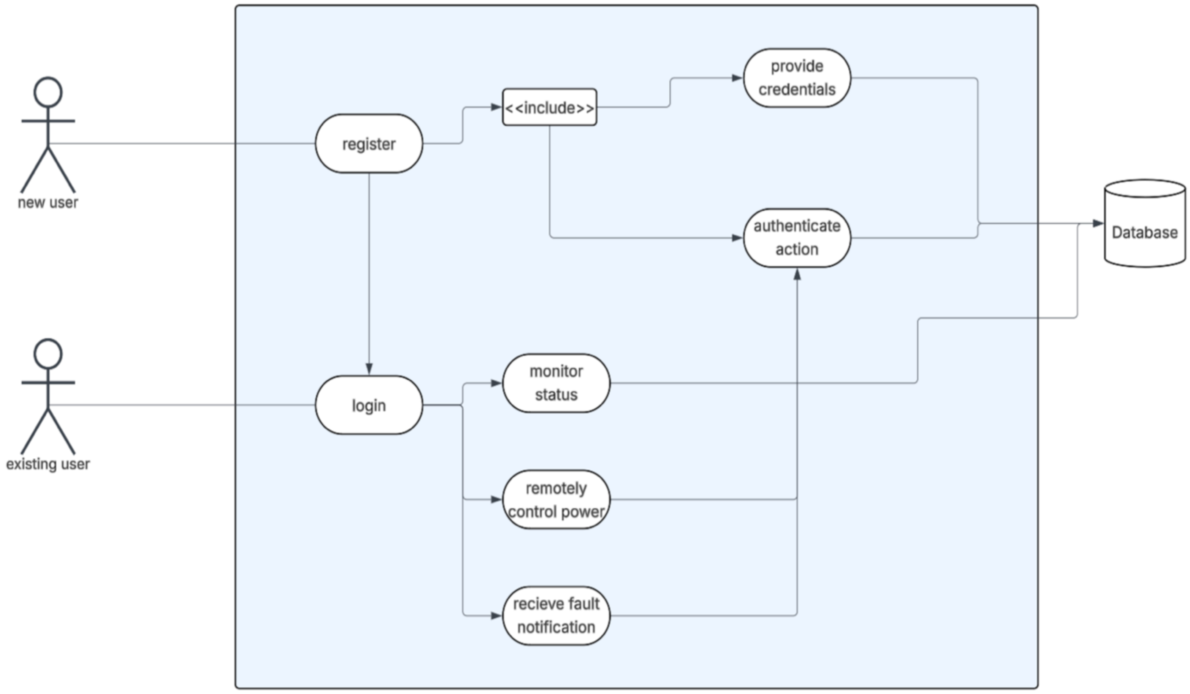

Figure 7.1: Use Case Diagram for the Webapp

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: Smart Breaker, Communication Module, Sensor Module, and User Interface. The Smart Breaker 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 Sensor Module. Additionally, a one-to-one relationship exists between the breaker and its Communication Module, which manages connectivity. Lastly, the system's design for remote monitoring and control is reflected in the User Interface class, which represents the app/website and is associated with one or more Smart Breakers. 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 User Interface sends a command to the Smart Breaker through the established association. The Smart Breaker uses its Communication Module to carry out the operation, and its Sensor Module components would detect the resulting status change.

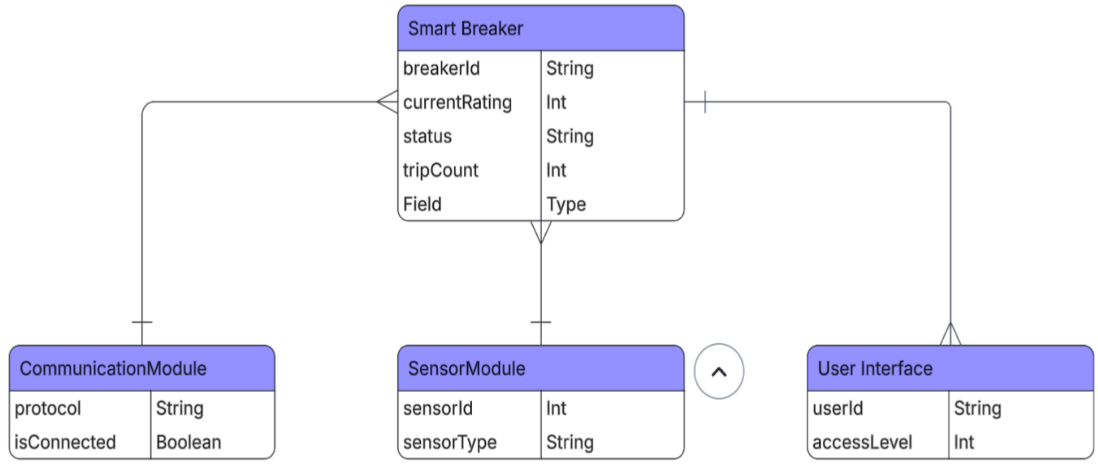

Figure 7.2: Class Diagram for Smart Breaker Website

The sequence table provided details the step-by-step interaction between the system's components and the: Existing User, User Interface, Database, Smart Breaker, Communication Module, and Sensor Module 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 power control (ON/OFF) action on the User Interface (Step 1), which requires database authentication (Step 2). The device verifies the change by checking its Sensor Module (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 Smart Breaker (Step 4), executed via the Communication Module (Step 5).

Table 19: 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

7.4 Testing and Validation

The SABRE smart breaker system's strong performance depended on a thorough testing and validation approach that covered the whole technological stack, from the full-stack system handling user interface and data persistence to the embedded firmware carrying out real-time control. Three main stages comprised testing: Full Stack Backend Testing, which focused on scalability, security, and data integrity; Full Stack Frontend Testing, which guaranteed user experience and accurate data representation; and Embedded Software Testing, which focused on real-time constraints and hardware interaction. This multi-layered strategy ensured that the system requirements were met by both the remote monitoring features and the safety-critical operations.

7.4.1 Full Stack Backend Testing

The real-time dashboard, user authentication, and collection of data from thousands of devices were all handled by the Node.js and Express.js backend. Here, testing primarily made use of Swagger and Postman and focused on security, performance, data persistence, and API dependability.

The API testing strategy was greatly enhanced by utilizing both the OpenAPI Specification (Swagger) and the Postman platform, each serving a distinct and critical role in ensuring API quality. The API contract was defined using Swagger, which was essential for tight data structure enforcement and documentation. Every component of the Node.js endpoints, such as arguments, request body structure, and security criteria (such as the required JWT for the /api/v1/data/live POST endpoint), was fully defined. This ensured that the ESP32 embedded programmers and the React frontend followed the same contract by establishing a single point of truth for all developers. To prevent integration problems, Swagger tools also provided the required schema validation, enabling automated tests to verify that the API response payloads were constructed as intended.

Postman, on the other hand, was the main tool used to carry out functional, integration, and manual testing against the deployed Node.js server. It provided a direct, interactive environment to mimic the behavior of the ESP32 devices and client dashboards, and it was actively utilized throughout the development cycle to build and manage collections of API requests. The manual verification of the authentication middleware by executing POST requests with purposefully altered or absent JWT tokens to verify the correct 401 (Unauthorized) security response, and the end-to-end flow testing of data ingestion, where a real-time data POST was immediately followed by a GET request to MongoDB to confirm data persistence and integrity were two important tests carried out in Postman.

7.4.2 Full Stack Frontend Testing

An accurate, responsive, and user-friendly interface for monitoring and control had to be provided by the frontend, which was developed using React for the client dashboard. Component Unit Testing and End-to-End (E2E) Testing were the two categories of frontend validation.

To separate UI elements, component unit testing was carried out using programs like Jest and React Testing Library. For example, dummy data representing the three main states ON, OFF, and TRIP was passed to the Breaker Status Card component for testing. The test verified that the component accurately produced the corresponding color, text label, and icon for each condition, guaranteeing that consumers received clear and instant feedback on the status of their device. Additionally, tests validated interactive components. For example, they simulated a user's click on the remote toggle switch and verified that the component successfully attempted to send the required WebSocket control message to the backend using a simulated Socket.IO connection.

End-to-end (E2E) testing replicated a complete user experience in an actual browser environment and was frequently carried out with tools like Cypress or Playwright. This demonstrated how the frontend and backend worked together seamlessly. The Remote Control Loop Validation was a fundamental E2E test case that involved a virtual user logging into the application, navigating to the device dashboard, and clicking the "Turn OFF" button. The test asserted the following sequence: the command was successfully sent to the server, the server transmitted the command to the SmartBreaker, and most importantly, the UI was updated almost instantly to show the OFF status, reflecting the WebSocket confirmation received from the server. This validation ensured that the system as a whole, as shown in the Sequence Table (Table 18), was operating in unison. Other E2E tests included user registration, device linking, and ensuring the historical data charts correctly loaded and displayed data retrieved from MongoDB through the REST API. The SABRE system ensured that its foundation was secure, scalable, and dependable for commercial deployment through this thorough testing process.

Chapter 8: System Fabrication/Prototype Construct.

8.1 MCU PCB Layout

The brain behind the SABRE smart breaker was the MCU board, at the center of the board contains the MCU to allow ease of access to the rest of the components, reducing the risk of latency in signal communication. Since through-hole soldering was one of the main techniques implemented, the risk of cutting through long wires was apparent. Furthermore, larger devices such as the MCU were given a substantial amount of space to reduce the risk during the soldering process. For the rest of the components, surface mounted soldering was used due to its slim and quick nature. USB ports were implemented by themselves and given enough space to allow access for both cables to fit as well as being far enough away from each other to reduce the risk of signal noise disturbing the analysis of signals within our MCU.

Beyond component placement, careful consideration was also given to routing practices to ensure stable operation of the SABRE system. High-current traces, particularly those carrying the AC load, were intentionally routed with increased width to minimize resistive heating and voltage drop, while low-voltage signal lines were kept short and isolated from noisy sections of the board. The grounding strategy was also prioritized. Strategic via placement helped maintain clean return paths and reduce electromagnetic interference across the board. Additionally, clearances were maintained around sensitive analog traces, and decoupling capacitors were placed as close as possible to the MCU and regulator pins to ensure stable power delivery during fast switching events. These practices not only enhance measurement accuracy but also improve the overall reliability and manufacturability of the PCB, ensuring that SABRE can withstand the mechanical stresses and electrical noise typical of AC circuit-level hardware.

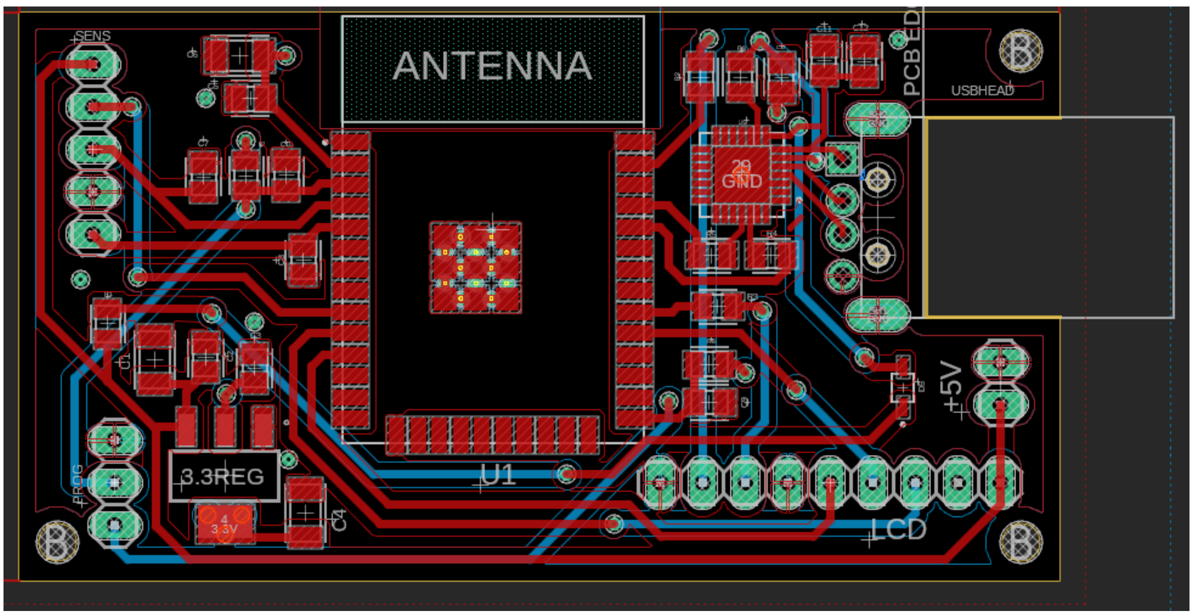

Figure 8.1: MCU PCB Layout by Authors

Figure 8.1 presents the complete printed circuit board layout and how it will look without the components being soldered on. Vias are noticeably sparse to further reduce the risk of latency within the entire system. No battery pack or power system is apparent in this design as the system will use the signal itself as a source of power. Hence, the input will serve as the source of power and will power the MCU, Hall-Effect sensor, solid state relay, antenna, digital communication setups, and others. Various external PCBs will attach to the main PCB via male and female header pins to provide proper voltage regulation of the components at 5V. A large enough space was given for the separate PCB in the bottom left corner of the MCU clearly visible as a square with a female header pin in the middle

As is evident by the board itself, not many components were required in the final design of the main board due to the nature of the smart breaker itself. Most of the device operations will occur within the MCU and website where they will incorporate smart operations such as wireless communication and live monitoring to a database through software implementation.

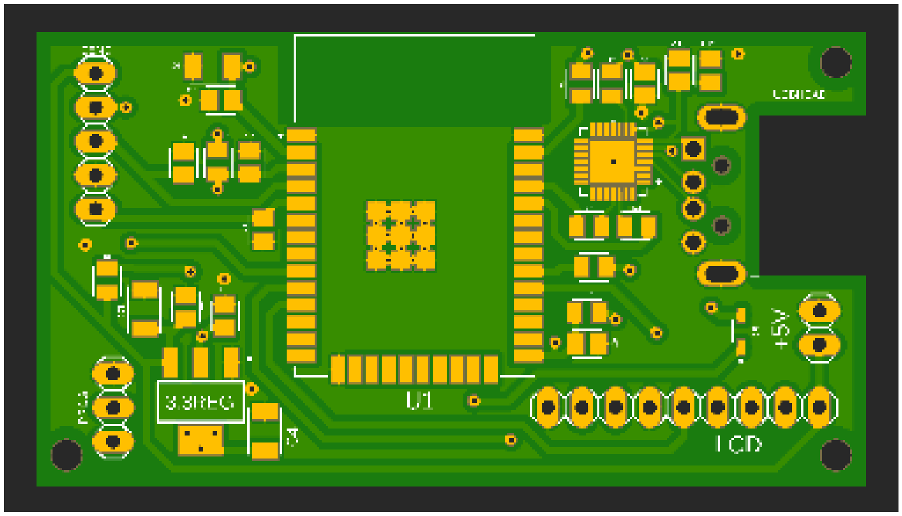

Figure 8.2: MCU PCB Manufacturing Preview by Authors

8.3 Power Regulation Board

Power regulation is primarily facilitated by the switch-mode power supply, responsible for rectifying, and then dropping the 30 VAC signal down to an appropriate 5VDC signal for providing power to the secondary side components. To provide an adequate signal to the ESP32, a 3.3V linear regulator was included to provide a 3.3V source for the microcontroller to properly operate with. Due to there being no power damping components in series with the 5V transmission line, the other components such as the Hall-Effect sensor and the solid-state relay are both powered by this line. No voltage drops or loss occurs when running through these components, thus their uses are not limited to the power regulation of this device.

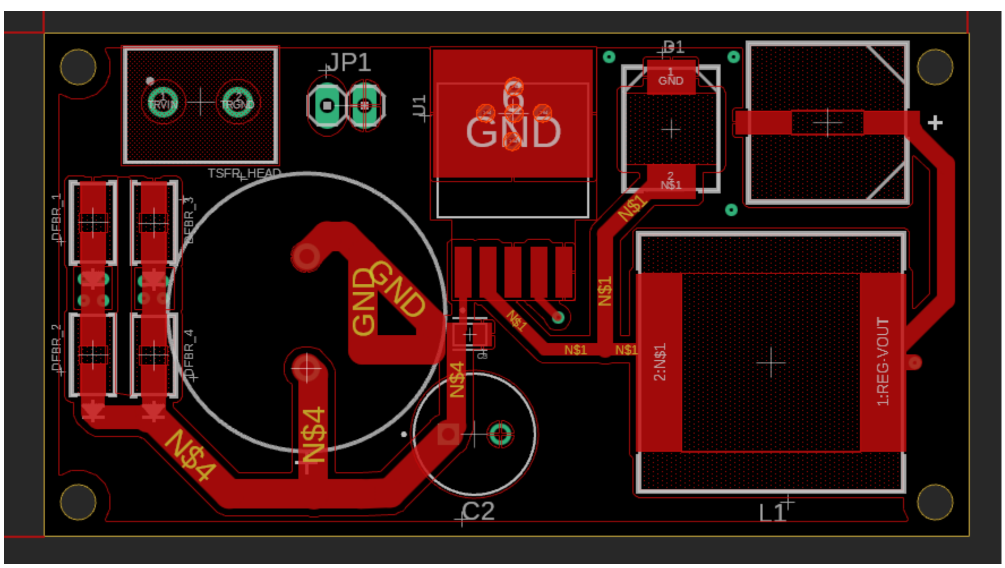

Figure 8.3: SMPS/Rectifier Circuit Layout by Authors

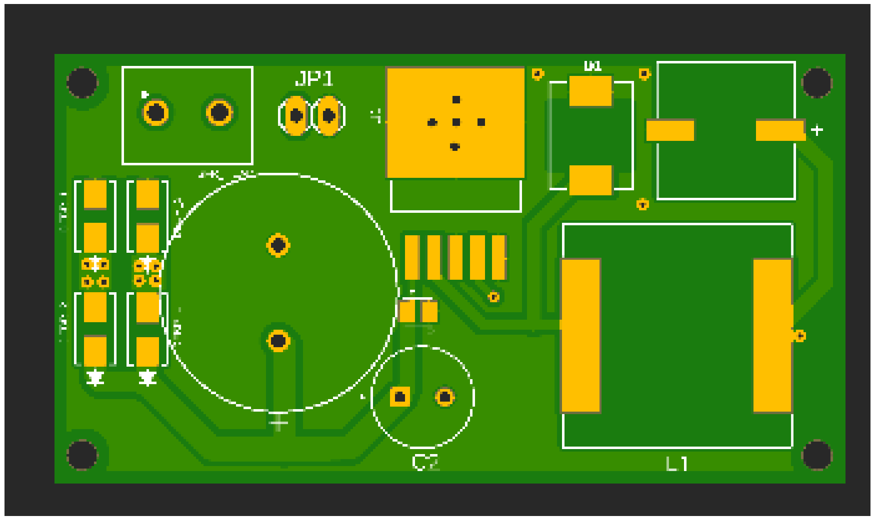

Figure 8.4: SMPS/Rectifier Manufacturing Preview by Authors

8.4 Sensor Board

For a current and voltage measuring device, the Hall-Effect sensor was deemed more fit for the job of fault-current detection and implementation. Unlike irregularities in the voltage detection, the fault-current detection is much more efficient as it does not require the need for extra calculations of phasor math, hence it does not need to be connected directly to the MCU. Instead of being directly connected to the solid-state relay, the output of the hall effect sensor is connected. Along with the hall effect sensor is the temperature sensor which relies on the same physical phenomenon as a conventional breaker to sense when it is an appropriate time to trip, hence perfect for our voltage trip mechanism.

8.5 Solid-State Relay

The Solid-state relay interconnected with the Hall-Effect sensor and MCU serves almost as a transistor in our PCB where it will open and close circuits based on a voltage input that will be sent to it either from the MCU. The main power signal will be sent directly to here. The signal will be sent here from a separate power supply uninterrupted. To ensure nothing else can flow from the power supply to the load if the relay rails, the relay will close the circuit ensuring no current flows through.

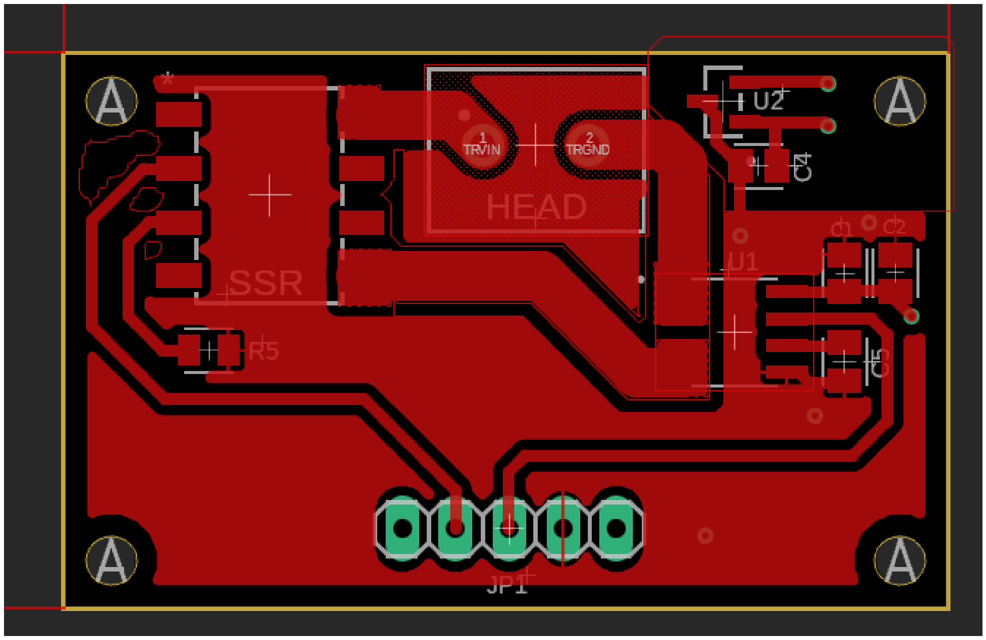

Figure 8. 5: Sensor Circuit Board Layout by Authors

8.6 LCD Board

The last board is the LCD driver board that is in direct communication with our MCU board. The LCD driver stepped down to 3.3 V which had already been stepped down previously from the 5 V on the regulator board. The LCD board serves as another means of communication for the user to provide immediate data of the sensor readings from the sensor board. Figure 8.6 shows the layout of the LCD board.

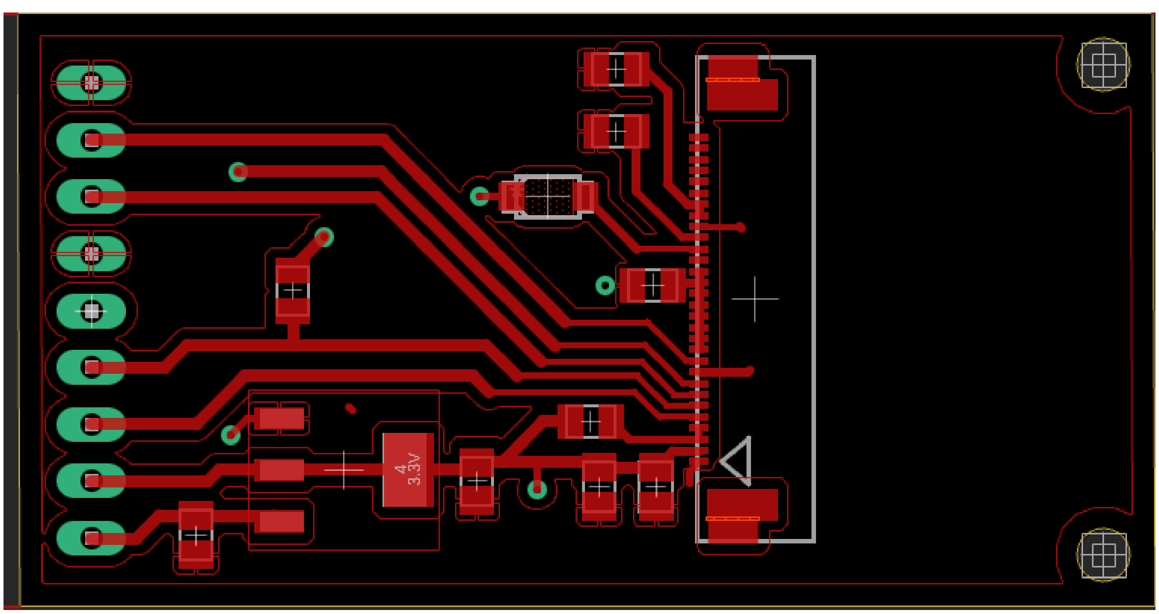

Figure 8. 6: LCD Board by Authors

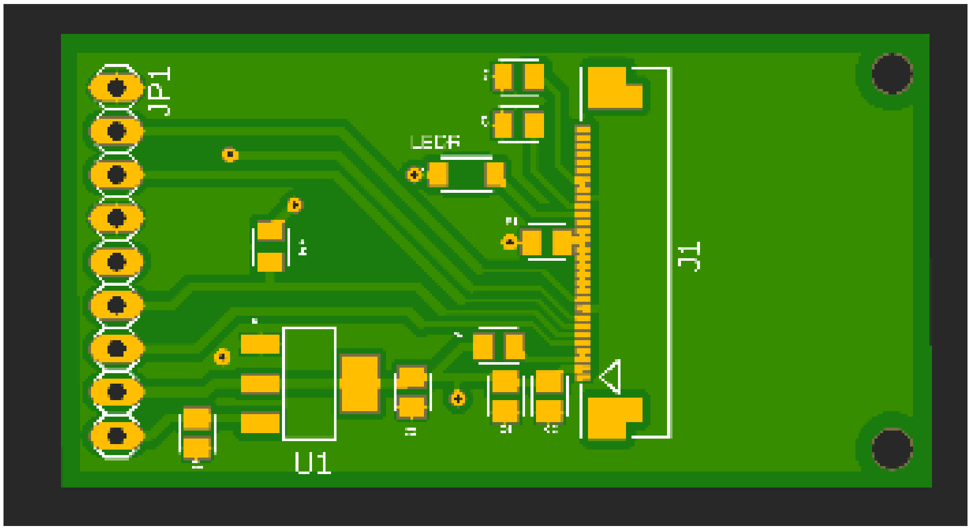

Figure 8. 7: LCD Board Manufacturing Preview by Authors

8.7 PCB Conclusions

There are 4 PCBs in total to form the SABRE smart breaker, all of which must fit within the size constraints of our chassis which are 45 mm x 70 mm x 73 mm to simulate the size of a conventional dual pole breaker. All PCBs were made as compact as possible to fit within these constraints. The MCU board being the largest was left with the most space within the chassis and thus had to get its large separate chamber. All other boards were given smaller individual chambers with holes in between to allow wirings to flow correctly and without lag. During testing the LCD was found to be synced up with the website interface down to the millisecond, so no lag in communication appeared there either. All in all, the four PCBs performed harmoniously with each other and better than expected.

Chapter 9: System Testing and Evaluation

9.1 Simulated Power Source

To simulate a 25VAC signal, the TR100VA001 was used for high stress performance testing. To test its output delivery rating, a resistive load of 12 Ω, rated for a total of 100 watts, was placed in parallel alone with the power source to measure its effectiveness. An expected alternating current of a little of 2A was measured being output from the transformer, confirming proper operating conditions.

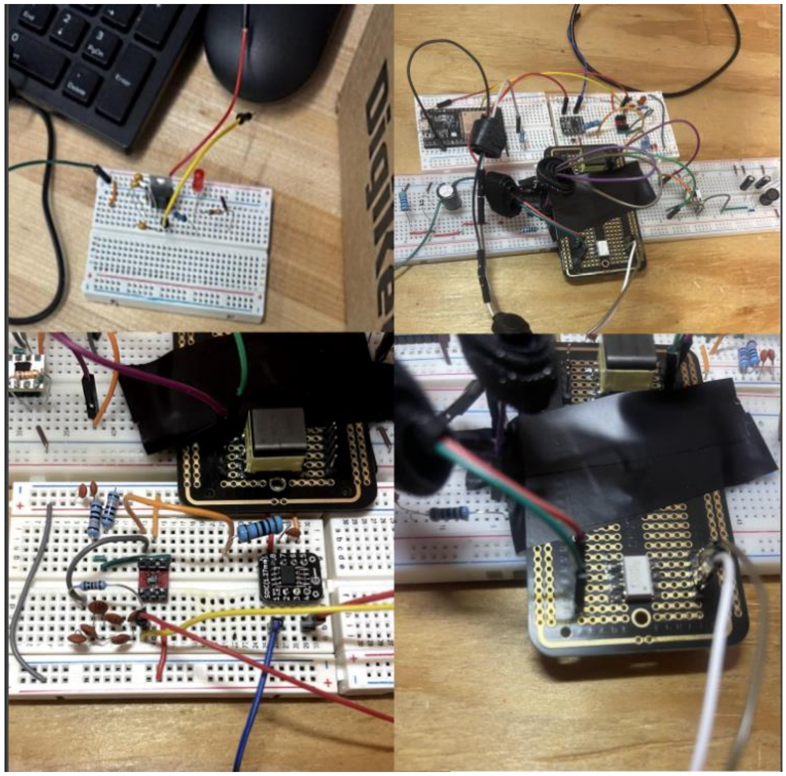

Figure 9.1: (From Top Left Going Clockwise) 3.3V Linear Regulator, Isolated SMPS, Solid-State Relay, Current Monitoring Circuit

9.2 Switching / Breaking

The component responsible for the switching of the conductive line is the TLP3547 Solid State Relay, an optocoupler based SSR designed to allow use of AC signal being passed through. Initial validation began with confirming complete isolation between the LED driven control side and the primary MOSFET output stage to ensure no measurable leakage or continuity to prevent ground loops, regardless of the state the relay was in. Once that had been confirmed, a low-voltage DC conduction test was performed using a 9V battery placed across the input terminals and controlled through a 5V signal sourced from a generic microcontroller. This verified correct turn on thresholds for current driven LED for the optocoupler inside and gave a rough real-world measurement to showcase the minimum power loss over the internal MOSFET array. Following this, the SSR performed a high-voltage AC conductivity test by applying the secondary side of the transformer to the input terminals to assess proper operation during the intended scenario, and to confirm minimal to no waveform distortion from the internal solid-state components. To ensure effective performance under continuous load, the relay was subjected to 2.5A of alternating current by introducing the previously mentioned 12Ω resistive load. The load was placed in series on the output terminal and ran continuously for approximately 10 minutes to monitor the thermal dissipation and stability under extended operation. Finally, reliability under dynamic conditions was evaluated by rapidly toggling the control input to assess the

TLP3547's ability to switch on and off repeatedly with consistent timing, minimal delay variation, and without any observable degradation in conductivity performance.

9.3 Current Monitoring

The ACS712 Hall-Effect sensor is the primary component tasked with providing load current measurements to the ESP32 for real-time monitoring. The sensor was configured in tandem with an auxiliary LM321 OPAMP to increase the output resolution to 610 mV / A. This current monitoring circuit was first evaluated under no load, being supplied directly with 5V to confirm the measured quiescent output voltage to be VCC / 2. Following this, the output voltage was dynamically measured by applying a known DC voltage, a 9V battery in this case, to drive a 100KΩ potentiometer to dynamically measure the full spectrum of the sensor's analog output compared to the current draw to confirm reliable consistency. This was done twice, routing the current draw orientation in opposite directions to effectively test the output signal in relation to a "positive", and "negative" current. To evaluate the performance under an AC signal, the simulation transformer was applied in tandem with an 18Ω resistive load to both confirm whether the sensor captures values frequently enough to supply accurate measurements to the ESP32 and whether the sensor's output analog sensor waveform remained centered around the 0A midpoint. Using a DMM to measure the DC voltage, the output remained centered around this midpoint as expected. When switching to AC measurement, it showed the expected RMS voltage swing in relation to the AC current being drawn from the load.

9.4 Power Regulation

The LM5180QNGUTQ1 flyback controller IC is at the heart of the power regulation circuit used to achieve a safe operating voltage for powering all the secondary side components. Before testing the regulating circuit, it was necessary to construct a full bridge rectifier with a 100uF bulk capacitor in parallel to the load signal to convert the full AC waveform into a DC signal with minimal output ripple. This was confirmed to be functioning properly, with a measured output rippled from peak to peak to be around 100mV, an adequate signal for inputting into the flyback stage. Initial testing of the regulating stage involved utilizing the Tektronix AFG 3022B function generator to feed in a 60 Hz sin wave with an amplitude of only 5V to confirm clean startup and switching in a lower power environment to test, troubleshoot, and monitor the regulator's switching waveform before feeding it the high-power output from the transformer. Once the primary side was confirmed to be in proper operating order, the secondary side output voltage was evaluated with no additional load attached over a 5-minute period to gauge whether continuous switching operation on the primary side had any discernible effect on the performance of the secondary side output voltage. A 100k Ω potentiometer was then connected to the output of the regulating stage to evaluate both the primary side frequency switching, and the secondary side output voltage when varying loads were applied to the output. In addition, the efficiency of the regulator was evaluated during this varying applied load phase by measuring both the input and output power, and by taking thermal measurements to ensure that the regulator did not surpass the safe operating threshold. Once this initial low input voltage testing was completed, the module was then evaluated under the full weight of the transformer supply voltage, performing the same tests as above to ensure proper operating characteristics under the proper expected conditions.

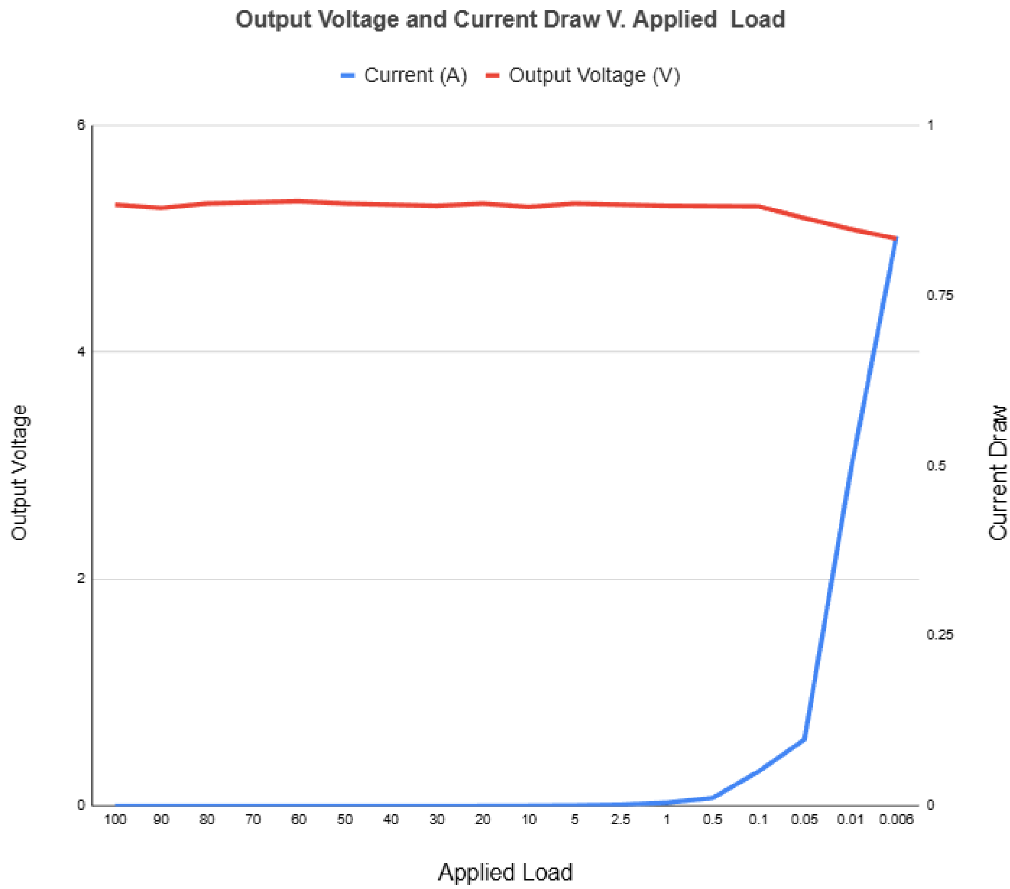

Figure 9.2: Voltage Regulator Output Voltage and Current V. Applied Load

Figure 9.3 illustrates the output voltage and current drawn from the regulator using a 100K Ω potentiometer, allowing for adjustments down to 1K Ω. Subsequently, resistors ranging from 500 Ω to 6 Ω were applied individually as loads to test the regulator's ability to deliver current near its rated threshold. The output voltage remained stable at just over 5V until the current exceeded 500mA, at which point a slight voltage sag was observed. This sag was relatively minor, with the voltage dropping to approximately 4.9V when the current reached around 800mA.

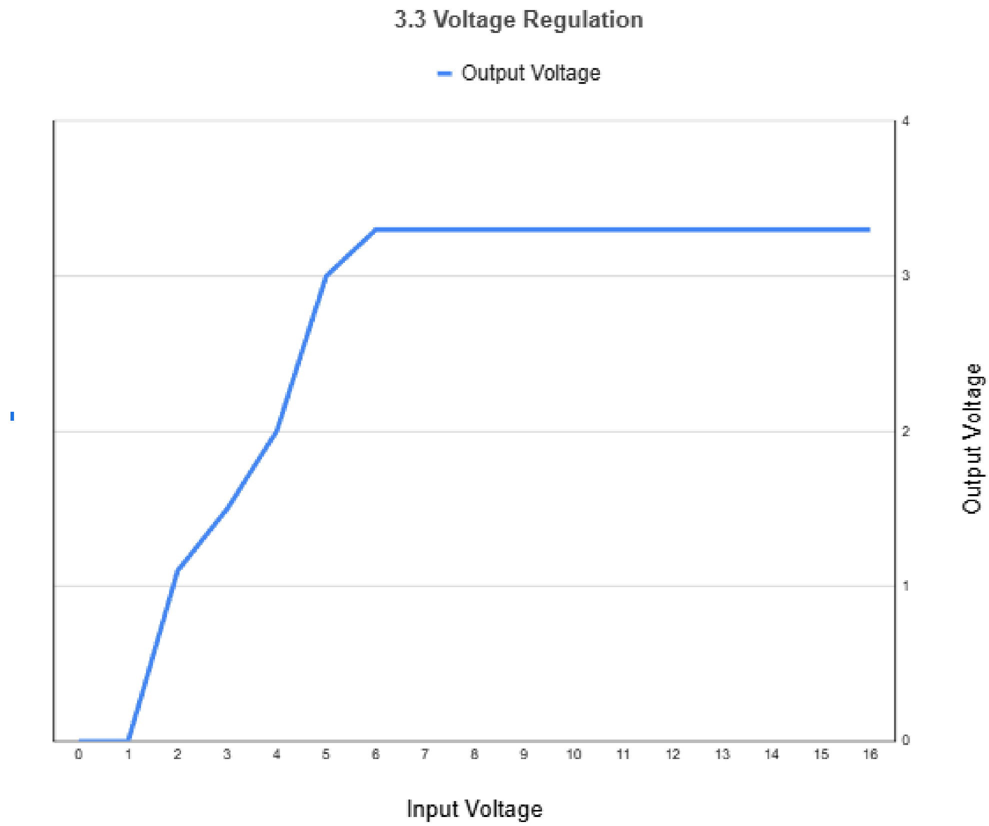

Figure 9.3: 3.3 V Linear Regulator Input V. Output Voltages

Figure 9.3 illustrates the output voltage of the 3.3V linear regulator in response to varying input voltages from a DC power supply. The necessity for this linear regulator arises from the ESP32's requirement for a 3.3V supply to maintain its appropriate logic levels, and the switched-mode power supply operates at 5V. Instead of designing a separate SMPS solely for the microcontroller, a linear regulator effectively remedies this issue, reducing the voltage down to the required levels. Linear regulators are commonly employed in many microcontroller development kits, including the ESP32 itself, allowing them to be powered with a 5V USB connection while maintaining 3.3V logic levels.

9.5 Embedded Systems Performance

The embedded software encapsulates the monitoring, transmission, and operation of the measuring and current switching hardware components within the circuit breaker.
Each of the auxiliary components on the hardware side relies on stable operation of the microcontroller software to ensure correct functionality. Initial testing of the ESP32 involved manual tests of interacting with the other components individually while being powered via USB to ensure no problems arose that could be attributed to the flyback converter. Small programs were written to perform actions such as manually driving the input of the SSR based on serial input within the terminal and to read known DC current values measured by the Hall-Effect sensor to adjust appropriate calculations based on discrepancies between reported values and the actual value. The ESP32 was then powered

from the flyback converter fed into a 3.3V linear regulator to ensure that no issues such as brown outs arose from the switching regulator not being able to properly supply the microcontroller. Each subsection was then fully put together to run demo trials on the functionality of all the components working together.

With each component properly integrated with one another, it was time to perform performance testing on the full circuit. Initial testing began with having all components powered on from the flyback controller to ensure that each part was adequately powered to maintain correct operation. This included probing with a DMM to measure the voltage levels of nodes such as the input to the Hall-Effect sensor, the output from the gain stage of the current measuring circuit, and the output from the 3.3V linear regulator. Once proper operating voltages were confirmed, it was time to apply a load across the breaker. Doing this involved using 18 Ω of resistance across the load output, giving a supply current of roughly 1.3A. A DMM was connected in series from the output of the load back to the return of the transformer supply to confirm current to serve as an accurate basis of comparison for measuring the current draw of the load. The ESP32 was connected back onto USB, so that current measurements from the Hall-Effect sensor could be read from the serial monitor. Current measurements were taken across a 12 Ω, 18 Ω, and 24 Ω load. During this period of testing, evaluations were performed on the reported accuracy of a known 1.3A current draw, compared to the DMM, in relation to certain parameters for calculations being adjusted.

These parameters included the number of samples taken within the sampling phase, the frequency of the samples taken, and the resolution about the analog signal produced by the current. All these values were fine tuned to optimize the accuracy of the readings while minimizing the time taken during the sampling period.

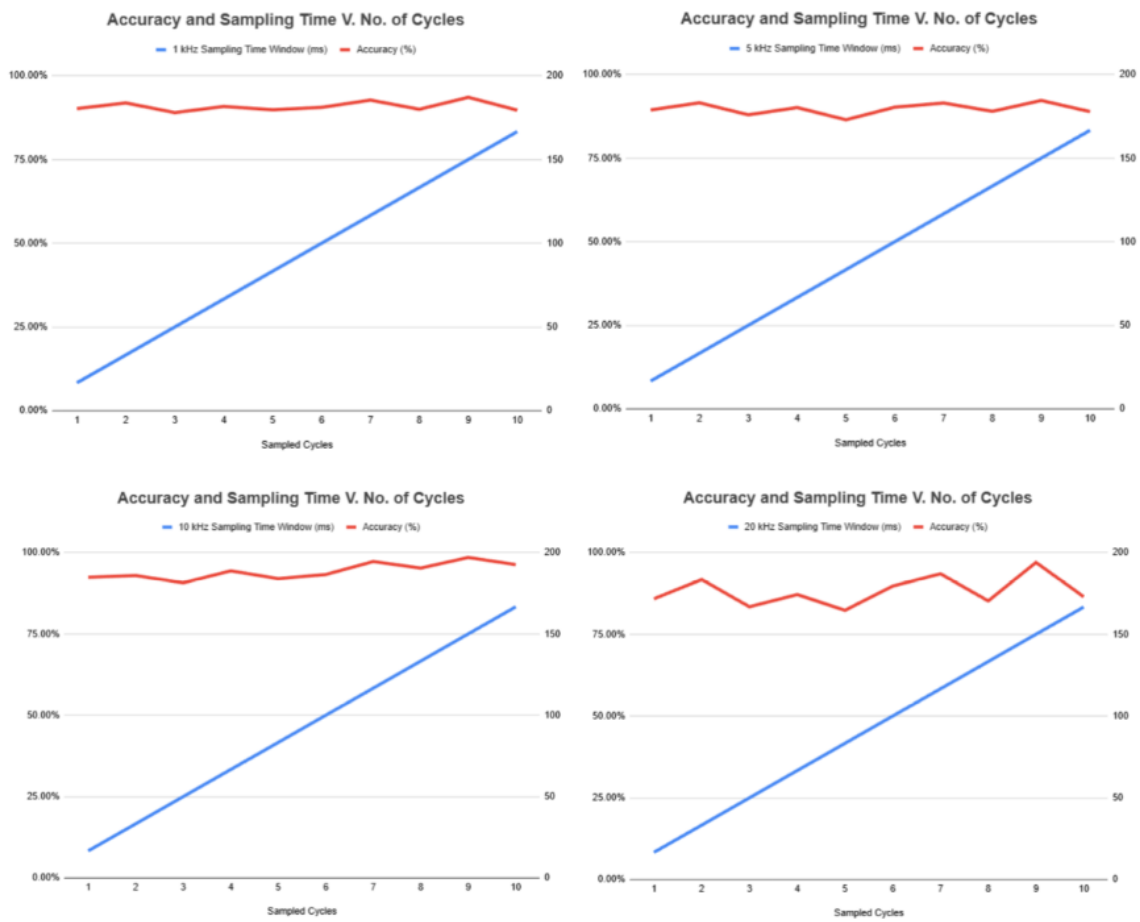

Figure 9.4: Comparison of Accuracy Over N No. of Cycles Between 1 kHz - 20 kHz

Figure 9.4 displays the accuracy of mean measured current samples over a range of 1 to 10 full AC cycles at varying sampling frequencies between 1kHz and 20kHz. The results show that increasing the number of full AC cycles sampled at any frequency will generally increase the accuracy of the RMS current computed. Prior to testing, it was thought that maximizing the sampling frequency would be the absolute best for computing accurate current values, but that turned out not to be the case. The ACS712 has a maximum bandwidth in reporting analog signals to the microcontroller, and because of this, at a certain point, increasing the sampling frequency leads to diminishing returns in terms of reported accuracy. Going above 10kHz, the overall accuracy began to not only decrease, but more variation was found in the calculated accuracy between sampling counts. This has been determined to be because after passing 10kHz, performing faster sampling leads to capturing more noise within the waveform, leading to less accurate measurements overall when averaging the collected samples. In addition to this, increasing the sampling frequency while fixing a sample count that lines up with the number of full cycles leads to a higher software overhead for the processor to bare.

9.6 Software Performance

The software performance of the SABRE smart breaker included the full stack software performance, enabling the user to remotely monitor and interact with the embedded systems components. The full stack software is divided into two parts, the front-end software, handling task considerations such as user interface, previous users to the website, direct communication between interrupting handling and the MCU, and overall user experience. The backend handles all the communication of the software and database which handles the data such as previous users and saving all their data between the last usage as well as what should be communicated between the website and the SABRE system.

Front-end implementation testing of the software was simply the design process as it just involved the user interface. Though it did require some testing with the backend development seeing if the database truly connected directly to the front-end showing live readings of the smart breaker in action, though in this case a simple voltage source was applied and scaled up and down for user notifications. Also, semaphores were tested simply by including a button and checking if the rest of the software was picked up on it by checking the outputs for a simple return signal. Most difficult came from the backend development process.

Backend development testing required the use of the MCU with the frontend code. Involving direct lines of communication to be sent through each. For example, if a button was pressed on the website through the front end of the software it would need to communicate with the backend to communicate with the antenna embedded within the ESP32 board. A simple test was performed by adding LED and resistor in series to one of the outputs of the development board, then further integration of the code was tested with the Hall-Effect sensor, voltage readings, and solid-state relay were all implemented as discussed in the embedded systems section.

9.7 Final Design Comments

The PCB designs went through multiple iterations to reach our desired constraints by having them be as small as possible while still being able to maintain their large power lines. At first the PCBs were all set on one board, however, if we had continued with this design, we would not have been able to fit this inside our chassis. Hence, the large PCB was separated into four smaller PCBs, though the chassis had to be resized to fit the new sizes of the PCBs it was far more reasonable than an extremely large chassis. In the end, the reviewers loved our final design.

Chapter 10 - Administrative Content

10.1 Work Distribution

In this project, the work was distributed amongst everyone who had the most expertise in a specific field. Two members of the research group were electrical engineering majors, and two members were computer engineering majors. Logically it followed that the electrical engineers with more experience in power distribution and component applications would contribute more to the work associated with the smart breaker and its tripping capabilities while the computer engineers would work through the software components of the entire system. Both teams would help each other along the way.

Table 10.1: Distribution of Work Table

Electrical Engineering	Responsibilities
Emmanuel Lopez	Administrative Documentation
	PCB Design
	Chassis Design
	Soldering

Electrical Engineering	Responsibilities
Eliezer Urdaneta	Project Lead
	Design Documentation
	Research Documentation
Computer Engineering	**Responsibilities**
Carter Harman	Sensor Selection and Implementation
	MCU Software Implementation
	Frontend Software Implementation
	Backend Software Implementation
	PCB Schematics Design
	Chassis Design
	Chassis Manufacturing

	Soldering
Computer Engineering	Responsibilities
David Durosinmi	Frontend Software Implementation
	Backend Software Implementation
	Website Design and Communication
	Soldering

10.2 Budget and Financing

The budget of the SABRE smart breaker was not limited to anything specific by the sponsors, however, the parts were bought by the researchers themselves. No money was allocated to the researchers during the semester, instead, the receipts were kept by the researchers that bought the parts and were given to the sponsors to the project so that they could return the money back. Because of this the strain on the budget of each researcher was kept to a minimum due to our own budget constraints. Hence the entire budget for the project was kept around $500, allocating the budget to specific areas as needed.

Most of the budget was sent to the PCB design to account for costs of components, shipping, and extra parts in the event of breakage. To get an exact cost of the components and parts, go to the bill of materials.

Table 20: Budget table

Sub-System	**Budget**
PCB Designs	$475
Web Application	$35
User Interface	$3
Total	**$513**

10.3 Bill of Materials

Costs for the bill of materials were taken as exact prices and do not include shipping or tax. In some materials such as the cost of shipping and the cost for the design for the PCB, the cost is estimated as not exact amounts were found until the completion of the PCB design.

Table 21: Bill of Materials for PCB

Bill of Materials for PCB			
Component	**Name**	**Qty**	**Cost**
Flyback Regulator	LM5180NGUR	5	$22.65
Replacement Buck Reg.	LM2576HV	3	$26.40
30-Pin LCD Connector	WM7976CT-ND	2	$5.42
60 mA LED DRV	AL5809-60P1-7	2	$1.44
3.3 Linear Reg.	LD1117S33TR	5	$1.70
30V Schottky Diode	BAT760-7	3	$1.41
ESP32	ESP32-WROOM	2	$9.68
UART Bridge	CP2102N	3	$12.96
Hall Sensor 1	ACS71230A	2	$5.84
Hall Sensor 2	ACS71220A	2	$5.84
Screw Terminal	691137710002	5	$1.80
Temperature Sensor	MCP9700T-E/TT	5	$2.00

60V Schottky Diode	MBRS360T3G	4	$1.28
FT LCD Display	ER-TFT019-1	2	$12.78
Solid State Relay	TLP3547	3	$22.98
SOT23 TO DIP ADAPTER	1568-00717-ND	2	$2.50
LCD Breakout Boards	SPI TFT LCD Display Module	2	$15.99
USBA Female Header	MEETOOT	10	$6.99
Wire wound Potentiometer	Electronics-Salon 200W 500 Ohm	1	$35.00
100 VA Transformer	TR100VA001	1	$54.99
Micro Current Transformer	DL-CT08CL5	1	$7.99
Generic Perfboard Kit		32	$8.50
Misc.	Resistors, Capacitors, Switches, Inductors		$82.44
PCB Boards		5	$41.61
PCB Shipping		5	$84.01
Total			$474.20

10.4 Project Milestones

For a project of this scale multiple milestones were mentioned in the table below to keep the entire team updated on what needs to be completed by what time during the two semesters of our project design. 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 at certain meetings. Because we have a sponsor for this project, we have incorporated sponsor meetings with both Dr. Qun Zhou Sun and the company she is working with, Grid Interactive Things Inc. The Senior Design I and II milestones have certain dates attached to them.

Table 22: 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
Init. Demo Video	10/20/2025	11/25/2025	1 Month

Table 23: Senior Design II Project Milestones

Project Fabrication			
Title	Start Date	End Date	Duration
Initial Model Assembly/Software	01/05/2026	02/02/2026	1 Month

Development (Prototype)			
Initial PCB Order	01/12/2026	01/26/2026	2 Weeks
Bug Testing and Fixing	02/02/2026	03/02/2026	1 Month
PCB Revision 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	04/20/2026	04/20/2026	1 Hour

Senior Design I and Senior Design II tasks are accurate and have been completed as expected. No issues arose during manufacturing, and the presentation went over smoothly with no hiccups.

Chapter 11 - Conclusion

In conclusion, the SABRE smart breaker project, developed in collaboration with Grid Interactive Things Inc. is the next step when discussing smart protective devices within residential buildings. The primary objective of the SABRE smart breaker is to protect the load device for which it is connected to from damage via sudden overload, short circuit, or strong voltage implementing standards and codes as covered by the National Fire Protection Association, the Institute of Electrical and Electronics Engineers, and the International Electrotechnical Commission. The device is meant to expand upon the applications of the conventional breaker by integrating smart technology within the breaker as devised by the research team from the University of Central Florida. The SABRE Smart breaker performs fault current protection, overload protection, and monitoring via Wi-Fi to keep the user informed on any irregularities or disturbances that may have occurred within the system, this also allows them direct control over the breaker.

Three major components encompass the design of the SABRE smart breaker. The ESP32 MCU provides direct communication between the analysis of signal parameters and how the microcontroller must react to mitigate the situation. The MCU operates via a step-down voltage transformer, full-bridge rectifier, and voltage regulator to both power the MCU keeping it at a steady power rating as well as providing direct access to the signal without damaging the microcontroller. Furthermore, the transformer used allows for extreme precision of the input signal hence allowing for a correctly stepped-down voltage signal that can be assessed. In terms of its first major component, the over voltage detection system, it consisted of a temperature sensor, piggybacking on the idea of the conventional breaker using a bimetallic strip bending in a specific manner in order to trip the breaker. Instead of implementing this design, the SABRE smart breaker used a temperature sensor to monitor the trace of the live wire connected to the load for this mechanism.

The second major component of the smart breaker was the fault-current detection of the system. The devices implemented a Hall-Effect sensor instead of a counterpart commonly used in substation industry which is known as the Rogowski coil. Within substations current levels must be watched and regulated but they cannot watch over the current levels directly, instead the currents are stepped down via a step-down current transformer. From there the currents are sent through a system that contains a Rogowski coil that uses the magnetic fields of the electromagnetic field to determine the current levels. Though the Rogowski coil is not being used in the final design, the method of current level detection is used. A cheaper alternative through the hall effect sensor was used instead since the Rogowski coil is both much bulkier and harder to implement through a printed circuit board and because it costs more than the alternative. Though the hall-effect sensor can be used in conjunction with the microcontroller that was used in the final design, the software calculations were a lot more complex due to the calculations of the magnetic field patterns. Though the coil is more robust and harder to break, the hall effect sensor provides more benefits in its sleek nature and compact design. If the current signal is kept below the maximum threshold, threat of breaks can be reduced, also due to the limits of the Rogowski coil, use of currents as small as this become difficult. Hence the fault-current aspect of the smart breaker becomes part of the design.

The main tripping mechanism to stop current from flowing within the smart breaker is a solid-state relay. Like how a mechanical relay works in larger power devices, solid state relays can break a circuit based on the input of a control signal like how a MOSFET operates. MOSFETs were considered in the design of the smart breaker but most were too small in terms of power regulation and based on how it operates in physics, it is dangerous to keep the MOSFET within the design. MOSFETs depend on their gate voltage to control the flow of current within the transistor, however, if the current within the drain to source aspect becomes too high, leakage current can flow through and destroy anything connected to the device at hand. This is dangerous, especially with fault currents since fault currents tend to be in an extremely high range and occur within an extremely short amount of time. Though in both regards the MOSFET and the solid-state relay the amount of delay to properly trip the breaker is almost negligible, the solid-state relay outperforms the MOSFET in full protection capabilities.

A fourth side component with the microcontroller that does not need to be soldered or wired in any method is the antenna allowing the microcontroller to connect directly to any Wi-Fi that the software tells it to. This component can mainly be considered a software aspect as most work will be conducted in communication of the software of the device and the software of the website developed by our two computer engineers. With the microcontroller being connected directly to the website, live readings from the microcontroller can be delivered in real time allowing the user to determine any course of action if they wish to proceed. Actions such as manually tripping the breaker, resetting the breaker, or accessing previous histories of irregularities within the power source can be read directly from the website. For this reason, the ESP32 board that was chosen earlier was the best choice, its use of radio frequencies and built-in antennas allows it to excel in areas where other microcontrollers do not.

Altogether, the ESP32 MCU is the main processor behind the operations that goes on within the circuit breaker. The temperature sensor will detect the thermal readings of the trace within the PCB to determine if the signal contains any error readings and relay all this information through the antenna to the website allowing the user to access the history of previous irregularities within the system. This action can also be performed via the hall effect sensor, where instead of a simple voltage being analyzed, current will be analyzed, and its readings will be relayed to the microcontroller and website as well. Through the website, the user can communicate with the microcontroller where the MCU will inform the user of specific data on previous readings, such as what was tripped, when, and possibly how such a trip occurred. Users can decide when the breaker can be reset or trip it via their phone through the website so long as they are connected to Wi-Fi as the signal can be sent to the antenna where it will communicate with the microcontroller through the software developed by our computer engineers and directly tell the solid-state relay to trip immediately. Proper scheduling algorithms were created to ensure that the tripping mechanism within the solid-state relay remains the highest priority within the coding tasks to keep the system as safe as possible.

The document serves as a comprehensive record of SABRE's design process covering the developmental process, research process and methods, design methodologies, industry standards and codes used to guide the research team along the way, components used, cost summaries, and various other topics. SABRE could not have been completed without the assistance of the University of Central Florida and its staff along with all the members of the SABRE team. As the design reaches its final stages the team is undoubtedly confident in its ability to deliver a safe and effective project hoping to expand upon innovation of protective technologies of tomorrow.

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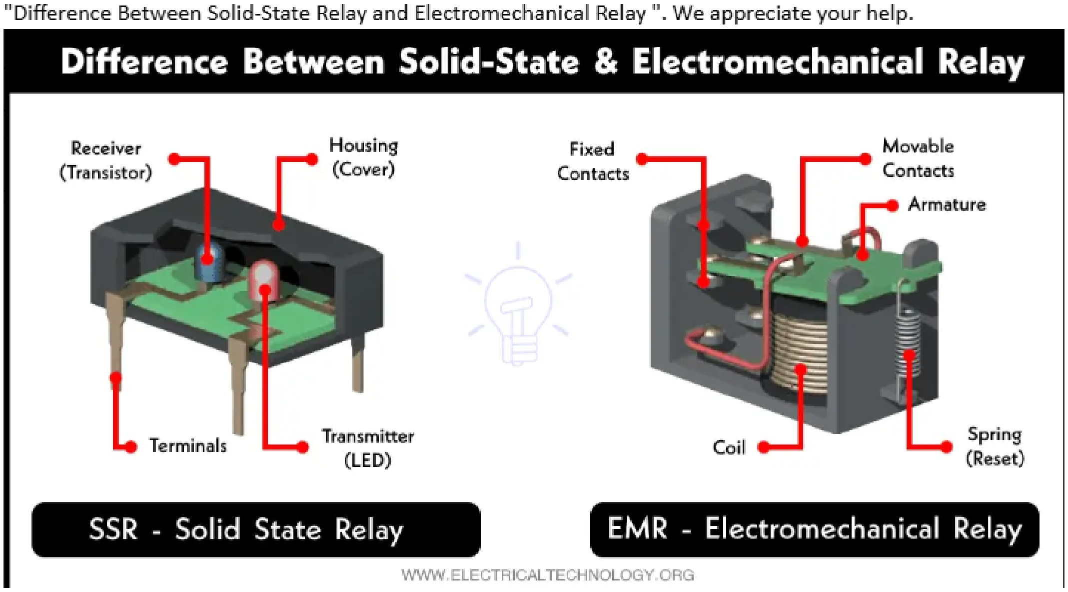
Appendix B – Copyright Permission

Figure 5.1 Permission Requested

Good Morning,

My name is Emmanuel Lopez; I am a student at the University of Central Florida. My team and I are currently working on a project for our senior design project.

My team and I were hoping to obtain permission to reproduce the following image(s) in our project documentation relating to research on our project as attached. The image(s) is from one of your articles "Difference Between Solid-State Relay and Electromechanical Relay ". We appreciate your help.



Thank you,
Emmanuel Lopez

Figure 3.1 Permission Granted

ET

Electrical Technology<eeetblog@gmail.com>
To: You

Mon 11/24/2025 1:13 PM

Hi there,

Your request is approved. Please link back with proper credit to the original link.

Thanks and best regards

Advertisement & Content Management Team Manager at
Electrical Technology

...

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?

Share Link: https://chatgpt.com/share/68ed7f89-0c3c-8005-a414-9a84490541c4

[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."

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Flowchart of Smart Breaker